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The Water Footprint of Winter Wheat in Sweden

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PREFACE

This report has been written as a master thesis in Environmental Engineering for the department of Water Resources Engineering at Lund University and Lantmännen. The examiner has been Linus Zhang and the supervisors were Rolf Larsson for the department and Sofie Karlsson for Lantmännen.

I would like to extend my gratitude to my supervisors Rolf and Sofie, and also Martin Johansson at Lantmännen for their invaluable input and support. I would also take this opportunity to express my appreciation and thanks to my friends and family who have supported me throughout my studies and this project, as well as the governmental bodies such as Jordbruksverket and Statistiska Centralbyrån without the help of which this project would not have been possible.

SUMMARY

Key words: Water footprint, winter wheat, liquid fuel ethanol, wheat flour, macaroni, Lantmännen

This study attempts to calculate the green blue and gray water footprint of the crop production of winter wheat and three derived winter wheat products: liquid fuel ethanol, wheat flour and macaroni. The calculations were done for Sweden for the period 2008-2010, covering an average of 80% of the annual winter wheat production. The south of Sweden was divided into 18 climate zones for which sufficient climatic data was available. The crop water use and requirements were then calculated for each of these zones using the CROPWAT model developed by the UN Food and Agriculture Organization, FAO. Other activities such as transportation, energy use and processing water were included in the study but combined these activities contribute to less than 1% of the water footprint of raw winter wheat production, referred to as the supply chain system. It is completely dominated by the cultivation component and the total water footprint is 875 m^3 (59.4% green, 0.8% blue and 39.8% gray) per ton of wheat with a water content of 14%. Out of the supply chain system the cultivation component stands for 871 m^3 (59.5% green, 0.6% blue and 39.9% gray) or about 99.5%. The result compares well to an earlier study by Mekkonen & Hoekstra (2010a).

In the case studies of refined winter wheat products the total water footprint is still dominated by the supply chain in general and the cultivation component within it specifically.

The water footprint of wheat flour from winter wheat at the mill in Malmö is found to be 1.15 m^3 (59.1% green 1.2% blue and 39.7% gray) per kg of flour out of which 99% is from the supply chain component.

The water footprint of liquid fuel ethanol from the Agroetanol plant in Norrköping is calculated to 1 477 m^3 (57.5% green, 4.2% blue and 38.3% gray) per m^3 of ethanol, out of which the supply chain component is almost 95%, while the rest is mostly energy use in the form of bio fuel based steam production and electricity.
The water footprint of the production of macaroni at the Ceralia factory in Järna is calculated to 1.30 m^3 (57.7% green, 3.8% blue and 38.5% gray) per kg of macaroni. About 95% of this is from the supply chain component while the remaining 5% is mostly attributed to the energy used in the processes.

SAMMANFATTNING

Nyckelord: water footprint, höstvete, drivmedelsetanol, kärnvetemjöl, makaroner, Lantmännen

Studien syftar till att beräkna det gröna, blå och grå vattenfotavtrycket vid odling och produktion av höstvete och tre fallstudier av höstvete-produkter; drivmedelsetanol, kärnvetemjöl och makaroner. Beräkningarna har utförts för Sverige under perioden 2008-2010 och täcker ungefär 80 % av den svenska produktionen av höstvete under de berörda åren. Södra Sverige delades in i 18 klimatzoner för vilka tillräckliga klimatdata fanns tillgängliga. Grödornas vattenanvändning och behov beräknades sedan för var och en av dessa zoner med hjälp av FN-organet FAOs (Food and Agriculture Organisation) vattenmodell CROPWAT. Andra aktiviteter i systemet som transport, energiproduktion och processvattenanvändning inkluderades, men bidrar med mindre än 1 % av vattenfotavtrycket sammanlagt i produktionen av höstvetekärnor. Denna del kallas supply-chain systemet i resten av rapporten.

Supply-chain systemet domineras helt av odlingskomponenten och det totala vattenfotavtrycket är 875 m^3 (59.4 % grön, 0.8 % blå och 39.8 % grå) per ton höstvetekärnor med 14 % vatteninnehåll. Av detta står odlingskomponenten för 871 m^3 (59.5% grön, 0.6% blå och 39.9% grå) eller ungefär 99.5%. Resultatet kan med fördel jämföras med en tidigare studie av Mekkonen & Hoekstra (2010a) I fallstudierna där vattenfotavtrycket av höstveteprodukter studeras dominerar supply-chain komponenten generellt, och odlingskomponenten inuti den, specifikt.
Vattenfotavtrycket av kärnvetemjöl från kvarnen i Malmö beräknas till 1.15 m^3 (59.1 % grön, 1.2 % blå och 39.7 % grå) per kg kärnvetemjöl. Ungefär 99 % av detta härrör från supply-chain systemet.

