Water Requirements for Food Assessed at Different Levels of Scale

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PREFACE

This report is the result of the first major research of the author. Six months was spent on the relation between food consumption and water appropriation, with the current report as outcome.

The author wants to thank his first supervisor Sanderine Nonhebel for the supervision and support during the research. Her feedback was useful and the author learned a lot about doing research and about writing a report. Cindy Visser, the second supervisor, is to be thanked for her comments on the concept version of this research.

The author strongly believes that today's environmental problems have to be addressed and solved in an interdisciplinary manner. The current research was a useful exercise in combining insights from several disciplines.

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SUMMARY

English summary

Fresh water scarcity is a major and increasing problem. Increasing water scarcity will have consequences for food security; thus strategies are needed to reduce the appropriation of water. Since agriculture uses 70% of all freshwater withdrawals, the production of food is a major reduction target. Most present reduction strategies are aimed at the decrease of the water footprint of our food. From this perspective, two major strategies are suggested: technology to increase crop yield and trade from water-rich countries to arid countries. This combination will lower the water footprint of crops and of our food. In this research, it is argued that more fundamental reduction strategies are possible. To show this, the food production system is assessed on different scale levels: photosynthesis & macronutrient synthesis level; crop level; agricultural level; and cultural level. By doing so, relevant reduction factors for each scale level are obtained. The lowest scale level is the photosynthesis & macronutrients synthesis. This route needs 100 liter for the production of daily nutritional requirements. Using a combination of crops, excluding the effect of local production circumstances, 200 liter is required to produce our daily diet. Local agricultural influences have an effect on water use: the Dutch system needs 300 liter and the Spanish system needs 700 liter for the production of our diet. In the end, consumer preferences and associated diet choices lead to a daily water appropriation of 1500 liter per capita. Three categories of reduction strategies are suggested in this research. First: 'shifting cultural choices' to less meat and low water-consuming products. Second, 'increasing agricultural efficiency' to target water inefficiencies in the agriculture. Third, 'breeding for nutrients' emphasizes the more fundamental approach which highlights the quality of crops instead of the quantity of crops. This finding *'It's the nutrient'* opens a new perspective on crop breeding, fodder production and other issues. Further research is needed to examine more practical applications of this new perspective. By drawing more attention to nutritional quality, water appropriation can be reduced over the total agro-food system.

Dutch summary

De schaarste aan zoet water is een groot en groeiend probleem. De groeiende schaarste aan zoet water heeft gevolgen voor de voedselzekerheid in de wereld en daarom zijn strategieën nodig die het gebruik van zoet water verminderen. De productie van voedsel is een belangrijk doelwit voor deze strategieën, omdat de landbouw verantwoordelijk is voor 70% van het zoet water gebruik. De huidige strategieën om watergebruik te reduceren in de landbouw zijn gericht op het verminderen van de watervoetafdruk van ons voedsel. Dit perspectief leidt tot twee belangrijke reductiestrategieën. De eerste is een technologische strategie, gericht op opbrengstverhoging in de landbouw. De tweede strategie heeft te maken met handel en is erop gericht dat voedsel gaat van landen met veel zoet water naar landen met weinig water. De combinatie van beide strategieën zorgt voor een verlaging van het totale watergebruik. In dit onderzoek wordt echter beargumenteerd dat er fundamentelere strategieën zijn om het watergebruik van voedsel te verminderen. Om dit te laten zien, wordt een theoretische systeemanalyse gedaan. Het voedselproductiesysteem wordt op verschillende schaalniveaus ingedeeld: het fotosynthese & macronutriënt-synthese niveau; gewasniveau; landbouwniveau; en het culturele niveau. Op deze manier kunnen voor elk schaalniveau relevante reductiefactoren verkregen worden. Het laagste schaalniveau is het fotosynthese & macronutriënt-synthese niveau. De productie van de dagelijks benodigde hoeveelheid macronutriënten kost 100 liter water op dit niveau. Als dezelfde hoeveelheid macronutriënten geproduceerd moet worden met behulp van een combinatie van gewassen, dan is 200 liter nodig. Hierbij wordt geen rekening gehouden met de lokale productieomstandigheden. Worden deze wel in de analyse meegenomen, dan kost de productie van de dagelijkse hoeveelheid macronutriënten 300 liter in het Nederlandse productiesysteem en 700 liter in het Spaanse productiesysteem. Dit laat zien dat lokale omstandigheden een groot effect hebben op het uiteindelijke watergebruik. Op het hoogste schaalniveau zorgen culturele voorkeuren en keuzes van consumenten er voor dat 1500 liter nodig is om de dagelijkse hoeveelheid macronutriënten te produceren. Drie categorieën van strategieën worden geadviseerd in dit onderzoek. De eerste bundel van strategieën is gericht op het verschuiven van de consumentenkeuzes richting minder vlees en naar meer 'waterarme' producten. De tweede bundel van strategieën bestaat uit het verhogen van de

landbouwefficiëntie. Dit reduceert de waterinefficiënties in het landbouwsysteem. De derde bundel van strategieën bestaat uit de fundamentele benadering waarbij de nutriënten centraal staan. Deze aanpak benadrukt de kwaliteit van gewassen in plaats van de hoeveelheid gewassen. Dit opent een nieuw perspectief op de veredeling van gewassen, de productie van veevoer en andere onderwerpen. Vervolgonderzoek is nodig voor meer praktische toepassingen van dit nieuwe perspectief. In ieder geval, meer aandacht voor de kwaliteit in plaats van de kwantiteit van gewassen kan leiden tot een watervermindering in het gehele voedselproductiesysteem.

1. INTRODUCTION: RESEARCH AND REPORT

1.1 Subject of the research

Fresh water scarcity will be the major constraint to increased food production over the next few decades, according to the United Nations (UNDP, 2006). Increasing food production is needed to maintain food security over the next decades, as the world population is growing rapidly (UN, 2009) and becoming more affluent. It is shown that an increasing wealth leads to more affluent consumption patterns, illustrated by e.g. increasing use of animal products (Gerbens-Leenes *et al.,* 2010). Together, the growth of the population and the change in nutritional habits are leading to an enormous challenge for the agricultural sector to satisfy the needs of the people. The anticipated increase in global food production will have major consequences on the appropriation of water. Water scarcity is already a critical concern in parts of the world and will worsen if no action is taken. It is estimated that agriculture is responsible for 70% of total water appropriation (FAO, 2003). This implies that our food consumption has a large impact on water use and that strategies are needed to reduce the water appropriation associated with food production.

In this research, the water appropriation by our food production is investigated. As most attention in recent years has been drawn to the reduction of the water footprint of food, this water footprint method will be introduced first. The water footprint method is used in this research to show the development of Dutch water appropriation over the last 40 years, and to examine the reduction possibilities of the water footprint. After this short inquiry, it is argued that the water footprint methodology is just one scale on which the water appropriation can be targeted. Other scale levels will lead to other strategies. Therefore, more scales are introduced in this research. Each chapter will handle a different scale for our food production system. By assessing the water appropriation on different scales, the relevant factors per scale level are highlighted. These factors could provide important reduction targets for the total water appropriation.

1.2 Structure of the report

The structure of the report is basically the same as described in the previous section. The report is structured in four major parts: the introductory chapters, the body of the report, the concluding chapters and the appendices. The outline of the report is given below.

Introductory chapters. In the introductory chapters, the water footprint and the system description are introduced. The chapters are the following: ‘1. Introduction: research and report’; ‘2. Decreasing the water footprint of food’; and ‘3. System description and research questions’.

Body of the report. The body of the report handles the different scales and consists of the following chapters: ‘4. Photosynthesis & Macronutrient synthesis’; ‘5. Crop system’; ‘6. Agricultural system’; and ‘7. Culture’.

Concluding chapter. One concluding chapter is presented for an overview of the different scales and strategies and an overall conclusion will be given: ‘8. Discussion and conclusion’.

Appendices. Two appendices are provided. One will investigate the role of meat in more detail; the other contains the data used during this research: ‘I. Meat: what about meat?’; and ‘II. Data sheets’.

2. DECREASING THE WATER FOOTPRINT OF FOOD

2.1 Introduction

A lot of attention for the reduction of indirect water consumption has been drawn to water footprints (WFs). (See Water Footprint Network (2011) for an overview). Water footprints are the water equivalent of the well-known ecological footprint. The water footprint is a measure for the water use of a product, crop or service. In this chapter, the water footprint method is introduced and used for the calculation of water appropriation caused by the Dutch diet, over the last 40 years. It is shown that indirect water consumption has been decreasing over time and the reasons for this decrease will be explained. Thereafter, it is argued that the WF reduction is only one scale level at which water appropriation can be targeted.

The WF concept is, according to its creator Arjen Hoekstra, '*primarily rooted in the search to illustrate the hidden links between human consumption and water use and between global trade and water resource management.*' (Hoekstra, 2009). Water footprints can be calculated for all products or services. In this research, only the water footprints of crops are calculated, since the analysis is performed from an agricultural perspective. To calculate the water footprint of crops, evapotranspiration per hectare is estimated and divided by the yield per hectare. To explain evapotranspiration, a short introduction of evapotranspiration and soil water balance is given.

Soil water balance & Evapotranspiration

The hydrological system of a crop field comprises six main water flows: precipitation, irrigation, run-off, evaporation from the soil surface, transpiration of the crop and drainage (Gerbens–Leenes & Nonhebel, 2004). Evaporative demand is the driving force causing water to move from the soil to the atmosphere. This process is called *evapotranspiration (ET)*, involving direct water transport from the soil surface (evaporation; *E*) and indirect transport through the plant (transpiration; *T*). Besides water availability in the topsoil, the evaporation part is mainly determined by the solar radiation reaching the soil surface. In a small canopy crop, water is primarily lost by soil evaporation, but once the canopy is well developed, transpiration is the dominant process (Allen *et al*,. 1998). Evapotranspiration is mostly used to assess the total water needed to grow a crop. Weather parameters, crop characteristics, management and environmental aspects are factors affecting evaporation and transpiration (Allen *et al.,* 1998). The principal weather characteristics affecting evapotranspiration are radiation (*radiation driven component*) and air temperature, humidity and wind speed (*drying power or aerodynamic driven component*).

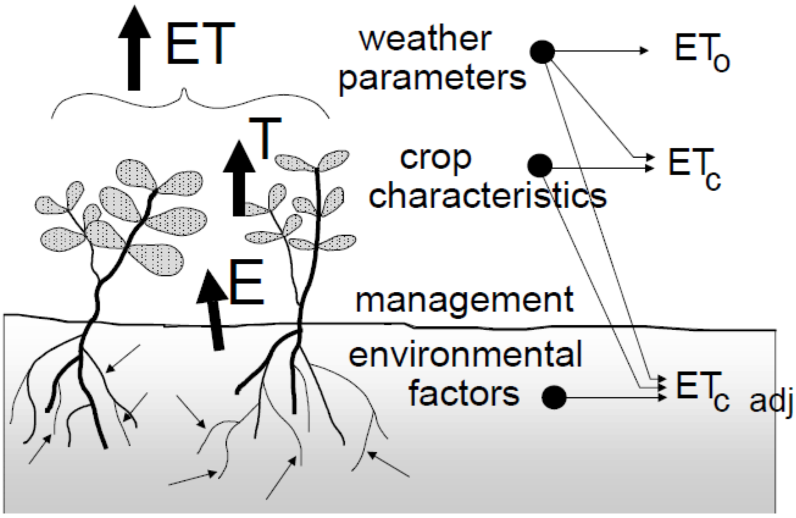


Figure 2.1. Evapotranspiration (ET) and affecting factors (Allen *et al.* 1998).

Crop characteristics include crop type, crop variety and development stage, which all have their influences on the ET levels. Management and environmental factors include soil water content, soil salinity, land fertility and application of fertilizers. They influence the evapotranspiration directly or indirectly by influencing crop growth. See figure 2.1 for an overview.

Mostly, when assessing evapotranspiration, standard conditions (ET_c) are assumed. This refers to '*the evaporating demand from crops that are grown in large fields under optimum soil water, excellent management and environmental conditions, and achieve full productions under the given climatic* *conditions'* (Allen *et al.*, 1998). Since it is very difficult to measure evapotranspiration in reality, evapotranspiration is estimated by calculation for which different equations can be used. The result is a so-called reference crop evapotranspiration (ET_o). In this research, the Penman-Monteith equation is used, as it is incorporated in the FAO software program CROPWAT (FAO, 2012).

The calculated evapotranspiration per hectare is divided by the yield per hectare to obtain a crop WF. Water footprints are the sum of a green WF, a blue WF and a grey WF. A green WF is the amount of water supplied by rain water, a blue WF is supplied by ground water or surface water and a grey WF is the amount of water needed to dilute pollution. In the current research this division is, for simplicity reasons, not made.

To see how the WF accounting is performed and to understand the major drivers behind water footprints, the development of the water appropriation of the Dutch diet over the last 40 years is studied. First, it is shown which crops are included in the analysis. Next, three different analyses are performed: one to see the effect of consumption, one to see the effect of yield and one to see the effect of the weather. In the end, it is concluded that some strategies are possible for reduction of water footprints, but that more fundamental strategies are possible for reduction of total water appropriation.

2.2 Methodology

To see the effect of the Dutch diet on water appropriation, seven products are included as indication for the total diet. The choice of the diet is based on three sets of data: the total consumed amount of the products, the total consumed calories of a product and the water footprints of the products. The consumption data are obtained from the FAO Food Balance sheet of 2007 (FAO, 2011). The water footprint data are derived from the WaterStat database (Mekonnen & Hoekstra, 2010a). To obtain the food categories with the highest water requirements for The Netherlands, the consumption data from the FAO are multiplied by their corresponding water footprint (for instance, if 200 kg wheat is consumed and the WF of wheat is 20 l/kg, total water requirements equals 4,000 liter). The water needs for the annual sugar consumption is calculated by using the *sugar, derived from beet*, water footprint in the WaterStat database. This is done because it is assumed that all sugar consumed in The Netherlands is derived from beets. After multiplying consumption data with water footprints, the highest total water consumers are included: wheat, potatoes, sugar beet and soybeans. Three livestock categories are chosen: pig, bovine, and poultry meat (see table 2.1).

Table 2.1. Crops and meats used in this chapter.

Crops	Meat
Wheat	Pig
Potato	Poultry
Sugar Beet	Bovine
Soybean	

Meat is an indirect water user, because crops are fed to animals before the animals are consumed. In the first, 'variable consumption' analysis, fixed water footprints for meat are used, derived from the WaterStat database (Mekonnen & Hoekstra, 2010b). For the 'variable yield' and 'variable weather' scenarios, a very basic assumption is made, obtained from the study of Goodland (1997). The water requirements of meat are calculated by making use of grain-equivalents. Grain-equivalents are an estimation for the amount of grain needed as feed to obtain a kilogram of meat. These grain equivalents differ per type of animal. The grain-equivalents for bovine, pig, and poultry meat are 7 kg, 4 kg and 2 kg, respectively (Goodland, 1997). Therefore, to assess the water need of meats, the water footprint of wheat is multiplied by their corresponding grain-equivalent.

Calculations water footprint

Three analyses are performed, with different variables. These analyses and their corresponding variables are described below.

Analysis 1. Variable consumption

The first trend calculations are performed with fixed yield and fixed weather characteristics. For this, a static water footprint from the WaterStat database is used. By keeping the water footprint constant, all observed changes can be attributed to changes in consumption. Global average water footprints are used first (because of the inclusion of soybeans) and the footprint used is the sum of the green, blue and grey water footprint. Next, Dutch average water footprints are used. Soybeans are excluded from this analysis, since the Dutch climate is not suited for the production of soybeans.

The consumption data per capita are derived from FAOSTAT (FAO, 2011) for the years 1961-2007. These consumption data are multiplied by their corresponding water footprint. The result is the annual *per capita* water footprint.

Analysis 2. Variable yield

To obtain a water footprint per ton of yield, the estimated evapotranspiration per hectare of a crop is divided by the yield. This implies that by *increasing* the yield, the water footprint per ton is *decreasing*. In analysis 2, the yield changes over time are incorporated in the analysis. Yields are obtained from Statistics Netherlands (CBS, 2001). Due to the availability of data, the trend is calculated for the years 1961-1998.

The weather characteristics are kept constant. The calculation of the water footprint is performed with the aid of CROPWAT, a software program from the FAO. By using CLIMWAT, another FAO software program, average weather data for the last 30 years was obtained for Groningen and this data is used for assessing the evapotranspiration in CROPWAT.

In table 2.2, the main characteristics for the introduced crops are listed. They are available in CROPWAT. For the soil characteristics, the FAO-standard ‘medium’ is used. Soybeans are excluded from this analysis, since this product is no part of the Dutch agricultural system.