Vattenfotavtrycket från drivmedelsetanol från Agroetanolfabriken i Norrköping beräknas till ungefär 1 477 m^3 (57.5 % grön, 4.2 % blå och 38.3 % grå) per m^3 etanol. Supply-chain komponenten står för nästan 95 % av detta, medan övriga avtrycket kommer från produktionen av bioenergi i form av ånga från E.on samt elektricitet.

Makronerna som produceras vid Ceralias anläggning i Järna beräknas ha ett vattenfotavtryck på ca 1.30 m^3 (57.7% grön, 3.8% blå och 38.5% grå) per kg makaroner. Ungefär 95% av detta härrör från supply-chain komponeneten, medan kvarvarande 5% mest kommer från produktionen av energi som används i tillverkningsprocessen.

GLOSSARY

14% Wheat - Refer to wheat kernels with a 14% water content. Other percentages occur as well, such as 19% wheat, or 12.9% wheat depending on the process

ArcGIS – A geographic information system used for geographic analysis of spatially explicit data.

Consumptive water use: Water that is not returned to the same catchment area, lost either through evapotranspiration, incorporation into a product or it is returned to another catchment area or at another point in time.

D0 flour – D-zero flour, a flour of pure winter wheat used in a number of production processes in Järna. It is used in the macaroni case study and is produced at the Ceralia mill in Malmö.

Degradative water use: Water that is returned to the same catchment area, but is of lower quality than when it was extracted.

Environmental flow (also: ecological flow): The base flow needed to sustain ecological activities, often abbreviated EFR or EWR.

Evapotranspiration: the combined process by which water is transferred to the atmosphere by evaporation from soil or transpiration by plants.

Filling degree – The degree to which a transportation unit is filled, e.g. 80% of capacity.

Gammaldags Idealmakaroner – A brand of macaroni produced at the facility in Järna. The production of the macaroni include only winter wheat flour and is therefore chosen as the object of this analysis. The origin of the flour used is 100% Swedish.

In-stream and off-stream water use: Refers to *where* water is utilized. Examples could be hydropower and irrigation for the two uses respectively.

Incorporated water: The water that is retained within the physical product, e.g. the moisture content of grain.

Jordbruksverket – The Swedish agricultural agency

Kungsörnen kärnvetemjöl – Wheat flour produced at the mill in Malmö. Is referred to as wheat flour or simply flour.

Net-green water: The decrease in the part of precipitation that becomes run-off or is infiltrated due to land use changes related to the production system. Often a reference system is used instead of actual pre-production conditions.

Organic fertilizer –Manure from beef cattle is used as an estimation of the water footprint characteristics of organic fertilizer.

River basin (also: drainage area, catchment area, watershed): The area of land from which precipitation drains into a river or its tributaries. A watershed drains into a smaller body of water, and a river basin consists of many watersheds.

Virtual water: Water used in the production of a product, but is not necessarily incorporated into it; in fact the incorporated amount is often negligible.

Winter wheat – A type of wheat grain, which is planted in the fall and is left in the soil over winter (Swedish: Höstvete).

ABBREVIATIONS

DDGS – Dried Distillers Grains with Solubles, are the remaining material after the fermentation of the wheat starch into ethanol. It is high in protein and fiber content and is used mainly for animal fodder

EtOH – Short for Ethanol or C_2H_5OH which, used for transportation fuel, is also referred to as bioethanol or liquid fuel ethanol

LCA – Life Cycle Assessment, a method for calculating the environmental effects of a specified system. The term is explained more thoroughly within the report

NO_3-N – Signifies the amount of nitrogen in a NO_3 compound, e.g. 11.2 mg NO_3-N is approximately 50 mg of NO_3.

SMHI – Swedish Meteorological and Hydrological Institute

UN FAO – The United Nations Food and Agricultural Organization

US EPA – United States Environmental Protection Agency

WHO – World Health Organization

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1 Introduction

1.1 Background

Freshwater is an increasingly scarce resource, yet it is essential to humans and ecosystems and cannot be replaced by any other substance. The distribution of water however, is uneven and almost a fifth of the world population live in areas with physical water scarcity, and another 500 million are approaching this situation (CAWMA, 2007). The use of water is poorly regulated in some areas, which leads to overexploitation for economical purposes, especially for industrial and agricultural uses, but also to meet the needs of a growing population (WWAP, 2009). The pressure on freshwater resources is expected to increase even more, both due to climate change, but also to cope with the demand from measures to decrease greenhouse gas emissions, an example being the cultivation of bio fuel crops. The ability to measure the use of freshwater and the impacts it has, is therefore crucial to be able to minimize the damage associated with it.

1.1.1 Lantmännen and Water Footprints

Lantmännen is one of the largest groups within food, energy and agriculture in Scandinavia, owned by 36,000 Swedish farmers and has over 10 000 employees.

Lantmännen operates on an international market, where Sweden constitutes the foundation for the group's activities. It conducts business operations in a total of 18 countries, and are a market leader in several business areas. Examples of Lantmännen brands include AXA, Kungsörnen, Start, Hattings, Regal and Kronfågel.

Lantmännen also conducts research and development work in association with universities, colleges and companies. As a leading player in food, bio-energy and agriculture, Lantmännen also works actively to promote the development of a healthy and sustainable society. Lantmännen is active in all the parts of the value chain, from field to fork (Lantmännen, 2012).

The water footprint is an important part of the environmental, social and economic aspects of any company, especially within the food, bio energy and agriculture sectors. The latter accounts for as much as 85% of global water use (Hoekstra & Chapagain, 2006) which implies that a significant share of the water footprint of Sweden is related to activities by Lantmännen or their subsidiaries, making them an important player in the future of Swedish water resources. A water footprint of one of the base raw materials within Lantmännen, winter wheat, is therefore an important measurement of how the company affects local and regional water resources.

1.2 Purpose and Goal

The purpose of this report is to create an understanding of the concept of water footprints and how it applies to Lantmännens activities. An additional purpose is to identify the key components of the processes involved, to improve the scope and focus of future water footprint studies of Lantmännens agricultural and processing systems.

The goal is to make an analysis of the water use in the production of winter wheat and of refined winter wheat products. The result can be used to break down the water uses per process and type, to determine appropriate measures to improve the water use efficiency.

The study was conducted as a Master's thesis in Environmental Engineering at the University of Lund. Lantmännen initiated the project in response to a growing international interest in the subject matter.

1.3 Method

The first part of the report is a literature study that outlines three methods of conducting a water footprint analysis and a brief description of LCA-methodology. This is followed by a study of the water footprint of winter wheat and three derived winter wheat products: liquid fuel ethanol, wheat flour and macaroni. The study is based on a combination of some of the methods described in the literature study and LCA. The method used in the literature study is defined within that section.

The study will be limited to the cultivation of winter wheat in Sweden during the years 2008-2010, and the scope and boundaries will be defined more in detail within each system description.

2 Literature Study

2.1 Introduction

Hoekstra introduced the concept of water footprint in 2003. It builds on the idea of *virtual water content* or *embedded water* (Allan, 1998). Hoekstra defined the water footprint as: The sum of all the freshwater that is used directly or indirectly to produce the product. This has later been refined to include quality as well as volumetric measurements and characterizations to make the water footprints of different products comparable. There is currently an abundance of available methods to calculate and characterize the water use and the effects it has on humans, the environment and on economic factors.

2.1.1 Water footprints and Life Cycle Assessments

Life cycle assessments (LCA) are a commonly used tool to describe the environmental effects of products and production systems. Traditionally they do not include water use, but it has been suggested that the water footprint concept could be incorporated into the LCA framework proposed in ISO 14040:2006. A number of suggestions on how this could be accomplished have been put forth, but none has has been established as a standard as of yet.

The development of an ISO standard for water footprint is underway and Elin Eriksson, who is in charge of this work within Swedish SIS said to the magazine Ingenjören in 2012, that within 5 years there would be a standard in place. In the meantime this master thesis will attempt to use water footprint calculation methods and present the results using a life cycle analysis framework.

Similar to Life Cycle Assessments (LCA), most water footprint analysis consists of four main phases: Goal & scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation according to ISO 14044:2006. Figure 1 show how these phases interact in an LCA and consequently in a water footprint analysis. There is consensus among most authors, that water footprints and LCA need to be interconnected, but disagreement on how this should be accomplished.