The estimated crop water requirements (CWR) are expressed in mm. To calculate this unit to cubic meters per hectare, the following illustration is used. Suppose a crop with CWR of 10 mm. This means that the crop needs a water layer of 10 mm. In terms of volume, every square meter of the field needs 0.01 m water, or 10 liters (1l = 1dm^3). As a hectare is 10,000 m^2, 10 mm equals 100,000 l/ha, or 100 m^3/ha. Simplified: to obtain m^3/ha, CWR in mm can be multiplied by a factor 10. Water use per hectare is divided by the yield per hectare to obtain the water footprint per ton (in m^3) (Hoekstra *et al.*, 2011). In table 2.2., the input and calculations for the WF of crops are shown. The results of this calculation are comparable or somewhat higher than already existing water footprints (WaterStat). This implies that the present estimation is sufficient (Wheat: ±600 m^3 vs. 511 m^3; Potato: ±80 m^3 vs. 79 m^3; Sugar Beet: ±65 m^3 vs. 55 m^3) (Hoekstra & Mekonnen, 2010a). The exact difference between the calculation and WF from the WaterStat database depends on the year used in the calculation, since the yields differ per year. The calculation in table 2.2 is an example for the year 1997. A larger difference is present for the water footprint of sugar, since we have to multiply the footprint of the beet to obtain values for raw sugar. In the water footprint accounting by Hoekstra and Mekonnen, this is done by dividing the sugar beet footprint by 0.14 (product fraction) and then multiplying it by 0.92 (value fraction). By applying this on the current sugar beet footprint, the values are less comparable (±500 m^3 vs. 358 m^3), but nevertheless used in this research.

Table 2.2. Input and calculations for the WF of crops.

Crop/Meat	Crop Characteristics	Planting date	Harvest date	CWR (mm)	CWR (m^3/ha)	Yield (ton/ha)	WF (m^3/ton)
Wheat	FAO – CROPWAT – WINTER WHEAT	10- 11	10- 10	471	4706	7.7	611
Potatoes	FAO – CROPWAT	10-05	16-09	338	3380	43	79
Sugar Beet	FAO – CROPWAT	01-05	07- 10	381	3810	58	66
Soy Beans	-	-	-	-	-		
Pig Meat	4x WHEAT	-	-	-	-		
Bovine Meat	7x WHEAT	-	-	-	-		
Poultry Meat	2x WHEAT	-	-	-	-		

Analysis 3. Variable weather

The calculations for analysis 2 make use of climate data derived from CLIMWAT and CROPWAT. These data are averaged over the last 30 years. Because of these average data, CLIMWAT is not suited for the calculations of separate years. Therefore, climate data for each separate year are needed. From the European Climate Assessment and Dataset, data can be derived for the potential evapotranspiration (PET). This value indicates the total annual evapotranspiration during a particular year, based on e.g. wind speed, solar radiation, temperature and humidity of the air. For each year, PET values are introduced in CROPWAT and the evapotranspiration of a particular year is calculated. The crop characteristics, as well as the planting and harvest data, are the same as in analysis 2.

In the end, the three major factors –consumption, yield and weather – are combined into one analysis. The crop water use is calculated per year, and divided by the corresponding yield of that particular year. This water footprint is multiplied by the consumption of that year.

2.3 Results

Analysis 1. Variable consumption

The changes in indirect water consumption are calculated by the water footprint approach. Results of the calculation with a fixed water footprint, and thus only consumption effects, are given in figure 2.2. Compared to 1961, today's indirect water consumption is nearly 20% higher (600 m^3 vs. 500 m^3). This suggests that our water appropriation has increased during the last decades, due to a changing diet.

The indirect water consumption has peaked, according to this analysis, between 1990 and 1997 and has decreased a little after those years, mostly because of the lower quantity of pig meat consumed.

It is shown that especially the consumption of pig and poultry meat has been increasing over time, with a marked decline in the last decade for pig meat. The consumption of soybean is oscillating, while the consumption of potatoes and sugar stays more or less the same. Wheat has decreased over time, with a slight increase during the last decade.

Dutch and global agricultural systems are compared by using Dutch and global average water footprints. Local circumstances play a very important role and differences can be seen between global production and Dutch production. For an impression, the same calculation is performed as in figure 2.2, but with using Dutch averages. As was anticipated, the Dutch agricultural system uses less water than the global agricultural sector (figure 2.3). This is especially the case for bovine and wheat, which are produced much more efficient (2.5 times less water required) in the Dutch system. Pig meat requires nearly 1.5 times less water. Most products consume a factor 2.5 less water in the Dutch system. The effect of wheat is reflected in the lower requirements for meats, as grain-equivalents are used. Sugar from sugar beets consumes approximately 2 times less water compared to the global averages. It must be noted, however, that the Dutch scenario is also lower because soybeans are excluded. If soybeans are included in the scenario, using its global water footprint, the indirect water consumption is on average 80 m^3 higher.

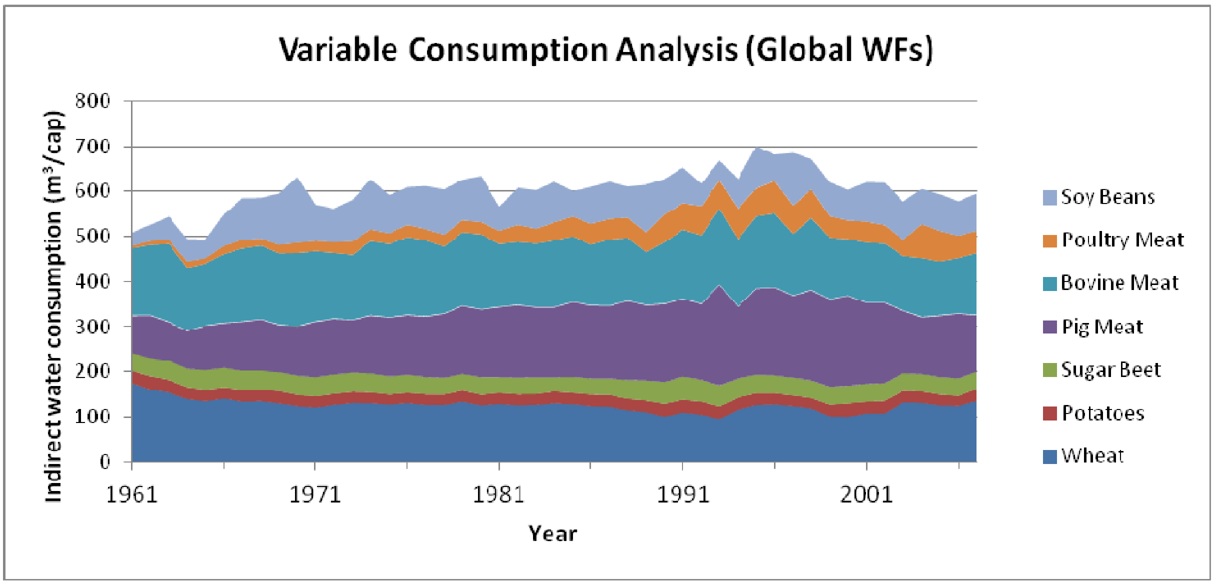


Figure 2.2. Indirect water consumption per capita, associated with the Dutch diet for the years 1961-2007. Calculated by the WF method using average global water footprints.

Analysis 2. Variable yield
In figure 2.4, the development of the water footprint per ton of crop is shown. The meats are not shown, as their footprints essentially reflect changes in the footprint of wheat. It is striking to see that the water footprint of wheat has decreased with 50%, while sugar beet and potatoes' water footprint did not decrease much. This can be attributed to the much higher improvement of yield in wheat.
An interesting picture is emerging: indirect water consumption is rising due to increased consumption, and crop water footprints are decreasing because of yield improvements. Therefore, it is interesting to combine these two trends, to see what the overall effect is. Figure 2.5 shows that the overall water footprint has decreased over time. The main reason is the large increase in the wheat yields. Since in this calculation the water footprint of meat is calculated by using grain equivalents, the increased wheat yields have a very strong effect.

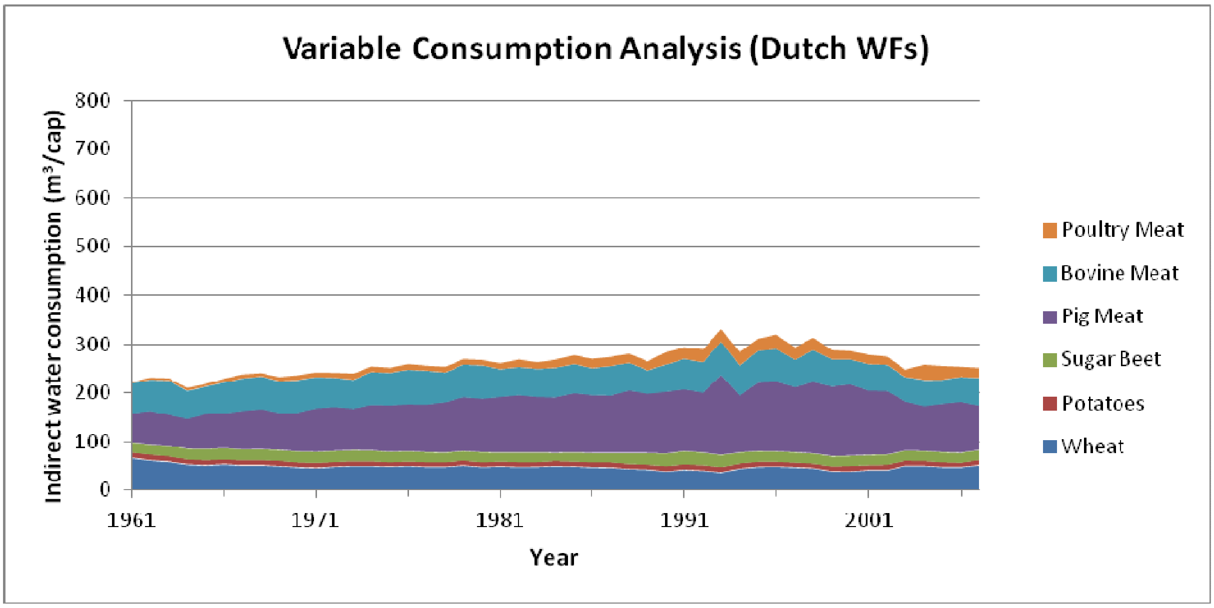


Figure 2.3. Indirect water consumption per capita, associated with the Dutch diet for the years 1961-2007. Calculated by the WF method using average Dutch water footprints.

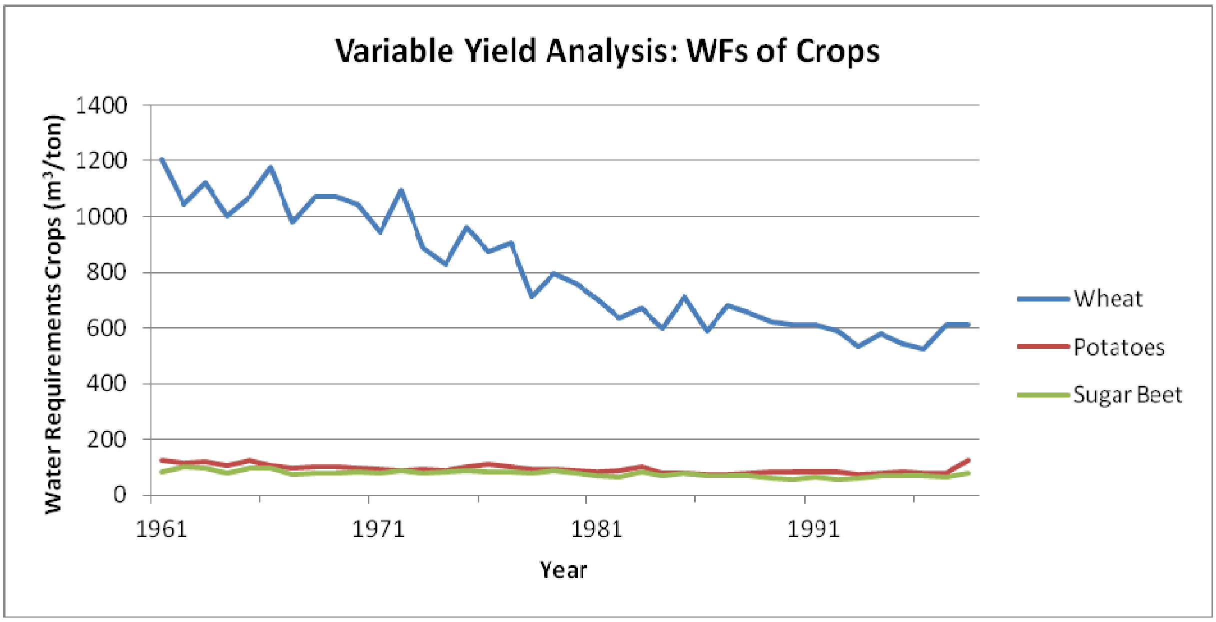


Figure 2.4. Water footprint calculated with variable yields.

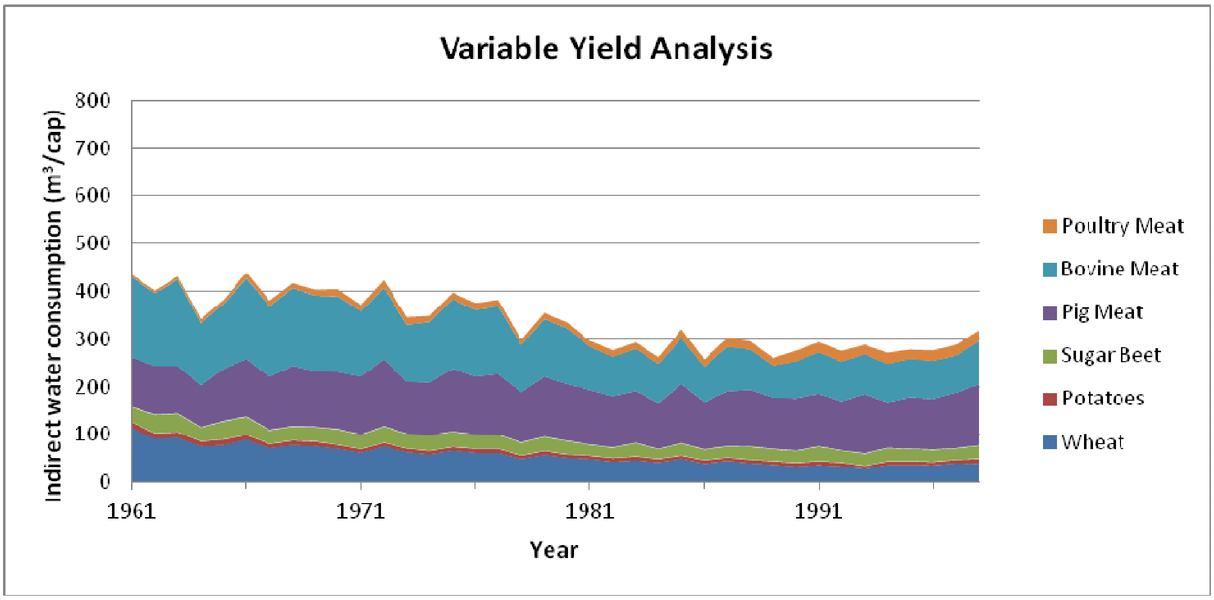


Figure 2.5. Indirect water consumption per capita, associated with the Dutch diet for the years 1961-1998. Calculated with variable yields and consumption.

Analysis 3. Variable weather

Using the evapotranspiration data from the European Climate Assessment & Dataset in CROPWAT, one can calculate the crop water requirements of a particular year. In a very hot and dry year, a crop 'uses' more water, because of the higher evaporative demand. This implies that the water requirement of a certain crop varies over the years because of weather characteristics and therefore the indirect water consumption associated with our diet varies. To give an indication of the changes in estimated crop water use, a graph of wheat, grown in The Netherlands, is provided (figure 2.6).

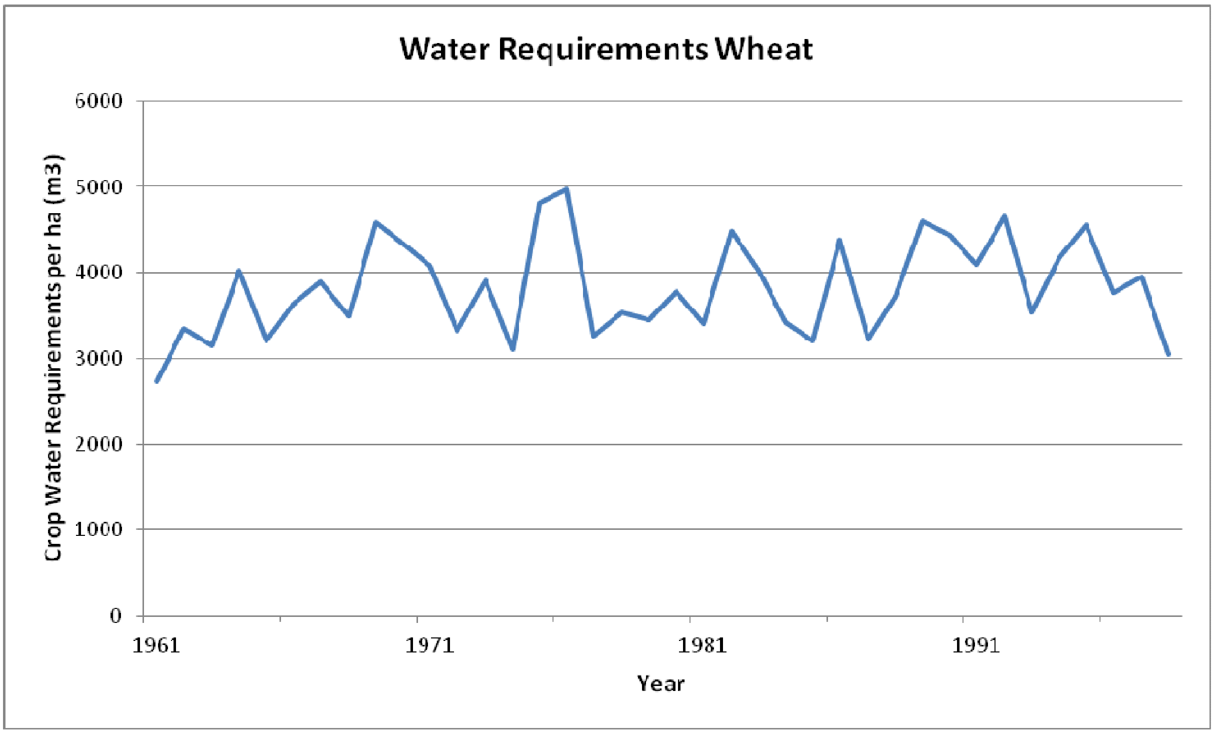


Figure 2.6. Water requirements of wheat over time, calculated with fixed yield and changing weather variables. The water requirements are the evapotranspirational needs of a hectare planted with wheat.

One can clearly see the dry and hot years (like 1976). Figure 2.6 only represents the changes associated with changing evaporative demand. When combining these data with previous data on consumption and yields, the following picture emerges (figure 2.7):

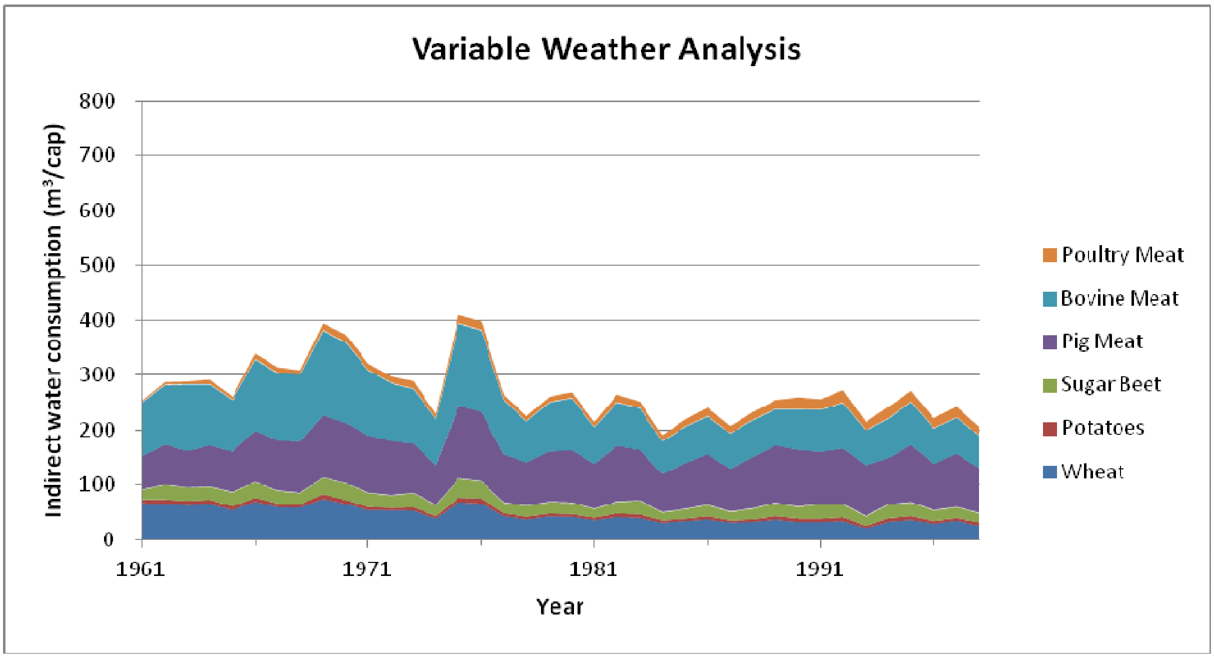


Figure 2.7. Indirect water consumption per capita, associated with the Dutch diet for the years 1961-1998. The figure contains the effects of consumption, yield and weather.

Overall, the water consumption associated with our diet is decreasing. A striking observation is the peak in the year 1975. This can be explained by a high evaporative demand during that year and a relatively low yield. The peaks which can be attributed to higher evaporative demand become less visible over time, because the increase in yield is overtaking.

2.4 Discussion

According to the water footprint approach, the total water appropriation has been decreasing over the last decades. The major cause for this decrease is the improvement of yield, especially for wheat. One of the reasons for this increase in yield is the rise in harvest index (Siddique *et al.,* 1990). The higher harvest index leads to more useful product per hectare, and therefore, total yield per hectare rises. The rise in yield causes the water footprint per ton to decrease. The trend in consumption patterns leads to more indirect water consumption, but the yield effect is much larger. Weather has no overall strong effect, but for some individual years, weather can have a large influence.

Using the water footprints of WaterStat, it is shown that the Dutch agricultural system requires substantially less water than the global system. The Netherlands have a temperate climate and therefore a relatively low evapotranspiration per hectare, which results in low water requirements in the water footprint scenario. Besides, the Dutch agricultural system is known for its high yields. The combination of both leads to a very low water footprint for Dutch crops.

In the weather analysis, hot and dry years can be distinguished very well. If we add this trend to the consumption and yield trends, it can be seen that peaks in the indirect water consumption due to hot and dry years becomes less marked. The reason is that the decrease in water footprint attributed to yield, is ‘overtaking’ the effect of the weather. The overall trend, when combining yield, weather and consumption, is that the water consumption associated with our diet is decreasing.

The analysis in this chapter is performed to examine the relevant factors on water footprints and the magnitude of these factors. The analysis is performed to obtain a qualitative picture, rather than a quantitative one. Some assumptions could have a substantial influence on the analysis and are therefore discussed.

For this research, the diet is constructed out of 7 most-consumed and water-using crops and meats. It is assumed that changes in these crops reflect the overall changes in the indirect water consumption, although other products might counteract this trend. For a more correct indication, more products and their respective water requirements have to be included. Another remark can be made about the sugar beet consumption. Only the sugar is eaten, and therefore Mekonnen and Hoekstra correct this by using 14% of the sugar beet (sugar percentage) and a value fraction (0.92). Because of this extra step some noise might be present in the computation. This could be the reason that the calculated footprint for sugar is higher than the footprint from the WaterStat database. The same applies to soybean. Soybean itself is not eaten; only the oil is used. However, in this analysis, soybeans are chosen for the calculation of indirect water consumption, while the consumption data are for soybean oil.

Not all evapotranspiration values are present in the ECA&D database, which is solved by taking the average value over the years. This might have an influence for particular years. Crops and soil characteristics are FAO-standards and might not represent the actual situation in The Netherlands. However, as weather has no large influence on the overall trend in water footprints, it is assumed that the conclusions about yield and trade are rather robust. Another important assumption is the use of grain-equivalents for meat consumption. This leads to the heavy weight of wheat in this analysis and changes in wheat's footprint have very large consequences. In reality, animals do not only feed on grain, but on a mix of different products, and this could dampen the large effect of the yield increase in wheat. However, the overall conclusion of yield increases is not affected. Therefore, from a water footprint perspective, increasing the yield has a large effect on our total indirect water consumption, so this might be a fruitful strategy. Another possibility is the trade of water-consuming crops from water-rich countries to arid countries.

Value of water footprint assessment

Two major reduction strategies arise from the water footprint methodology: trade and technology. By improving the technology and increasing the yield, the water footprint per ton of yield will decrease. And by trading water-consuming crops from water-rich countries to arid countries, water will be saved. These two strategies are very useful, especially from a policy perspective. However, more *fundamental* strategies are possible. The water footprint gives, for instance, no answers to questions like: what crop characteristics determine the water requirements? How can we increase the total efficiency of the agro-food system? The water footprint is related to things *as they are now.* Given the crops which are consumed at this moment, how can we reduce their water use? More fundamental questions are concerned with *what is optimal*: How do we *construct* a crop with lower water requirements? Can we match the agricultural products better with human nutritional needs? The goal of the current research is to examine these kinds of questions. Therefore, the system is expanded with other scale levels and these are introduced in the next chapter.

3. SYSTEM DESCRIPTION AND RESEARCH QUESTIONS

3.1 System description

The goal of this research is to perform a system analysis of the agro-food system, and to search for options to reduce our water appropriation by using different scale levels. In the previous chapter, it was shown that the water footprint method gives rise to two major strategies: trade and technology. However, it was also argued that more elemental strategies are possible. Therefore, different scale levels are used to assess different kind of solutions. The scale levels are presented in figure 3.1. Figure 3.1 also highlights the previous statement on the water footprint: the water footprint is almost on top of the production system (agriculture), and levels below represent more fundamental scales. During the current research, it will be argued that lower scale levels will also yield useful insights for the reduction of water appropriation.

The essence of the food production system is the nutritional requirement of the human body. The ultimate reason for food consumption is that people who do not eat will die. The human body needs a range of different nutrients and minerals. This finding is central to the present research and therefore a reference diet, consisting of macronutrients is constructed. The different production levels are used to produce this reference diet. This means that, for instance, it is investigated how much water the photosynthesis process needs to produce macronutrients. By doing this, relevant factors will be highlighted and used for the development of reduction strategies.

The nutritional requirements of the human body are simplified in this research to the macronutrient requirements. These requirements are derived from the Dutch Food Institute (Voedingscentrum) and listed in table 3.1. By using the different scale levels for the production of these macronutrients, it is investigated how much water is required per scale level.

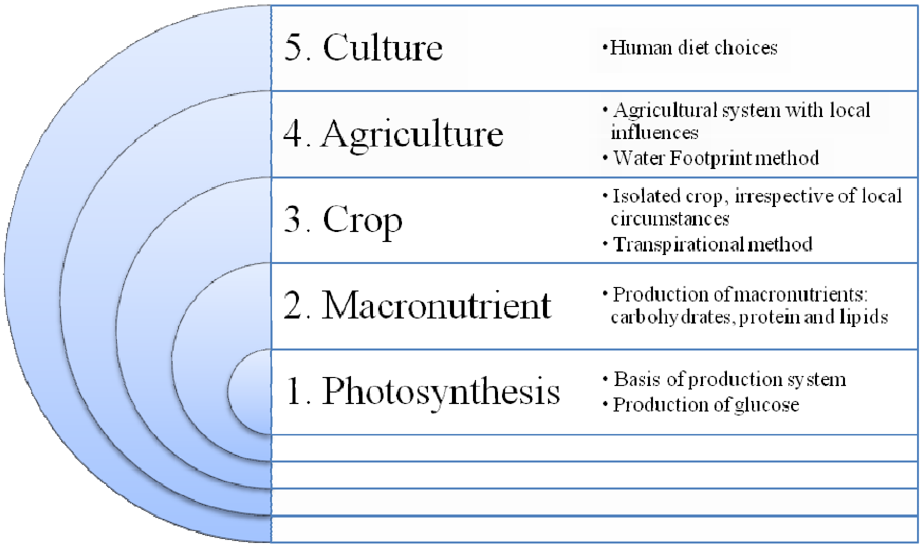


Figure 3.1. Agro-food system description and scale levels.

Scale levels

The basis of food production is the photosynthesis process. This process uses CO_2, water and radiation for the formation of glucose and oxygen. This process takes place in the chloroplasts of plants, mostly located in the leaves. The produced glucose is used for the growth of the plant, but also for the production of macronutrients. This implies that the lowest production level for macronutrients is the combination of photosynthesis and macronutrients. If we can 'capture' these two processes and use them for the production of the daily nutritional requirements, we have the most efficient production route.

One level higher, more closely to reality, is the 'crop system'. For the production of macronutrients and the process of photosynthesis, leaves and seeds are needed. Thus, crops are needed for the photosynthesis and macronutrient synthesis to take place. This crop system is conceived as isolated

crops and is irrespective of local production circumstances. This scale will assess crop characteristics' influence on water use of a crop. Using these insights, recommendations can be given for breeding.
Another level higher, and thus even more close to reality, is the 'agricultural system'. This scale includes the local production circumstances, such as weather and yield. To assess the water consumption associated with this scale, the water footprint methodology is used. From this scale, reduction strategies associated with local circumstances will be obtained.
The final, highest level is the cultural level. The food production system is very much influenced by human food preferences. To see the effect of human choices, the four most-consumed products are assessed to see their influence, compared to an optimal situation. This final level will examine reduction strategies associated with our diet choices.
Combining these different scales and their corresponding solutions, a broad spectrum of strategies will be available to reduce our water appropriation associated with food.

3.2 Definitions

The system description of the current research is very broad. Topics from disciplines like production ecology and nutritional sciences are addressed. Definitions of crops, food products etc., differ among these disciplines. To prevent confusion, the definitions used during the current research are given in this section. It might be possible that in other literature different definitions are used.

Definitions related to crops
Plant: all non-animal species that obtain most of their energy from sunlight via photosynthesis.
Crop: non-animal species that are grown to be harvested as food or feed. The composition of a crop is divided into three parts: product (edible), non-product (crop minus product and roots) and roots (chapter 5).
Product: economic part of crop, which is actually consumed. This includes, for instance, the grains of wheat and the tubers of potato.

Definitions related to consumption
Humans do not eat whole crops, they only eat the edible product. However, to produce the edible products, a whole crop has to be grown. Therefore, when referring to water requirements for human consumption, the water requirements of the total crop are intended, unless otherwise specified. This implies that a statement like 'the consumption of 1 kg wheat leads to an indirect water consumption of 400 liter' means that to produce 1 kg edible wheat product, 400 liter water was needed.

Definitions related to water consumption
In this research, the term 'water use' or 'water loss' refers to the water needs of a crop. The term 'indirect water consumption' refers to the water required to produce crops which are eaten by humans. This consumption of water is referred to as 'indirect water consumption' as opposed to direct water consumption (like tap water). Thus, 'water use' and 'water loss' refers to crops and '(indirect) water consumption' refers to humans. The term 'water requirements' is used for the water requirements of a crop, and for the total water requirements for the production of the 'reference diet'. This will become clear in the text.

3.3 Research questions

Using the system as described in the previous section, the following research questions are proposed:

What are, besides water footprint strategies, possible water reduction strategies related to the production of our food?

1. What is the water use of the photosynthesis process and what are possible reduction strategies?
2. What is the water use of the 'crop system' and what are possible reduction strategies?
3. What is the water use of the 'agricultural system' and what are possible reduction strategies?
4. What is the water requirement associated with our 'culture' and what are possible reduction strategies?

Every chapter of the 'body of the report' will address one sub question. In the end, the water requirements of all routes will be summarized and options for reduction strategies will be briefly suggested.

Reference diet

One so-called 'reference diet' is used throughout this research. This diet consists of macronutrients and equals the daily nutritional requirements for an average man (*Dutch Food Institute*, Voedingscentrum). The total energy is 10,467 kilojoules. These energy needs are satisfied by 55% carbohydrates, 30% lipids and 15% proteins. In later chapters, the reference diet is expanded with two micronutrients: zinc and vitamin A. Zinc is chosen as a mineral because it is estimated that 33% of the world population has a zinc deficiency (Zhao & Shewry, 2011). For the expansion of the recommendations with a vitamin, vitamin A is chosen, since it is estimated that more than 40% of all children have a deficiency. Vitamin A is, together with zinc and iron, among the ten leading causes of illness and disease in low-income countries (WHO, 2002).

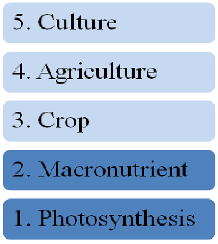
Table 3.1. Composition of the 'reference diet'. RAE: retinol activity equivalent.

Component	Energy (%)	Energy (kJ)	Gram
Carbohydrates	55%	5,763	339
Protein	15%	1,564	92
Lipids	30%	3,140	83
Energy	100%	10467	-
Zinc (mg)	10		
Vitamin A (µg RAE)	1000		

Structure of the chapters

The structure of each chapter represents the traditional 'article format': introduction, methodology, results and discussion. In this report, the same format is used. However, concerning the content, another line is also present. Each chapter introduces a different level in the food production system. The reference diet is used to compare the indirect water consumption of the different levels. For instance, the production of the reference diet by the lowest two levels (photosynthesis and macronutrient synthesis) differs from the agricultural system in terms of water quantity. Therefore, each chapter has the following structure: introduction of scale; relevant factors or crop differences; calculation of reference diet water needs; evaluation and possible reduction strategies.

4. PHOTOSYNTHESIS & MACRONUTRIENT SYNTHESIS



4.1 Introduction

The basis of the food production system is the photosynthesis process. In this process, water and CO_2 are, under the influence of radiation energy, used for the production of glucose and O_2. The produced glucose is used for the formation of the plant itself. Macronutrients are formed during the growth of a plant.
Agricultural research has shown that a linear relationship between the synthesis of dry matter and radiation exists. There is also a linear relation between radiation and water evaporation. Combining these two principles, it can be shown that there is a relation between gain in dry weight and water loss (or 'water use'). This finding has been used by Gerbens-Leenes & Nonhebel (2004) to develop a 'transpirational water' method. More about this method can be found in the next chapter.
The finding that photosynthesis is linearly related to water loss is used in this chapter to calculate how much water is required for the production of glucose and macronutrients. Since the formed glucose can be used by crops to produce macronutrients, the next step is the calculation of water requirements for the production of macronutrients. This is done by calculating the amount of glucose needed for the production of a macronutrient. For this calculation, conversion factors are available: e.g. carbohydrates need 1.28 gram glucose for the production of 1 gram carbohydrates.
Using these two principles (linear relation between glucose formation and water loss & conversion factors for macronutrients) the water requirements for the 'reference diet' can be calculated. Since the photosynthesis and macronutrient synthesis is the lowest production level, this can also be conceived as the most efficient production route. No water is lost due to crop or agricultural circumstances. The only processes which are used are photosynthesis and macronutrient synthesis. Because this is the lowest scale level, this production route will lead to the lowest water appropriation.

4.2 Methodology

Photosynthesis
As stated in the introduction, there is a linear relation between glucose formation and water use. It is important to note that this linear relationship is especially present in temperate climates. Therefore, and because the Dutch system is studied in this research, it is assumed that the photosynthesis process takes place in a temperate climate. There is a difference in radiation efficiency (the amount of glucose formed per unit of radiation) between C_3 and C_4 crops. C_3 and C_4 crops differ in the first carbon compound formed out of CO_2 during the photosynthesis process. In C_3 crops, the first molecule formed contains 3 carbon atoms, while in C_4 crops this number is 4. It is estimated that the solar energy conversion efficiency is 40% higher in C_4 crops than in C_3 crops (Gerbens-Leenes & Nonhebel, 2004). Most crops are C_3 crops and therefore the emphasis is on the C_3 efficiency. From the Gerbens-Leenes & Nonhebel study, the water per gram glucose needed is obtained: 0.11 liter per gram glucose formed for C_3 crops and 0.08 liter per gram for C_4 crops.

Macronutrient synthesis
For the synthesis of macronutrients and their associated water use, conversion factors are needed. These conversion factors are derived from the study by Penning de Vries (1983) and are 1.28 gram glucose for 1 gram carbohydrate, 1.92 gram glucose for 1 gram protein and 3.23 gram glucose for 1 gram lipid production. By multiplying these values with the water use per gram of glucose, the total water use for the production of 1 gram of macronutrient is calculated.
The reference diet, as introduced in chapter 3, consists of 10,467 kJ of energy: 55% carbohydrates, 15% protein and 30% lipids. To obtain the total water requirements for this diet, the energetic value of the macronutrient must be taken into account, as the reference diet is expressed in kilojoules. The caloric values of the macronutrients are: 17 kJ / gram for carbohydrates and protein, and 38 kJ / gram for lipids. Using the amount of water needed per gram of macronutrient and the caloric values of the nutrients, one can assess the quantity of water needed per kJ of macronutrient. These values can then be used for the calculation of water requirements for the reference diet.

4.3 Results

Table 4. 1 shows the results for the combination of the linear relation between glucose formation and water use, the conversion factors for macronutrients and the caloric values of the macronutrients. The energy efficiency of the different macronutrients is expressed in kJ/l, which states how much kilojoules can be produced by the different macronutrients per liter of water.

The result implies that crops which invest in protein are less efficient in producing calories. The production of 1 kJ via proteins requires 0.012 l water, while the same production requires 0.009 liter via lipid production and 0.008 via carbohydrate production. Therefore, crops which invest in carbohydrates are most energy-efficient, while fat-rich crops fall somewhere in between. In a crop situation, as can be seen in the next chapter, this means that crops with high-protein and high-fat content need more water to produce their product.

With the water needed per kilojoules of macronutrient, one is able to calculate the water requirements of the reference diet. The result is also listed in table 4.1.

Table 4.1. Absolute minimum water requirements to satisfy our daily nutritional needs with C_3 crops in a temperate climate.

Component	Construction Costs (g/g)	Water Use (l/g)	Caloric Value (kJ/g)	Water (l) needed per kJ	Energy efficiency (kJ/l)	Percentage (10467 KJ = 100%)	Water Needed for Production (l)
Carbohydrates	1.28	0.11	17	0.008	121	55%	48
Protein	1.92		17	0.012	80	15%	20
Lipids	3.23		38	0.009	107	30%	29
Total						**100%**	**97**

The absolute minimum for an average diet is 97 liter of water. This amount of water is based solely on theoretical calculations and assumes that our diet is produced only by the photosynthetic process.

If we assume that all the macronutrients are produced via C_4 crops in a temperate climate, the absolute minimum is estimated at 70 liters. The reason for this difference is the lower water required for the glucose production, 0.08 instead of 0.11 liter per gram.

4.4 Discussion

The aim of this research is to perform a system analysis of the agro-food system on different levels of scale, to seek water reduction options. Using principles from production ecology, it is shown that the minimal water requirements for the production of our daily diet equal 97 liter. This implies that we need ±100 liter of water per person to produce the recommended macronutrients, using the lowest production level.

The results obtained in this chapter are calculated using transpiration values for C_3 crops in a temperate climate. The study of Gerbens-Leenes & Nonhebel (2004) assumes a 40% increase in energy efficiency for C_4 crops in a tropical climate. However, transpiration is also higher in tropical climate, and therefore the total water requirements for a C_4 crop (maize) in a tropical climate are 17% lower. This implies that water requirements for C_3 crops are even higher in tropical climates (as their energy efficiency is lower), thus, the production of the reference diet will require more water. The obtained results are hence not completely independent from the local circumstances.

From the photosynthesis perspective it can be concluded that macronutrients differ in their water requirements. Proteins need more water for their production than carbohydrates. Therefore, from the lowest scale level, it can be concluded that producing too much protein can be costly in water terms. The photosynthesis cannot be captured and used without the assistance of plants. Therefore, the subsequent chapter will examine a higher level: the effect of crops on indirect water consumption. This chapter will also take into account that humans also need micronutrients and minerals. In conclusion, by assessing the critical water requirements, an anchor is available when thinking and talking about maximum efficiency and lowest water requirements possible. Besides this, it opens a new perspective, namely that (macro)nutrients are ultimately the useful components.

5. CROP SYSTEM

5. Culture
4. Agriculture
3. Crop
2. Macronutrient
1. Photosynthesis

5.1 Introduction

In the previous chapter, it was shown that, using photosynthesis and macronutrient synthesis for the production of the reference diet, 97 liter of water per day is needed per person. In this chapter, the production of the reference diet is investigated from a level higher in the agro-food system: via an (isolated) *crop*. This is done because photosynthesis and macronutrient synthesis need leaves and seeds to take place. By moving up one level higher in the system, these crop characteristics will be taken into account.
The water requirements of an isolated crop are irrespective of local circumstances. This route is calculated by using a modification of the 'transpirational water' method by Gerbens-Leenes & Nonhebel. The reason for this modified methodology is that crops with underground products could not be replicated. The modifications are explained in the methodology section. Total glucose needs for the growth of a crop are calculated in this chapter and used to assess the water needed for this growth. The results obtained via this method have to be seen as critical water needs of a crop. The water value calculated represents only the transpiration of the crop.

The content of this chapter can be divided in two subjects: first, the transpirational method is described and used to illustrate the differences between the water requirements of several crops. This is done to get a better understanding of both the method and the defining factors for water use.
Second, the differences between the crops are used in an optimization model, to obtain the most efficient combination of crops for the production of the reference diet. For instance, a crop with high carbohydrate efficiency is combined with a high-protein crop, to obtain the most efficient combination for the production of the reference diet. The water needed for the reference diet can then be compared to the water needed via photosynthesis and macronutrient synthesis.

5.2 Methodology

Transpirational method
Central to the transpirational method is the assessment of the glucose needed for the growth of a crop. When glucose needs are known, one can calculate the water requirements as there is a linear relation between photosynthesis (glucose formation) and water requirements. In the transpirational method, so-called hypothetical crops are constructed. This is done because crops differ in chemical composition and uniformity is desired. The variables for all crops types used in this research are listed in table 5.1.

Table 5.1. Crop variables for the calculation of transpirational requirements. Macronutrient values are expressed in gram per kilogram product. Caloric value is also for the product.

Product variables	Wheat^{a}	Potato^{a}	Sugar Beet^{b}	Soybean	Onion	Barley	Rapeseed	Carrot	Oats
Harvest Index	0.42	0.7^{a}	0.67	0.49^{c}	0.82^{e}	0.57^{f}	0.32^{g}	0.7^{i}	0.51^{j}
Root/Shoot ratio	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Water Content Product	15%	75%^{a}	76%	9%^{d}	89%^{d}	11%^{d}	8%^{h}	88%^{d}	9%^{d}
Carbohydrates (g/kg)	693	190	173	301^{d}	93^{d}	777^{d}	90^{h}	96^{d}	663^{d}
Protein (g/kg)	117	20	4	365^{d}	11^{d}	99^{d}	230^{h}	9^{d}	169^{d}
Lipids (g/kg)	2	0	0	200^{d}	1^{d}	12^{d}	400^{h}	2^{d}	69^{d}
Nutr. Energy (kJ)	14,364	3,570	2,957	18,660^{d}	1,660^{d}	14,730^{d}	20,640^{h}	1,730^{d}	16,280^{d}

a) Gerbens-Leenes & Nonhebel, 2004
b) IRS, 2011
c) Rogers *et al.*, 1986
d) USDA Nutrient Database for Standard Reference
e) Abdissa *et al.*, 2011
f) Hafla *et al.*, 2006
g) Clayton *et al.*, 2000
h) Calculated from macronutrient percentages derived from Erickson & Bassin
i) Quezada *et al.*, 2011
j) Peltonen-Sainio, 1990

Crop partitioning

In this research, every crop is divided into three parts: the roots, the non-product part and the product part. This division is made to calculate the construction costs of a crop, since the three parts have different characteristics and construction costs. Roots comprise the total amount of roots of a crop. It is anticipated that all crops need the same fraction of roots for their growth. Non-product equals the total crop minus roots and product. The product part is the edible, or useful part of the crop. Some crops have their edible product undergrounds (e.g. sugar beet), while others have their edible part above the ground (e.g. wheat).

Two ratios are used to calculate the size of the three respective parts. The harvest index is the ratio between the useful (economic) product and the rest of the yield. In this research the harvest index is conceived as the ratio between product and non-product part. For the wheat crop, this is the grain yield divided by the total harvested crop. Since the roots are not harvested, they are not included in this index en it is therefore not possible to calculate the glucose needed for the root construction.

Another ratio is used for the calculation of the root amount: the root/shoot ratio. The shoot is the biomass above the ground. The root/shoot ratio is calculated by dividing the root amount by the shoot amount. However, since some crops (i.e. sugar beet) have a product that is essentially a root, a slightly different approach is used in this research. It is anticipated that every crop needs the same fraction of roots for their growth. A hypothetical value is taken: 15% of the product and non-product weight. This is a bit lower than the average root/shoot ratio of wheat, which is around 20%. However, it is estimated that an average crops needs somewhat less roots; rice for example is estimated at a root percentage of 10%. The root ratio is used in order to standardize the amount of root, since it is very difficult to obtain exact root ratios of different crops. By using the harvest index and the root ratio, one can calculate the corresponding root amount and non-product amount of a crop with a given yield.

Construction costs

Since it is known that there is a linear relation between the glucose production and water requirements of a crop, it is important to know the construction cost of a crop. For the construction of roots, different values exist: tree roots and bushes roots need 1.66 gram of glucose per gram, while grass needs 1.49 gram (Martinez *et al.*, 2002). For this research the value of grass is chosen, since it is hypothesized that grass roots resemble the roots of crops best. Therefore, it is assumed that 1 g root requires 1.49 g glucose for its growth. The construction costs for the leaves are 1.49 g glucose for a gram of leaves (Poorter *et al.*, 1997). It is anticipated that the construction costs of the non-product part equals the construction costs of leaves, since a large part of the crop consists of leaves. In reality this value might differ, but it is likely that this difference will not be large. The construction cost of the non-product part is consequently 1.49 g glucose per gram non-product. If crop-specific construction costs are known, this value can be used, but this does not apply to the current research.

The glucose needed for the production of the product is calculated via the specific chemical composition of the product. It is known that glucose needs for carbohydrates are 1.28 g/g; for protein 1.92 g/g and for lipids 3.23 g/g (Penning de Vries, 1983). The chemical composition per 1,000 g of fresh product is taken and the construction costs are calculated. It is important to note that the composition of fresh product is used, so the water content of a product plays a major role.

Water use

Once the total glucose costs are known, one can calculate the associated water use by multiplying it by 0.11 (Gerbens-Leenes & Nonhebel, 2004). Important remark is that this is the case for C_3 plants. For C_4-crops, the water use per gram of glucose equals 0.08 liter, because they have a higher solar energy conversion.

Remarks and schematic illustration

Figure 5.1 can be used for products similar to wheat. However, one has to be cautious in performing the calculations, since different definitions exist for the harvest index. The HI for sugar beet can, for instance, be expressed as sugar yield / total yield or as beet yield / total yield.

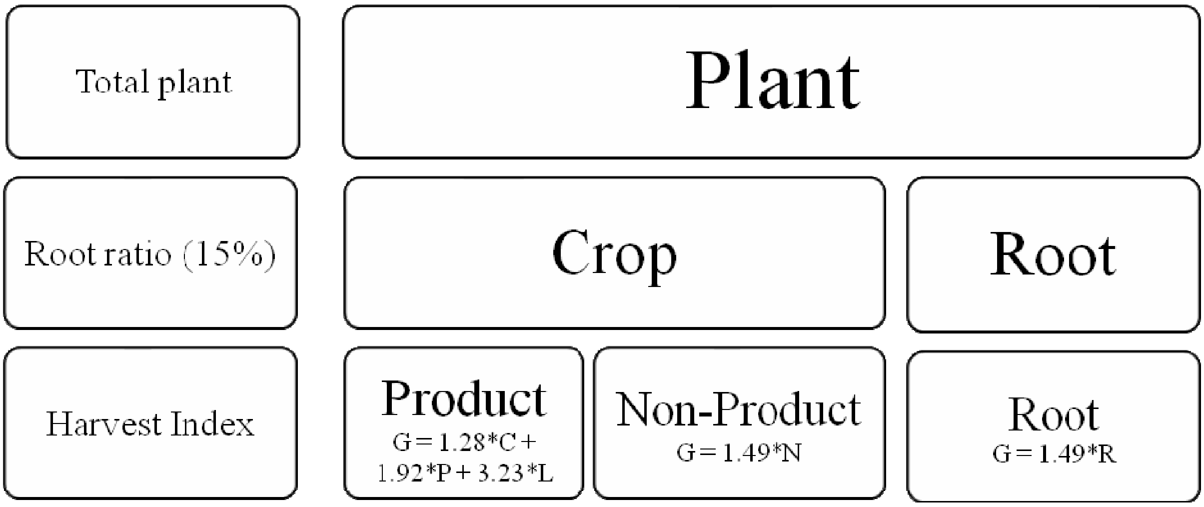


Figure 5.1. Schematic representation of a plant and its construction costs. G = glucose (g); C = carbohydrates (g); P = protein (g); L = lipids (g); N = non-product amount (g); R = roots (g).

In a schematic representation, the more detailed calculation is as follows:

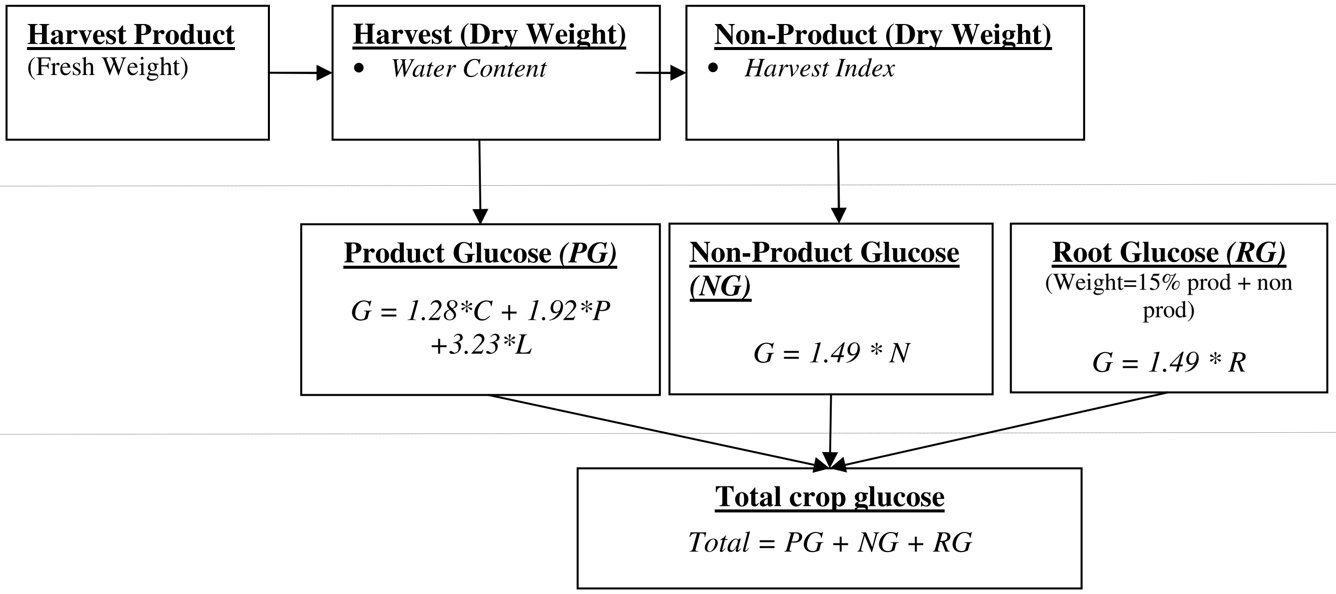


Figure 5.2. Schematic representation for the calculation of the construction costs of a whole crop. G = glucose (g); C = carbohydrates (g); P = protein (g); L = lipids (g); N = non-product amount (g); R = roots (g). See text for explanation.

The computation can be divided in three stages: calculation of the weight of different parts of the crop, calculation of their corresponding glucose needs, and finally the total computation of the total crop glucose. An example of a calculation is given below.

Example

The first step is the calculation of the dry weight of the harvest, since the harvest index is often expressed in dry matter. Wheat product has a water content of 15%, so 1,000 gram of fresh wheat product delivers 850 gram of dry weight. The next step is the calculation of the weight of the non-product part. Since the harvest index is 0.42, the non-product fraction is 0.58 and thus the weight of the non-product part equals 1,174 g. Together with the product this adds to 2,024 g. The next step is the calculation of root weight. It is anticipated that this is 15% of total weight, therefore, 15% of 2,024 g is taken, which equals 304 g.

Hereafter, the glucose needs are calculated. The root and non-product glucose needs are calculated by multiplying the amount with 1.49. The product glucose needs are calculated by multiplying the macronutrients with their corresponding conversion factor. Wheat product consists of 693 g carbohydrates; 117 g proteins; and 2 g lipids per kilogram of fresh weight. The corresponding glucose needs consequently equal 1,120 g. The non-product part needs 1,749 g (1,174*1.49) glucose and roots 452 g (304*1.49). The total glucose need of the crop is therefore 3,321 g glucose. Since it is known that 1 g of glucose requires 0.11 l water to form, the total transpirational water requirements of the wheat crop are 365 l per kg of wheat crop.

Subsequently, the transpirational water requirements allocated to the product (that is, the grain) can also be calculated. The glucose needs of the product are 1,120 g, and thus the water requirements of the product equal 123 l of water. This implies that 1/3 of the water requirements goes to the product. This is lower than the harvest index suggests. The reason for this is that the roots are not included in the harvest index.

Nutritional productivities

The crop water use, calculated via the transpirational method, can further be used to investigate the productivity for each crop. Productivity is defined as amount of macronutrient delivered per liter of water. The computation is performed by dividing the output (i.e. energy or protein) of 1 kg product by the water input in liters (water amount needed for the production of the crop).

Water required for reference diet: optimization model

The optimum combination of crops is investigated using an optimization model. The optimization model used is the What'sBest! model developed by Lindo Systems Inc. What's*Best!* is an Excel add-in which allows building optimization models within a spreadsheet. The model works with an A-B-C strategy: define Adjustable cells, define the cell to minimize or maximize (Best) and include the restrictions or limitations of the problem (Constraints). By doing this, the What's*Best!* model tries to minimize or maximize the 'Best' cell by altering the Adjustable cells, within the given Constraints.

In this chapter, the water appropriation must be minimized. This is the target of the model (Best). All nutrients (and energy) are expressed per liter. This is achieved by dividing the nutrient concentration by the corresponding water requirements. For instance, a crop with 200 g/kg carbohydrates and a productivity of 2 kilogram per liter, delivers 400 g carbohydrates per liter. All these productivities per liter are used in the model (see appendix II).

The constraints of the model are the nutritional requirements of the reference diet, introduced in the 'system description' chapter. The diet is expanded with Zinc and Vitamin A requirements: 10 mg zinc and 1,000 µg vitamin A. The Best cell can only be solved if these constraints are met. In practice, this means that the minimal water appropriation has to fulfill the basic nutritional requirements.

The model is allowed to 'use' units of different crops. These units consist of the liters of water dedicated to this crop. These units of water are multiplied with the corresponding productivities of the crop and the outcomes (nutrients delivered) are summed until the constraints are all met. The total units of water are counted, and the target of the model is to minimize the units of water.

5.3 Results

Transpirational method

From the calculation described in the methodology section, the following transpirational requirements are obtained. They are listed in table 5.2. The transpirational requirements are expressed in liters per kg fresh crop; per kg dry crop; for the product part, and expressed per kJ of energy.

The water requirement *per kg fresh crop*, is the transpirational water use for the whole crop as it is grown on the field. This value contains the requirements of the roots, non-product and the economic product. Onion crop needs very little water, mostly due to its high harvest index. Rapeseed crop has high water requirements, due to its low harvest index and its high protein and lipids content.

The transpirational requirement *per kg of dry crop* is used to compare different crops with diverse water content. The requirements per kg dry weight are obtained by correcting for the water content of a crop. It shows that sugar beet crop and potato crop now have requirements in the same order as the vegetables. The main reason is that vegetables have a higher water content and thus fewer chemical components per fresh weight, and consequently lower water requirements per fresh weight.

Table 5.2. Transpirational requirements (in liters of water) for different crops.

Crop	1 kg crop (fresh)	1 kg crop (dry)	Product part (fresh)	Per kJ
Onion	23	210	16	0.014
Carrot	29	240	16	0.017
Sugar Beet	53	223	25	0.018
Potato	57	229	31	0.016
Barley	283	318	135	0.019
Oats	341	375	154	0.021
Wheat	365	430	123	0.025
Soybean	392	430	191	0.021
Rapeseed	594	646	203	0.029

The transpirational requirement *for the product part* equals the water needed for the production of the economic part. This is calculated by summing the carbohydrate water requirements, protein water requirements and lipid water requirements of the product. This is irrespective of the harvest index, since the product requirements are obtained via the chemical composition. The highest requirements are for the soybean product and the rapeseed product, as their product contains much protein and lipids. Lowest water use is for carrot and onion, because their products have low macronutrient contents.

The requirement *per kJ of energy* is used to see how efficient crops are in relation to their caloric value. This is calculated by dividing total fresh crop water requirements by caloric value of the product. Influencing factors are the chemical composition of the product and the harvest index. The harvest index shows how much crops invest in non-economic parts, while the chemical composition determines the caloric value. Lipids have a different caloric value (38 kJ/gram) than protein and carbohydrates (17 kJ/gram). Lipids also have higher construction costs, but the gain in caloric value is larger than for protein. Therefore, protein is the most expensive in terms of water requirements per kJ of energy. This was also shown in chapter 4.

Nutritional productivity

Based on the daily nutritional requirements of the reference diet, the ideal composition of a crop is 1 : 0.27 : 0.24 for carbohydrates, protein and lipids. This resembles the ratio between the different macronutrients in the reference diet. None of the investigated crops approaches this ratio, mostly because of the low lipid contents of crops. The crop which approaches this ratio the best is oats, with a ratio of 1 : 0.25 : 0.10.

Next, different nutritional productivities of crops are examined. Nutritional productivity is conceived as the amount of produced macronutrient per liter of water. The produced macronutrients per liter of water are calculated and the results are shown in figure 5.3. This figure shows that onion is most efficient in producing carbohydrates and energy (not shown), soybean is most efficient in producing protein and rapeseed has the most efficient lipid production. Figure 5.3 also shows that crops which invest heavily in carbohydrates invest very little in lipids (and protein) or *vice versa*: crops which invest in lipids and/or protein invest little in carbohydrates.

Water needed for reference diet

Using the optimization model, one can assess the most efficient way to produce our nutritional requirements with existing crops. The results are given in figure 5.4. First, the basic reference diet, consisting of energy and macronutrient needs, is calculated. Next, the diet is expanded with recommendations about zinc and vitamin A. This is done to see the effect of expanding the reference diet. The calculations are performed using the water requirements of the fresh crops, as shown in table 5.2, because it is anticipated that the total fresh crop had to be grown to obtain the product.

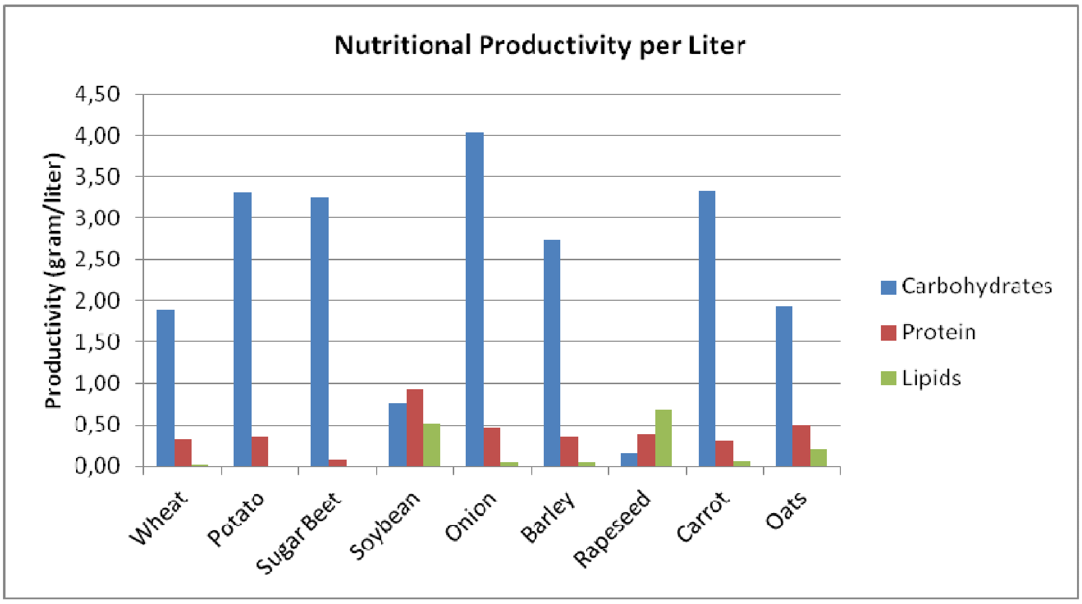


Figure 5.3. Nutritional productivities of different crops: production of macronutrients (in gram) per liter of water needed (transpirational requirements).

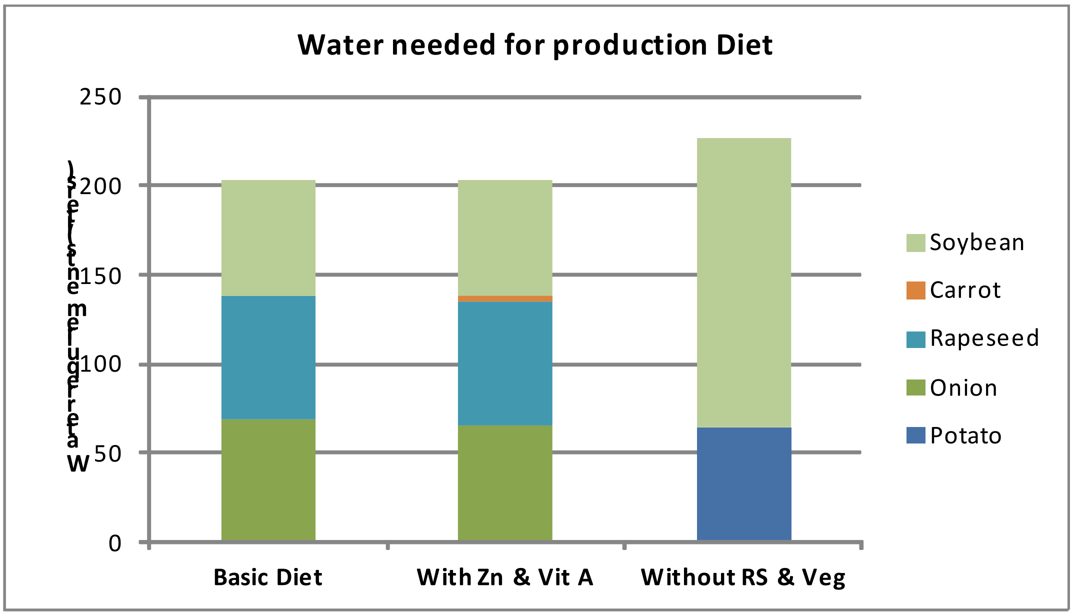


Figure 5.4. Water (in liters) needed for the production of the daily nutritional recommendations. Basic diet: recommended energy and macronutrient intake; With Zn & Vit A: basic diet expanded with zinc and vitamin A advices; Without RS & Veg: Analysis performed without rapeseed and vegetables, excluding the recommendation for vitamin A. See text for more information.

In figure 5.4, one can see that the basic diet can be satisfied with 203 liters of water. The three crops which are used by the model are soybean, onion and rapeseed. To produce the recommendations on vitamin A, carrot has to be included for fulfilling the vitamin A needs.
In the figure, the liters required to produce the diet are shown. This can be recalculated to weight of the crops. For the expanded diet, 66 liter is used for the production of onion, 69 liter for rapeseed, 3 liter for carrot and 65 liter for soybean. The corresponding weights ares: 2.87 kg onions, 0.12 kg rapeseed, 0.12 kg carrots and 0.17 kg soybeans. To see the effect of a diet which resembles current diets more closely, onions and rapeseed are excluded, because 3 kg onion is a large quantity and rapeseed is mostly used for the production of canola oil. Therefore, another analysis has been performed, with the exclusion of rapeseed and vegetables (that is, onions and carrots), to see which crops are then used. This result is also shown in figure 5.4. It shows that soybeans and potato are used.

The total water requirements equal 227 liter, which is an increase of 10% compared to the previous analyses. However, an important remark has to be made, since vitamin A is excluded from this analysis. The reason is that the other crops contain very little vitamin A. If the vitamin A recommendation has to be satisfied without carrots, one needs 39,152 liter of water for the production of 100 kg soybeans. This creates a large excess of soybean and is not realistic.

5.4 Discussion

The results of the modified transpirational water method indicate that vegetables and crops with a high water content and a high harvest index require less water per kg of crop. The high harvest index implies that crops invest less glucose and thus less water in non-economic parts, which results in lower water needs per kilogram crop. The main reason that onion has the lowest water requirements is because of it's high harvest index (0.82). If we increase the HI of potato and wheat to 0.82, the water requirements per kJ decrease to 0.013 and 0.012 respectively, which is even less than onion (0.014). This implies that breeding for HI is a fruitful strategy for water reduction. As Siggique *et al.*, (1990) show, the HI of wheat has been increasing over time. Continuation of this trend will lower the transpirational water requirements of wheat. Another determining factor is the chemical composition of the crop. Crops which invest in carbohydrates require less water than crops which produce proteins and lipids, since the production of carbohydrates from glucose is more efficient. This can be seen in the low water requirements of vegetables, potatoes and sugar beet; all crops with a high carbohydrate content.

In this research, it is assumed that all crops require 15% of the product and non-product weight for root formation. The amount of roots is difficult to measure, so this makes it difficult to assess the validity. However, it is estimated that wheat has around 20% of its mass dedicated to root formation, while rice is estimated at an allocation of 10%.

The chemical composition and the harvest index of the crops differ among the sources and therefore hypothetical crops were constructed. Even different wheat types have varying macro- and micronutrient contents. Harvest indices are sometimes expressed in fresh weight or dry weight harvest indices. In this research, the harvest index for dry matter is chosen, whenever possible. Despite these variations, by using this transpirational method, the determining factors for transpirational water requirements are elucidated and the same method can be used for other crops. Most of the crops can be grouped according to crop characteristics. Crops with a very high HI and low macronutrient content (vegetables) have very low water requirements. Crops with a high HI and relatively low macronutrient content (sugar beet and potatoes) also have low water requirements. Correcting for water content, these crops have water requirements in the same order: 210 – 240 l/kg dry crop. Crops with a medium HI and comparatively high macronutrient content (cereals and soybeans) have relatively high water requirements. Wheat has, compared to other cereals, higher water requirements per kJ, because of its lower HI. If wheat had a HI of 0.50, its water requirement would be 0.021 l/kJ, the same as for barley and soybeans. The crop with the highest water requirements (rapeseed) is characterized by a very low HI (0.32) and high macronutrient content (especially lipids).

Nutritional value of crops

As stated before, the chemical composition of crops differs widely. The USDA Nutrient Database for Standard Reference gives average values based on multiple data points. The number of sources varies per product. Besides this, the nutrient content is based on one variety of a crop. For instance, wheat is based on hard, red winter wheat.

The nutritional value of rapeseed is based on the seed itself and not on the oil derived from the rapeseed. One could argue that rapeseed is only consumed as canola oil, and therefore the nutritional content of the seed is not suited for the purpose of this analysis. Therefore, another analysis was performed without rapeseed. This showed that the exclusion of rapeseed causes a 10% increase in water appropriation. This underlines the importance of oil crops in the satisfaction of our diet. Furthermore, the zinc content of a crop depends on the zinc concentration in the soil, and, in some soils, zinc is present in very low concentrations.

Water needed for the reference diet

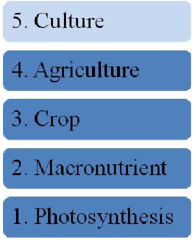
In the current analysis, crops are combined to minimize the water used for the production of our diet. The results show that vegetables and potatoes are very water efficient. However, high caloric efficiency is not sufficient, since our diet consists of different macronutrients. Consequently, a combination of crops is needed. By combining, onion, soybean and rapeseed, the production of the reference diet needs 203 liter. This is twice as much as the most efficient production route (photosynthesis and macronutrient synthesis). This underlines the larger water appropriation of levels higher in the food production system. The reason that crops production needs more water is because crops use glucose (and thus water) also for the growth of non-economic parts, such as leaves and roots. Another factor is that none of the crops has the ideal macronutrient content: the same ratio between macronutrients as the reference diet. Therefore, a combination of crops is needed, which is less efficient than using one crop with an ideal composition.

It is emphasized that this combination is optimized for low water requirements during production. This theoretical approach leads to 2.87 kg onions, 0.12 kg rapeseed, 0.12 kg carrots and 0.17 kg soybeans. Based on the analysis with exclusion of rapeseed and vegetables, potato and soybean are recommended. This increases the total water appropriation by 10%. This shows that with a little increase in water appropriation a diet close to current diets can be achieved.

This chapter shows that by moving one level up in the system, twice as much water is needed to produce the reference diet. Reducing the water requirements associated with this scale level, involves increasing the harvest index and optimizing the macronutrient content of crops. Increasing the harvest index decreases the investment in non-product parts and optimizing the macronutrient content leads to a more efficient production system, as crop characteristics are matched to human nutritional recommendations. Both strategies target the inefficiencies associated with the higher scale level.

6. AGRICULTURAL SYSTEM

6.1 Introduction



The water footprint method has already been introduced in the second chapter of this report. Most water requirement studies are related to this methodology. It was shown in chapter 2 that the water footprint leads to two major reduction strategies: trade and technology. In this current chapter, the water footprint methodology is used to examine the water needed for the production of the reference diet and to compare this to the other scale levels. This is done by using the same optimization model as in the previous chapter. The model optimizes the combination of crops for the reference diet with as little water as possible. It is investigated how much more water is needed when agricultural circumstances are taken into account, compared to the 'isolated crop' level. Since local circumstances play an important role in determining the water footprint of a crop, two agricultural systems with different circumstances are investigated: the Dutch agricultural system and the Spanish system. The Dutch agricultural system is characterized by a temperate climate and high yields, while the Spanish system is distinguished by more tropical temperatures and moderate yields.

The second part of this chapter will underline the argument that the water footprint is just one scale level at which water appropriation can be targeted. This is accomplished by comparing the water footprint of crops with the transpirational water requirements of crops, as discussed in the previous chapter. By doing this, it can be shown that WF efficiency has an upper limit. This upper limit underlines the argument that more fundamental strategies are needed, as the efficiency cannot increase forever.

6.2 Methodology

Optimization model

The rationale and methodology behind the water footprint has already been explained in chapter 2. This is not replicated in this chapter. The optimization model which is used is the same as in the previous chapter. The input for this model is derived from the WaterStat database (Mekonnen & Hoekstra, 2010). The water footprints are obtained for the same crops as in the previous chapter, for a proper comparison. Water footprints are Dutch or Spanish averages. In the database, water footprints consists of green, blue and grey WFs. Grey WFs are not taken into account, thus, the WFs used are the sum of green and blue water. The water footprints are listed in Appendix II.

The water footprint for soybeans is obtained for soybeans from the USA. Although soybeans are grown in Spain, most soybeans are imported. Therefore, and for a proper comparison with the Dutch system, it is assumed that soybeans are also produced in the USA in the Spanish situation.

The same three analyses as in the previous chapter are performed: first, the basic reference diet is calculated. Thereafter, the diet is extended with vitamin A and the zinc mineral. The third analysis is performed with the exclusion of rapeseed and vegetables.

Comparison water footprint and transpirational method

To compare the water footprint with the transpirational water requirements, both methods are investigated from a yield perspective. The development of both water footprint and transpirational requirements over the last 40 years are shown in this chapter. One crop, wheat, is chosen, because the yield of wheat has been mostly increasing over the last decades (see chapter 2). Since yield has a large influence on water footprints, wheat is most interesting to show. The water footprint of wheat is calculated as described in chapter 2 (*methodology: variable yield*). The transpirational requirements per ton of yield are calculated by multiplying the yield of wheat (CBS, 2001) with the transpirational requirements (*chapter 5: 365 l/kg*). To see which part of the water requirements is used to produce the economic product of wheat, the transpirational requirements for the product are also shown. These requirements are calculated by multiplying the yield with the water requirements of the product (*chapter 5: 123 l/kg*). In this analysis, a variable harvest index is introduced for wheat. Since it is known that the harvest index of wheat has been increasing over time (Siddique *et al.*, 1990), the harvest index is assumed to have increased linearly from 0.32 (1961) to 0.42 (1998).

6.3 Results

In figure 6.1, the result of the optimization model is shown. The total water requirements for the production of the reference diet equal 295 liter in the Dutch situation. The crops which are used for this production are sugar beet, rapeseed and oats. The corresponding weights are 0.71 kg sugar beet, 0.15 kg rapeseed and 0.32 kg oats. With the addition of vitamin A and zinc, the water requirements are slightly higher: 299 liter. Without rapeseed and vegetables, the reference diet is produced solely by oats and this requires more than 450 liters.

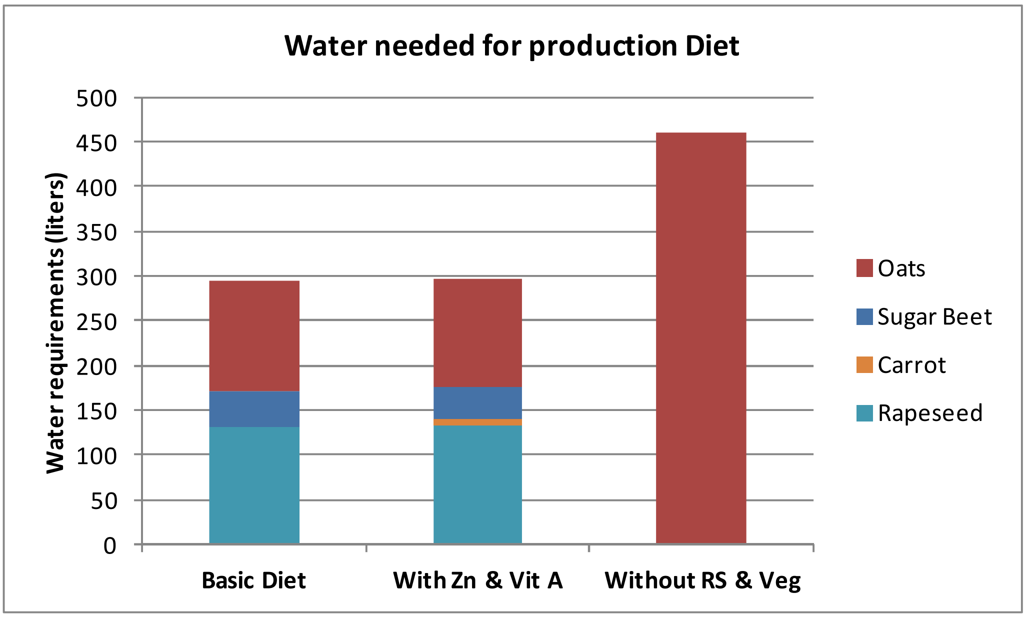


Figure 6.1. Water (in liters) needed for the production of the daily nutritional recommendations in the Dutch system. Basic diet: recommended energy and macronutrient intake; With Zn & Vit A: basic diet expanded with zinc and vitamin A advices; Without RS & Veg: Analysis performed without rapeseed and vegetables, excluding the recommendation for vitamin A. See text for more information.

Spanish system

The Dutch agricultural system is very efficient due to its temperate climate, state-of-the-art technology and fertile soils. Especially its temperate climate has beneficial effects for the water footprints of crops. Spain is characterized by a more tropical climate. This effect is resembled in the water footprins of crops. By optimizing the combination of crops for the production of the reference diet, ons can assess the difference between the Dutch and the Spanish system. To produce the basic reference diet, the Spanish system needs 686 liter of water (figure 6.2). This is more than twice as much compared to the Dutch system. Soybeans are used for the protein production. The corresponding weight of the products are: 1.67 kg sugar beet, 0.13 kg rapeseed and 0.15 kg soybeans. If rapeseed and vegetables are excluded, soybeans and sugar beet are used for the production of the reference diet. This requires more than 800 liters of water.

Comparison water footprint and transpirational requirements

Thus far, both transpirational (crop-specific) water requirements and water footprints are discussed and used for the assessment of water needed for the reference diet. Water footprints are reflecting the evapotranspiration and are highly influenced by weather and yield circumstances. Transpirational requirements are the water amounts needed for the growth of the crop, irrespective of local circumstances. They are an expression of the 'transpiration' part of the total evapotranspiration. (evapotranspiration is the sum of evaporation and transpiration). Since both methods are introduced and discussed, they can be compared against each other.

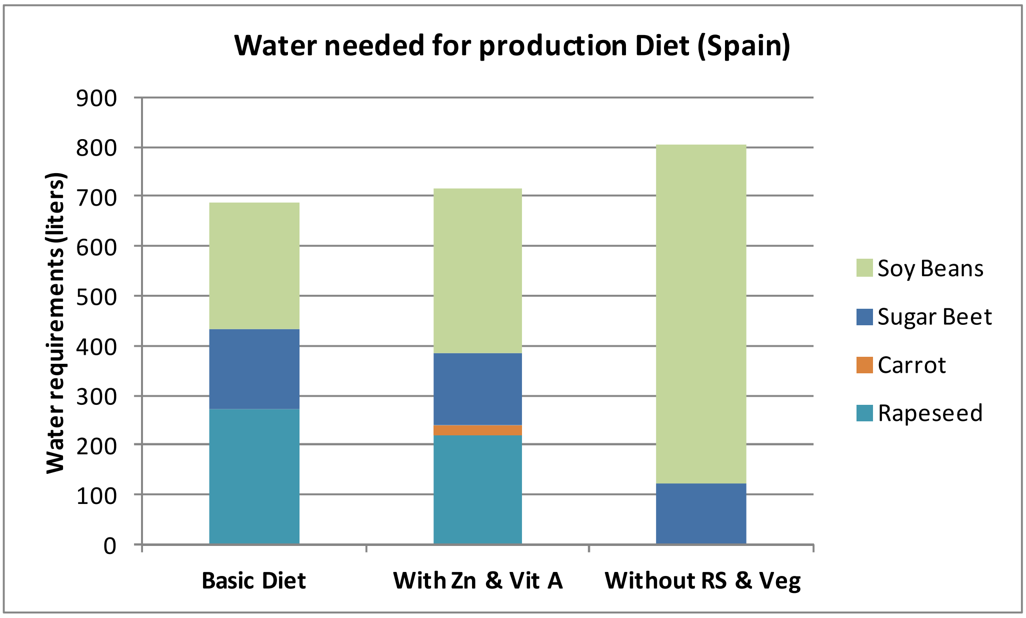


Figure 6.2. Water (in liters) needed for the production of the daily nutritional recommendations in the Spanish system. Basic diet: recommended energy and macronutrient intake; With Zn & Vit A: basic diet expanded with zinc and vitamin A advices; Without RS & Veg: Analysis performed without rapeseed and vegetables, excluding the recommendation for vitamin A. See text for more information.

As was shown in chapter 2, the water footprint of wheat has been decreasing over time, mainly due to increases in yield. In figure 6.3, the development of the water footprint of wheat is shown. In the same figure, the transpirational requirements of both the total crop and its economic product are depicted. As can be seen, the transpirational requirements of the crop have slightly decreased per ton of yield. This is caused by an increasing harvest index. Because a higher harvest index implies that more water is allocated to the economic product, a ton of yield will require less water. A simple illustration can explain this. Suppose a crop with a HI of 0.5. Thus, half of the crop is the economic product. If the yield is 1 kg, this implies that 2 kg crop was grown (1 kg product and 1 kg non-product). Therefore, the water requirements must be calculated for 2 kg crop. Suppose that it is possible to increase the HI to 1. If the yield is 1 kg, the total crop grown was also 1 kg. The water requirements have to be calculated for 1 kg crop, and will be less. Therefore, if the HI increases, the water requirements per ton of yield will decrease.

As is shown, the water footprint and transpirational requirements are more and more approaching each other. This implies that the agricultural efficiency continues to increase, which causes the smaller water footprints. However, the transpirational requirements are the upper limit of agricultural efficiency. Since the transpirational needs are irrespective of local circumstances, and thus represent the critical water needs, the water footprint cannot be lower than these transpiratonal requirements.

This accentuates the need for other strategies, beside the water footprint strategies.

6.4 Discussion

By moving up another level in the system, 50% more water is needed to produce the reference diet (295 vs. 203 liter). Local circumstances have a major influence, as shown by the comparison between the Dutch and Spanish system: the Spanish system requires twice as much water.

Due to yield improvements, water footprints have been decreasing over time (at least in The Netherlands). However, this decrease cannot go on forever, as the transpirational requirements (from the isolated crop) represent the upper limit of agricultural efficiency. This stresses the point made in chapter 2: water footprint efficiencies embody only a minor part of the possible reduction strategies and more fundamental approaches are needed.

In this chapter, water footprints obtained from a database (WaterStat) are used for the optimization model. These water footprints in the database are calculated based on the average yield of the period 1996-2005 and using long-term evapotranspiration data.

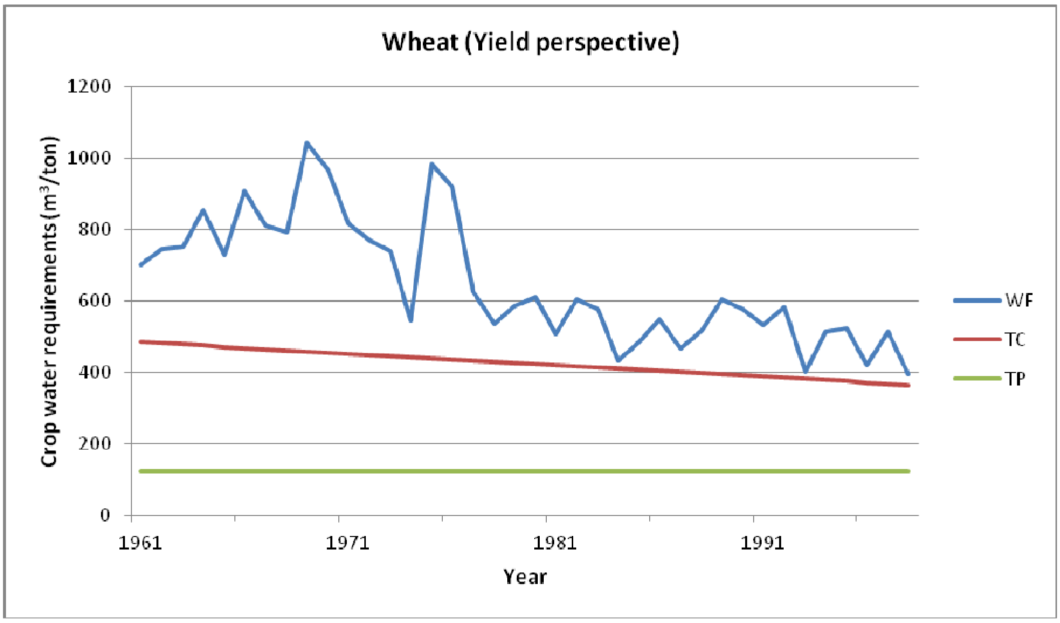


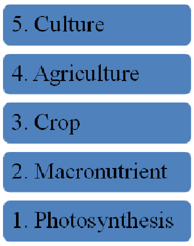
Figure 6.3. Comparison water footprint and transpirational requirements of wheat. WF: water footprint; TC: transpirational requirements crop; TP: transpirational requirements economic product.

For the comparison between water footprint development and transpirational developments, the same approach is used as in chapter 2. In this approach yearly water footprints are calculated to see the effects in separate years and over time. This is suitable for the optimization model, since separate years might not be representative for the average water footprint. Besides, for a proper comparison between the Dutch and the Spanish system, it is important to use the same methodology. As both Spanish and Dutch data can be obtained from the WaterStat databse, these water footprints are chosen for the optimization model.

The Dutch production system uses sugar beet, oats and rapeseed for the production of the reference diet. Sugar beets have a very low water footprint (54 l/kg) and therefore they are used as an alternative to onion (72 l/kg) for carbohydrate production. Sugar beet is highly efficient in water footprints terms, as transpirational requirements are 53 l/kg, while the water footprint equals 54 l/kg. Of course, it is difficult to compare both methods directly, as the water footprint is an average and assumptions have been made regarding the chemical consumption of the beet. However, it does show that sugar beet is very efficient in water terms. Another reason that the products in the current analysis differ from the products in the 'crop'-analysis, is that USA soybeans from the USA have a high water footprint. Therefore, they are not used by the optimization model for the protein production. Instead of soybeans, oats are used by the optimization model, as they have a relatively high protein content and a relatively low footprint. With the exclusion of rapeseed and vegetables, the water requirements are 50% higher for the production of the reference diet (± 450 l vs. ± 300 l). This is more than in the 'crop'-analysis (+10%). This emphasizes that it is more difficult to find an alternative crop with low water requirements when agricultural circumstances have to be taken into account.
The Spanish system uses soybeans, sugar beet and rapeseed for the production of the reference diet. Soybeans are derived from the USA, because it is assumed that most soybeans are imported. Soybeans from the USA have a relatively low footprint, compared to other Spanish products (such as oats) and they are therefore used in the optimization model.

The higher water requirements for the scale level 'agriculture' compared to the 'crop'-level, are due to the local circumstances, such as climate, soil characteristics and technology. Reduction options associated with this scale level have to target the local conditions, to move towards the theoretical maximum efficiency (represented by the 'crop'-level). Yield improvements, better water management and production favorable circumstances are examples of possible reduction strategies.

7. CULTURE



7.1 Introduction

The previous chapters have shown that by moving up in the agro-food system, each higher scale level leads to a higher water appropriation. The final scale level is the ‘culture’ level. In the end, consumers determine which crops and products are consumed. In the previous chapters, human preferences were not taken into account and the optimal combination of crops was assessed, irrespective of cultural habits. Since consumers ultimately determine which products are consumed, this chapter investigates the effect of human diet choices, by assessing the water appropriation of the four most-consumed products in The Netherlands: wheat, potato, sugar (from sugar beet) and pig meat. By investigating the effect of these four products, an indication can be given on the water appropriation of the Dutch diet. The water requirements of these products are expressed in water footprint terms, because this represents the actual situation best. In chapter 2, the Dutch diet was also investigated to see the effect on water appropriation. This chapter differs from that analysis as in this chapter the optimization procedure is followed. By optimizing with the four most-consumed products, one can compare the effect of human consumption to the optimal scenarios developed in the previous chapters. The target of this chapter is therefore not to assess the water appropriation of the actual Dutch diet. Rather, the target is to compare the effect of cultural influences (as resembled in the most-consumed products) on the production of the reference diet. These results can subsequently be compared to the optimized scenarios in the previous chapters, and it can be shown how cultural choices will lead to more water appropriation.

7.2 Methodology

The same optimization model is used as in the previous two chapters. The products which are incorporated in the model are wheat, potato, sugar beet and pig meat. This is done because these products are most consumed in the Netherlands (Food Balance sheet 2007, FAO). The water footprints are obtained from the WaterStat database (Mekonnen & Hoekstra, 2010ab). This database also contains footprints for meat types. Green and blue water footprints are summed in this analysis. Pig meat has a water footprint of 3,294 m^3/ton or 3,294 l/kg. For the water footprints of crops, see appendix II.

Only one analysis is performed: the production of the reference diet. The reason is that the satisfaction of vitamin A requirements with these four products will lead to very high water requirements, since these products contain little vitamin A. The third analysis in the previous chapters was a scenario in which rapeseed and vegetables were excluded. Since the four most-consumed products do not consist of vegetables or rapeseed, this analysis is basically the same as the production of the reference diet. Thus, only one analysis is performed in this chapter.

7.3 Results

Figure 7.1 shows the water requirements for the production of the reference diet with the four most-consumed products in The Netherlands. It can be seen that potato and sugar beet are used by the optimization model and that large water requirements are due to the production of pig meat. Wheat is not used by the optimization model, because the combination of the other three products is more efficient. Total water requirements equal 1,413 liters per day. The corresponding weights of the products are: 1.17 kg potatoes, 0.68 kg sugar beet and 0.39 kg pig meat. Pig meat is responsible for the total lipid production and for a large share of the protein production. Sugar beet and potato are used for carbohydrates and potato has also a substantial influence on total protein production.

7.4 Discussion

Using the same optimization model as in the previous chapters, but with the inclusion of only the four most-consumed products, it is shown that the reference diet is produced by 1,400 liters of water. This represents a factor 5 increase in total water appropriation, compared to the most efficient crop combination (WF scenario). The main reason for this large increase is the presence of pig meat and the absence of an oil crop. All lipids are produced by pig meat, and since pig meat has large water requirements, this has substantial consequences for the total water requirements.

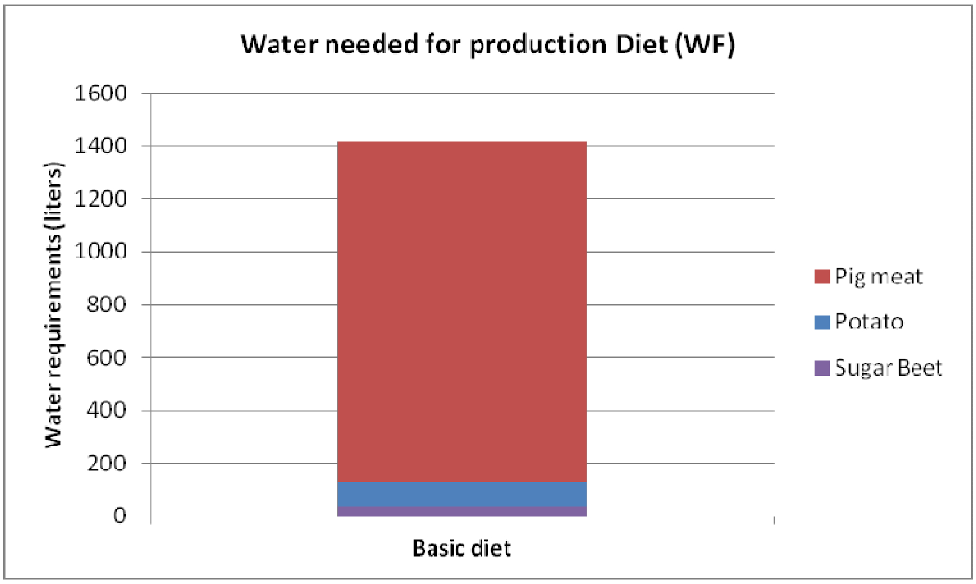


Figure 7.1. Production of the reference diet by the four most-consumed products in the Netherlands. Pig meat, potato and sugar beet are used by the optimization model.

Meat is an inefficient food type, because of the conversion of crops to animals. Useful energy and nutrients are ‘lost’ because animals consume and need this energy and nutrients. This inefficiency can be seen in the higher footprints of all meat types. To investigate the effect of meat, appendix I is provided. More information on the meat production route can be found in this appendix.

How does the 1,400 liter estimate compare to other estimations? The FAO, for instance, indicates daily water requirements for food at 2,000 – 5,000 liter. This is substantial higher than the analysis in this chapter. Three reasons can be given to explain this difference: first, only four products are used in the analysis and this may lead to an underestimation of indirect water consumption. Second, the products are derived from the Dutch production sector, which is known for its efficiency, while the FAO is a worldwide estimate. Third, the analysis is essentially an optimization analysis. The combination of products is optimized for macronutrient content of the reference diet, while in reality, people do not optimize their diet for the macronutrient content. Together, these three reasons explain why the approximation in this chapter is lower than the FAO’s estimation.

This chapter shows that consumer choices have a large impact on total water requirements. Reduction options targeted at cultural choices therefore have a large theoretical potential. The practical implications and acceptability have not been evaluated, so future research must be aimed at these issues.

8. DISCUSSION AND CONCLUSION

This research handles a very broad subject, covering disciplines ranging from production ecology to nutritional sciences. The agro-food system is assessed at different levels of scale. The discussion aspects for the different scale levels are present in the related chapters. This is done because these discussion issues are specifically related to the corresponding scale levels. In this chapter, an overall comparison from a system point of view is given.

As stated before, the objective of this research is not to perform a quantitative analysis. The qualitative system analysis can nevertheless tell something about the magnitude of the effects. In this research, it is shown that the most efficient production route needs 100 liters of water for the production of the reference diet. Taking into account the crops and the agricultural circumstances, this increases total water requirements with a factor 2 and 3, respectively. If cultural preferences are taken into account, water requirements are a factor 15 higher than the most efficient production route. This shows that there is a high theoretical potential for water reduction in the agro-food system.

8.1 Summary of strategies

In the introductory chapters, it was argued that current water reduction strategies are targeted at agricultural efficiency (measured by the water footprint method). These strategies comprised increasing yields and trade from water-rich to arid countries. It was also argued that more fundamental strategies are possible. The body of the report handled this question: *'What are, besides water footprint strategies, possible reduction options for the water appropriation associated with our food production?'*

To examine this question, the food production system was divided in five scales, ranging from the basic photosynthesis process to the broad scale 'culture'. The production of a reference diet was investigated on each scale level. This showed that each level higher in the production system required more water. This chapter summarizes the different outcomes of the scales and discusses potential reduction strategies.

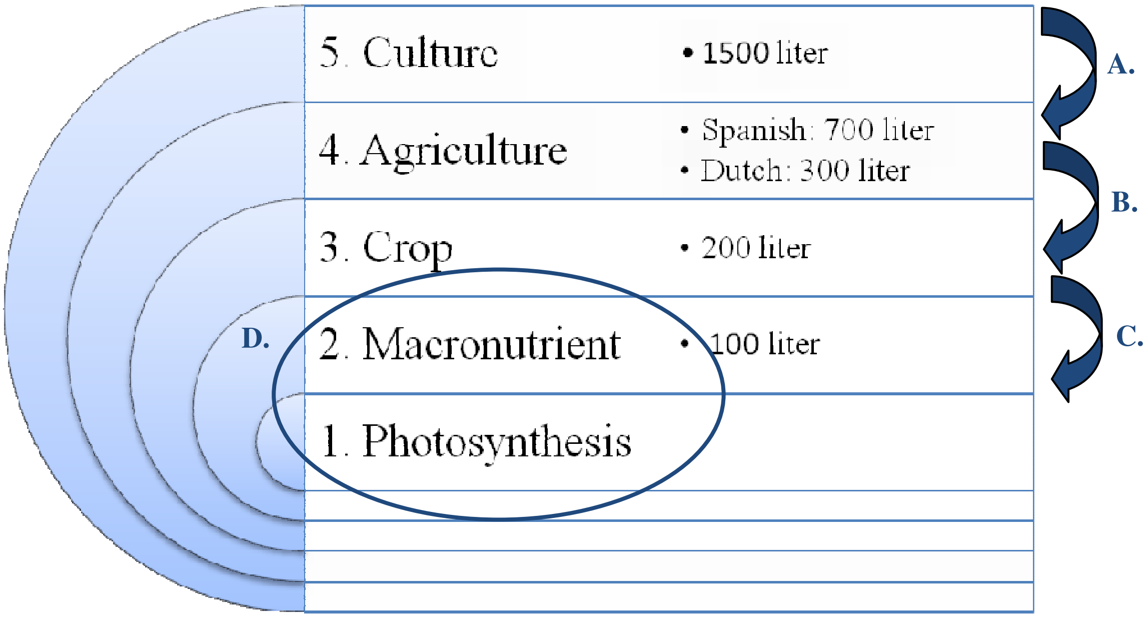


Figure 8.1. Summary of (rounded) water requirements per scale level and related categories of strategies. See text for more explanation.

In figure 8.1 the total food production system is depicted. Each scale level includes the (rounded) water requirements needed for the production of the system. It is possible to examine potential reduction strategies by trying to reduce the appropriation of each scale level.

A. The first category of strategies consists of policies targeted at cultural choices. For instance, it was shown that meat has large consequences for water appropriation. Shifting away from meat towards oil crops and crops with high protein content will lower the water appropriation. Potato and sugar beet have low water requirements, so consumption of these crops will have a beneficial effect, although it might be argued that sugar beet has a low nutritional value due to its high carbohydrate (sugar) content.

   Another option, which is related to the second category of strategies, is the choice for products from an efficient agricultural system. If all Dutch people choose only Dutch products, this will lower the total water appropriation. Making water footprint data available to consumers might lead to consumer behavior that lowers the water appropriation.

B. The second category of strategies can be summarized by ‘increasing agricultural efficiency’. These are the water footprint strategies, introduced in the second chapter. Increasing technology (and thus yield) will lower the footprint of all crops. Choosing production sites based on their local circumstances is another strategy that will lower water use, although in reality this might be difficult, due to other issues such as food independence and existing production sites. Better irrigitation practices can lower water use in countries which rely heavily on irrigation.

C. The third category comprises the more fundamental strategies. These strategies are targeted at the characteristics of food crops. It is shown that a high harvest index and a good ratio between macronutrients will lower the water use of crops and associated water appropriation of food. The importance of an oil crop is especially of interest. Breeding strategies must be aimed at a high harvest index and high nutritional quality.

D. The ultimate strategy is using the most efficient production route: providing macronutrients without other substances as byproduct. Of course, this is a theoretical strategy (thus far). However, it gives rise to a new perspective: producing nutrients (=quality) is the goal of the production system, not the production of crops (=quantity).

If the present system is considered, it is unlikely that strategy D ‘producing macronutrients’ is an option. People still want to eat food. The other three bundles of strategies (A-C) are options that can be implemented in the current system. The implementation of the suggested strategies is not studied in the current research, because the current research is a theoretical analysis. Therefore, further research is needed to assess the options for implementation.

8.2 Conclusion

The goal of this research was to perform a system analysis of the agro-food system, and to search for options to reduce our water appropriation. The reduction options have been summarized in three categories in this chapter (A-C). Some suggestions for practical applications have been given. However, the practical implications of these options have not been evaluated, as it was beyond the scope of this research. More research is needed to translate the theoretical findings into realistic and acceptable solutions. The main value of the current research is that it opens a new perspective *“It’s the nutrient”*. By using the results of this research, a perspective shift can be made towards the nutritional quality of crops. This focus can lead to a lower water appropriation of the total agro-food system.

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APPENDIX I: WHAT ABOUT MEAT?

10.1 Introduction

Thus far, only the role of crops in the appropriation of water is investigated. Besides the pig meat in the 'culture' chapter, no meat type is discussed. To examine the effect of meat, two analyses are performed in this chapter. First, the photosynthesis and macronutrient scale is expanded with meat. It is assumed that the macronutrients which are produced in the most efficient way, are used to feed animals. It is then calculated how much water is required to produce the reference diet. The optimization model is not used in this chapter, because meat does not deliver carbohydrates. In the most efficient route, it is assumed that meat does deliver carbohydrates, but for the optimization model the values from the USDA database are used and in this database, meat does not deliver carbohydrates. Therefore, only the most efficient route is studied, for the sole purpose of giving an indication of the inefficiency of meat production, compared to the crop production.

The other subject in this chapter is a more practical issue: what is the effect of feed on water appropriation of meat? Two types of feed are investigated: wheat and barley. Both feeds can be fed to the three most-consumed animals: chickens, pigs and bulls. If feed has a large effect on the water appropriation, a possible reduction strategy consists of choosing the best feed type.

10.2. Methodology

Theoretical scenario: production of daily diet by meat

Meat is an indirect way of consuming macronutrients and energy. For the calculation of our daily diet by meat production, the following steps are performed. First of all, the calculation of crops is expanded into the meat analysis. This implies that the production of carbohydrates, proteins and fats and their corresponding nutritional efficiency is used. It is assumed that C_3 crops are used for feeding the animals. From the previous analysis it is known how much water is required for the production of e.g. 1 kJ of carbohydrate energy (see chapter 4). The next step is the calculation of the metabolisable energy (ME) for animals of these macronutrients. These values are obtained from the Dutch Central Bureau for Livestock Feeding (CVB). These values state how much energy is delivered per gram of macronutrient. See table 10.1.

Table 10.1. Metabolisable Energy (kJ) of different macronutrients per type of animal. (CVB, 2004)

Macronutrients	Bovine	Pig	Poultry
Carbohydrates	14.64	13.7	17.32
Protein	15.9	10.8	15.56
Lipids	37.66	36.1	38.83

As the most efficient way is investigated, it is assumed that the digestibility equals 100%. This implies that 1 gram of carbohydrates delivers 14.64 kJ for bulls for gaining weight. With the ME of different macronutrients, one can calculate the energy which is provided by eating the macronutrients. The next step is the calculation of the energy needed to produce one kilogram of meat. The CVB developed a different scale for each animal species to express the nutritional value products. For beef it is expressed as VEVI (Voeder Eenheid Vleesvee Intensief), for pigs as EW (Energie Waarde) and for broilers OEslk (Omzetbare Energie Slachtkuikens). With these feed to gain ratios, the amount of feed needed for a kilo weight gain can be determined. In the first part of this chapter the nutritional values is expressed in kilojoules and in the second part in VEVI. 1 VEVI corresponds roughly with 6.9 kJ, and it is therefore possible to express the feed to gain ratio in kilojoules. 5,950 VEVI is needed for 1 kg of weight gain and this corresponds with 41,055 kJ. The dressing factor is also taken into account. The dressing factor is the consumable fraction of a certain animal. For instance, the consumable fraction of a pig (0.81) is higher than that of a bull (0.59). The same is performed for the other meat types. The EW value, used for pigs, corresponds with 8,800 kJ and the OEslk value corresponds with 1,000 kJ. In table 10.2, the meat-per-feed ratio is listed. By dividing the amount of energy needed to produce one kilogram of meat by the amount of energy delivered, one can assess the kJ meat / kJ feed ratio. Results of these steps can be found in table 10.2.

Table 10.2. Calculation of kJ meat delivered per kJ of feed.

	Beef	Pig	Poultry
Feed to gain ratio (kJ)	41,055	26,400	25,100
Dressing factor	0.59	0.81	0.75
kJ feed for kg meat	69,585	32,593	33,467
*kJ per kg meat (output)**	10,620	11,000	9,000
kJ meat / kJ feed	**0.15**	**0.34**	**0.27**

*** Based on values from the USDA Nutrient Database: "Beef, ground, 20% fat"; "Pork, fresh, ground"; "Chicken, boilers or fryers, meat and skin, raw".**

With these meat-per-feed ratios, one can combine the input in macronutrients with the output in energy available for humans. For instance, carbohydrates deliver 14.64 kJ energy per gram for bulls, and from this 14.64, 15% is available for human consumption (table 10.2). This implies that carbohydrates deliver 2.23 kJ per gram, when feeding it into an animal and consuming the same animal.

The next steps are the same as in the crop-analysis. Since we know that we need 5,757 kJ (55% of 10,467) of carbohydrates per day, we can calculate the nutrient needed to produce this 5,757 kJ of energy. In the case of carbohydrates in bovine meat, we need 2,577 gram carbohydrates to produce 5,757 kJ of energy. These 2,577 gram carbohydrates needed 0.14 liter of water/gram to be produced, and consequently 363 liter of water is needed to produce our daily carbohydrate amount via meat consumption. The schematic representation of the example above is depicted in figure 10.1.

The analysis can be done for all three macronutrients in the three types of meat: bovine, pig and poultry meat. One can sum the liters required for daily carbohydrate, daily protein and daily fat production, in order to derive the total water required for our daily diet.

Production Carbohydrates	**Energy available for animal**	**Energy available for human**	**Nutrient needed for daily consumption**	**Associated water consumption**
1.28 g glucose & 0.14 l water	14.64 kJ / gram	14.64*0.15= **2.23 kJ/gram**	5,757 kJ / 2.23 kJ = **2,577 g nutrient**	2,577*0.14= **363 liter water**

Figure 10.1. Calculation of daily indirect water requirements for the production of 5,757 kJ of carbohydrates via bovine meat consumption. Production needs 0.14 liter water per gram and 2,577 gram is needed, thus 363 liter is required.

Effect of feed

For this subject, the method of Elferink & Nonhebel (2007) is followed. This study discriminates between two important aspects of the livestock to feed conversion: the dressing factor and the feed to gain ratio. The feed to gain ratio is the amount of feed needed to gain a kilogram of weight. As introduced before, the CVB developed a different scale for each animal species to express the nutritional value. For beef it is expressed as VEVI, for pigs as EW and for broilers OEslk. With these feed to gain ratios, the amount of feed needed for a kilo weight gain can be determined. For instance, wheat has a VEVI value of 1,135 and 5,950 VEVI is needed for one kilogram of weight gain, so 5.2 kilo of wheat is needed for one kilo weight gain. If this value is divided by the dressing factor, the total amount of feed for a kilogram of bovine meat is obtained. In table 10.3 the dressings factors and gain ratio for the different meat types are given. After that, the nutritional values of the feed are given for each animal species (table 10.4).

**Table 10.3. Dressing factor and feed to gain ratio for different types of meat.
Feed to gain ratio is expressed in VIVO/Ew/Oeslk / kilogram**

Livestock	Bovine (VIVO)	Pig (Ew)	Poultry (Oeslk)
Dressing factor	0.59	0.81	0.75
Feed to gain ratio	5,950	3	25.1

Table 10.4. Nutritional values of wheat and barley.

Crop	VEVI value	EW value	OEslk
Wheat (fresh)	1,135	1.1	12.07
Barley (fresh)	1,036	1.04	9.9

With these factors, one can calculate the amount of feed needed for a kilogram of meat. By doing this, the following results are obtained (table 10.5). It can be seen that wheat has a higher nutritional factor than barley, because less wheat is required for the production of one kilogram of meat. The production of bovine meat is most costly with nearly 3 times higher crop requirements.

Table 10.5. Quantity of crop (in kg) needed for the production of 1 kg meat.

Meat type	Wheat	Barley
Bovine Meat	8.89	9.44
Pig Meat	3.37	3.56
Poultry Meat	2.77	3.38

With the use of these conversion factors, the indirect water use by meat consumption can be computed for the different meat and feed types. The quantity of crop needed is multiplied by the water footprint obtained from Hoekstra & Mekonnen (511 m^3 for wheat and 363 m^3 for barley) or by the transpirational water requirements, as calculated in chapter 4 (365 m^3 for wheat and 283 m^3 for barley).

10.3 Results

Theoretical scenario: production of daily diet by meat

The production of macronutrients by crops is quite straightforward. It is interesting to expand the theoretical approach for crops with the same theoretical approach for meat. The results of the different production pathways are shown in table for the macronutrients and total water requirements are shown in figure 10.2.

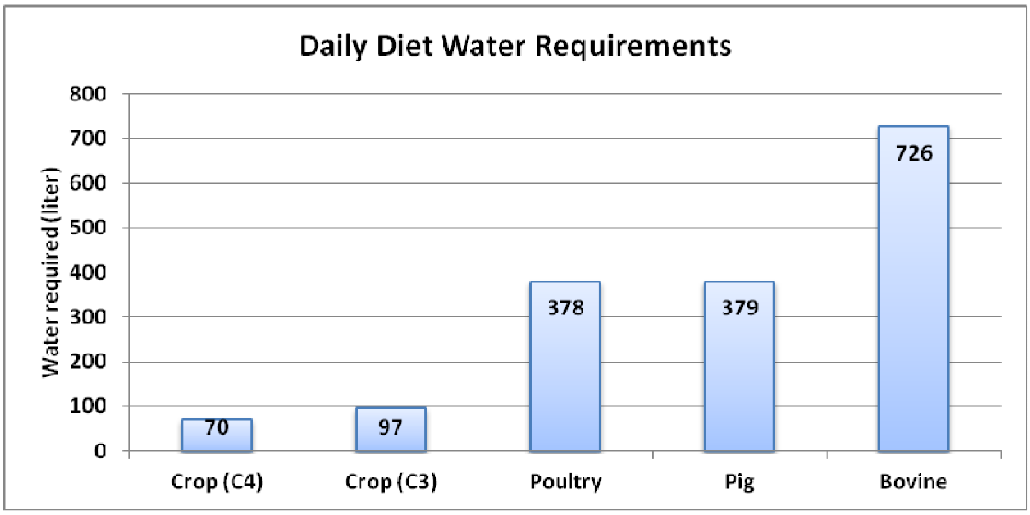

Figure 10.2. Comparison of different production routes for the production of the reference diet.

Figure 10.2 shows that meat is less efficient in producing our daily diet than crop production. Meat needs at least 4 times more water than crop production. This emphasizes the inefficient nature of meat production. A lot of assumptions have been made for assessing minimal meat water appropriation and these assumptions are discussed in the discussion section.

In the second analysis in this chapter, two feed types are compared: wheat and barley. The results are expressed in water footprint and transpirational requirements. From figure 10.3, it can be seen that the production of one kilogram bovine meat, requires 1,000 liters of water more when feeding bulls with wheat instead of barley. The use of wheat in bulls leads to an indirect water consumption increase of around 33%, compared to the use of barley. In pigs this increase is also around 33%, while it is 15% in poultry meat.

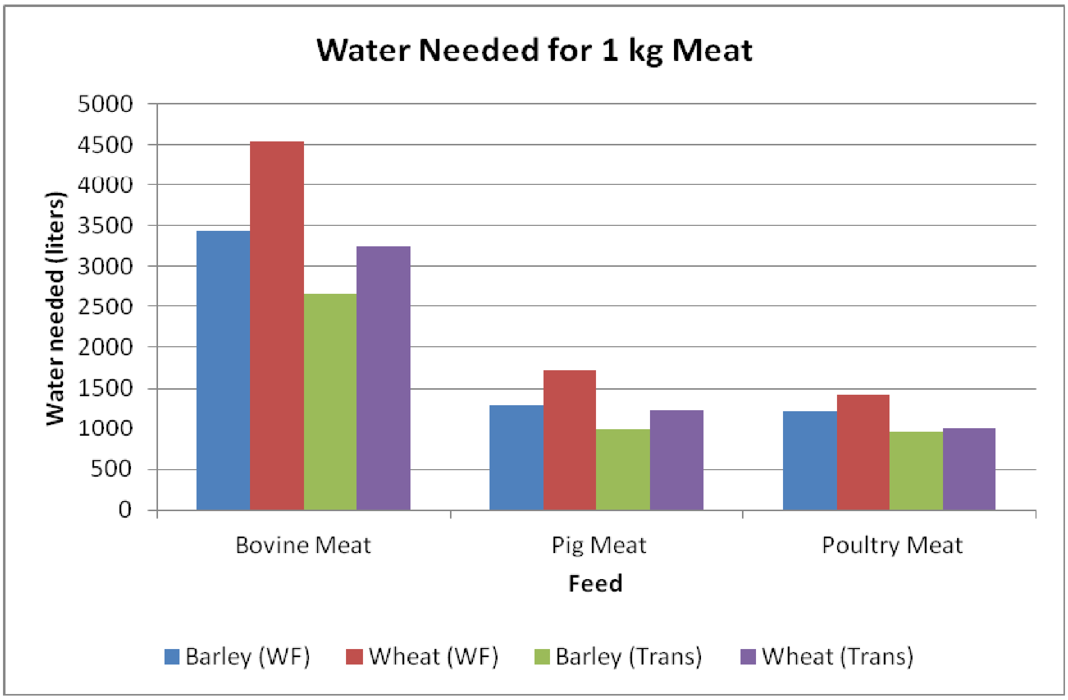

Figure 10.3. Water (in liters) needed for the production of one kilogram meat, for two different feed types: wheat and barley. Indirect water consumption is calculated by using a fixed water footprint (WF) (Mekonnen & Hoekstra, 2011) and using the transpirational water approach (Trans).

Using the differences in indirect water consumption through different feeds, one can calculate the differences on an annual base. This can be seen in figure 10.3. If we use barley for the production of all three types of meat, it is possible to save 40 m^3 per capita. If a population of 16 million is assumed, it is possible to save 650 million cubic meters of indirect water consumption, by switching from wheat to barley.

10.4 Discussion

Theoretical scenario: production of daily diet by meat

In this chapter, the effect of meat on water appropriation is investigated. It can be concluded that, in theoretically optimal circumstances, satisfying our daily nutritional needs requires at least 4 times more water than satisfying our needs by eating only crops. The consumption of bovine meat requires even more water (up to 7 times) because of its low feed-to-meat ratio.

A lot of assumptions have been made in order to compare the crop and meat pathways. It is assumed that the energy of macronutrients is readily and 100% available for animals. In practice, this is not the case. A crude estimation of carbohydrates is that starch from grains has a digestibility of 100%, while carbohydrates from raw straw have a digestibility of 30% (Dijkstra, WUR). The same holds true for protein and lipids, the digestibility is never hundred percent. Another major issue is the assumption that carbohydrates from crop origin are fed to animals and that this delivers carbohydrate energy available for humans. This carbohydrate energy is then used to satisfy our nutritional requirements. However, most meat does not deliver carbohydrates. Therefore, meat cannot be used for the satisfaction of our total daily diet. Thus, the carbohydrate energy can only be used for a theoretical calculation.

Despite all the assumptions and associated issues, the findings underline the inefficiency of the 'meat-pathway', not only in practice, but also from a purely theoretical perspective.

Effect of feed

The feed of animals can have a large effect on the indirect water consumption associated with the consumption of meat. In this research, two cereals are compared: barley and wheat. While wheat has a higher nutritional value, barley has lower water requirements, and the overall effect is that feeding with barley leads to lower indirect water consumption. If farmers could only choose between these two feeds, 40 m^3 per capita could be saved on a yearly basis. In reality, the feed of animals is a mixture of different substances. The current analysis is a gross simplification of the reality. However, it emphasizes the possibility of reducing the water appropriation by meat consumption.

Conclusion

In this appendix, it is shown that meat is in theory and practice an inefficient way of producing the reference diet. It can therefore be argued that the consumption of less meat will lower the water appropriation of our diet. Reduction of meat water appropriation in practice might be possible by shifting to other types of feed. This is not analyzed very extensively, but the preliminary findings from this appendix show that the effect of meat is very substantial.

APPENDIX II: DATA SHEETS

Crop	Wheat	Potato	Sugar Beet	Onion	Barley	Rape seed	Carrot	Fava Beans	Oats	Soy Beans	Bovine Meat	Pig Meat	Poultry Meat
Yield (kg/m^2)[ab]	0.77	4.4	5.8	5	0.63	0.63	5.2	0.652	0.56	0.26 (USA)	0.067	0.177	0.186
Water (l/kg)[c]	365	57	53	23	283	594	29	-	341	392	2,674	1,009	957
Water wf (l/kg) Dutch / Spanish	511 / 1,442	79 / 167	54 / 98	72 / 192	363 / 1,087	876 / 2,073	60 / 147	-	385 / 2,577	1,658 (USA)	-	3,294	-
Source chemical composition[d]:	USDA (hard red, winter) & Gerbens-Leenes	USDA (potato, red, flesh and skin)	IRS[e]	USDA (onions, raw)	USDA (barley, pearled, raw)	Based on Erickson & Bassin	USDA (carrots, raw)	USDA (beans, fava, in pod, raw)	USDA (oats)	USDA (soybeans, mature seeds, raw)	USDA (beef, ground, 20% fat)	USDA (pork, fresh, ground)	USDA (chicken (…), meat and skin, raw)
Energy (kJ/kg)	14,364	3,570	2,957	1,660	14,730	20,640	1,730	3,700	16,280	18,660	10,620	11,000	9,000
Carbohydrates (g/kg)	693	190	173	93	777	90	96	176	663	301	0	0	0
Protein (g/kg)	117	20	4	11	99	230	9	79	169	365	172	169	186
Lipids (g/kg)	2	0	0	1	12	400	2	7	69	200	200	212	151
Zinc (mg/kg)	26.5	3.3	?[f]	1.7	21.3	?[f]	2.4	1	39.7	48.9	42	22	13
Vitamin A (µg/kg) (RAE)	0	0	?[f]	0	1	?[f]	8,350	170	0	10	0	20	41

a. Yield derived from CBS, 2001 or FAOSTAT. Because of availability reasons, yield is for the year 1997 or 1998.
b. Yield of meat calculated for barley-fed animals. Yield of barley divided by kilograms needed for 1 kg meat (section..).
c. Water requirements calculated by the transpirational water needs, as described in Appendix I.
d. USDA = USDA National Nutrient Database for Reference (release 24) In brackets the corresponding food item.
e. IRS = Instituut voor Rationele Suikerproductie (Institure for Rational Sugar Production)
f. Not available from corresponding source. Is therefore assumed to be 0.

Nutritional Productivities

Nutritional productivities used in the Optimization model. Productivities are derived by dividing the nutrient concentrations by the transpirational water requirements (a) or by the water footprint of Dutch crops (b) or by the water footprint of Spanish crop (c). Energy is expressed in kJ; macronutrients in gram; zinc in mg; and Vitamin A in µg RAE.

a) Transpirational water

	Energy/l	Carbohydrates/l	Protein/l	Lipids/l	Zinc/l	Vitamin A/l
Wheat	39	1.90	0.32	0.01	0.07	0
Potato	62	3.31	0.35	0	0.06	0
Sugar Beet	55	3.24	0.07	0	0	0
Onion	72	4.03	0.48	0.04	0.08	0
Barley	52	2.74	0.35	0.04	0.08	0
Rapeseed	35	0.15	0.39	0.67	0	0
Carrot	60	3.33	0.31	0.07	0.08	289.97
Oats	48	1.94	0.50	0.20	0.12	0
Soy Beans	48	0.77	0.93	0.51	0.12	0.03
Bovine	4	0	0.06	0.07	0.02	0
Pig	11	0	0.17	0.21	0.02	0.02
Poultry	9	0	0.19	0.16	0.01	0.04

b) Water footprint (Dutch)

	Energy/l	Carbohydrates/l	Protein/l	Lipids/l	Zinc/l	Vitamin A/l
Wheat	28	1.36	0.23	0.00	0.05	0
Potato	45	2.41	0.25	0	0.04	0
Sugar Beet	55	3.20	0.07	0	0	0
Onion	23	1.29	0.15	0.01	0.02	0
Barley	41	2.14	0.27	0.03	0.06	0
Rapeseed	24	0.10	0.26	0.46	0	0
Carrot	29	1.60	0.15	0.03	0.04	139.17
Oats	42	1.72	0.44	0.18	0.10	0
Soy Beans	11	0.18	0.22	0.12	0.02	0.01
Bovine	-	-	-	-	-	0
Pig	3	0	0.05	0.06	0.01	0.01
Poultry	-	-	-	-	-	-

c) Water footprint (Spanish)

	Energy/l	Carbohydrates/l	Protein/l	Lipids/l	Zinc/l	Vitamin A/l
Wheat	10	0.48	0.08	0.00	0.02	0
Potato	21	1.14	0.12	0	0.02	0
Sugar Beet	30	1.77	0.04	0	0	0
Onion	9	0.48	0.06	0.01	0.01	0
Barley	14	0.71	0.09	0.01	0.02	0
Rapeseed	10	0.04	0.11	0.19	0	0
Carrot	12	0.65	0.06	0.01	0.02	56.80
Oats	6	0.26	0.07	0.03	0.02	0
Soy Beans	11	0.18	0.22	0.12	0.03	0.01