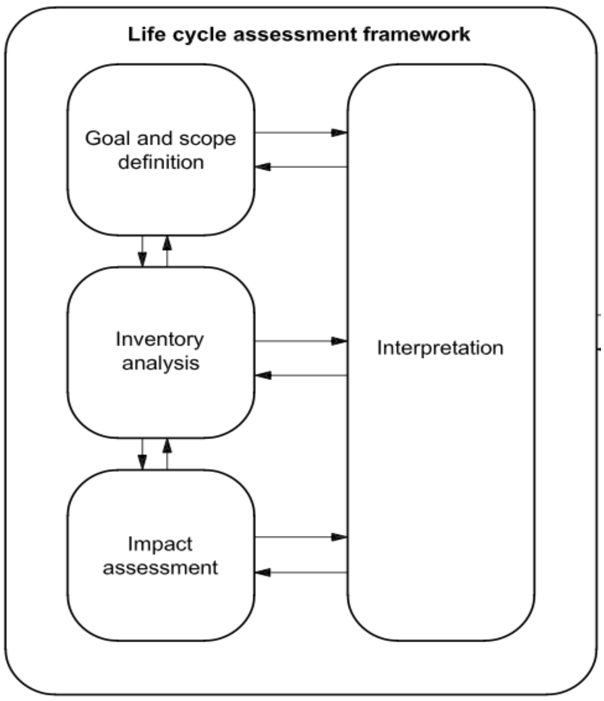

Figure 1: The framework of LCA, the image is from ISO 14040:2006.

The life cycle inventory is the accounting of water flows connected to the product's life cycle, while the impact assessment (LCIA) attempts to characterize the different water uses based on a set of predefined criteria. The most significant difference with conventional LCA's in these two phases is the location-specific impacts associated with water use. Both the *interpretation* and *goal & scope* phases are heavily dependent on data reliability and availability, and the specific product and production systems respectively, and therefore this literature study will focus more on the LCI- and LCIA-phases.

2.2 Goal and Purpose

The aim of the literature study is to get an overview of existing water footprint methodology, and the purpose is to be able to make an informed decision on how to best conduct a water footprint analysis of Lantmännens grain production. The selected method will also be revised to better suit the restrictions in data. The calculations in the supply chain study and the three case studies will be limited to a quantification of the size and composition of the water footprint without attempting an LCIA. The reasons for this are mainly time constraints and the lack of available data. The literature study does cover the LCIA methods to clarify the difference between the methods, and to create an understanding of the data required to complete an impact assessment.

2.3 Method

The literature included in the study was sourced from articles and papers found through the *Summon* search tool of Lund University library and through websites of various interest groups.

The search terms were initially 'water footprint' and variations of that. In the latter part, reference lists at the end of various reports were useful sources for reports but also for additional search terms. In addition to this, two literature reviews, Jeswani & Azapagic (2011) and Berger & Finkbeiner (2010), were used to identify additional sources.

2.4 Literature Search and Analysis

During the literature search and subsequent analysis, three different methods have been identified as the most relevant ones. The choice of method is influenced by a number of factors, mainly:

- How established, frequently applied or discussed the method is
- How comprehensive the method is
- If the method is broad enough to encompass many water sources and uses
- If the method is based on the concept of virtual water

The main authors are used to refer to the respective studies:

Hoekstra et al - The Water Footprint Assessment Manual: Setting the global standard (2009)

This method has been developed at the University of Twente, The Netherlands, in cooperation with a multitude of businesses, the WWF and the United Nations Environment Programme, UNEP (Water Footprint Network, 2012)
It has been used to study a multitude of water footprints, from global (Hoekstra & Hung, 2005) and regional (Hoekstra & Chapagain, 2004) totals, to product specific, e.g. the production of Nestlés bitesize shredded wheat (Chapagain & Orr, 2010) or electricity from hydropower (Hoekstra & Mekonnen, 2011), to mention a few.

Hoekstra founded the concept of a water footprint, and he and the group around him are responsible for a significant share of the water footprints being done today.

Milá i Canals et al - Assessing freshwater use impacts in LCA: Part 1 - Inventory modeling and characterization factors for the main impact pathways (2009).

The main author is active at both the University of Surrey in the UK and at Unilever. The method is an enhancement of the connection between the method of Hoekstra et al. and conventional LCA, where an attempt is made to weigh the impacts of the quantified water use together into a damage assessment. The application of the method has been limited, but there is a case study on broccoli in the UK and Spain, published as part 2 of the methodology report (Mila i Canals et al., 2010).

Pfister et al - Assessing the impacts of freshwater consumption in LCA (2009)**.**

Dr. Stefan Pfister is a senior research associate of environmental engineering at the University of Zurich in Switzerland. The suggested method is based on virtual water and the Hoekstra et al. life cycle inventory, but offers a different approach to the impact assessments than both previous authors, using the Eco-indicator 99 methodology. The Pfister et al method has been applied in some case studies at the university, and a revised approach has been further developed in cooperation with CSIRO, Australia's national science agency (Ridoutt & Pfister, 2010).

There is a range of other methods available, such as purely qualitative categorization (Boulay et al., 2011) and the use of *exergy* (maximum amount of work that can be produced by a system) as a measurement of water quality (Huang et al., 2007). These and many others have been excluded from this study due to limitations in the extent of this thesis, their suitability for the purpose or a combination thereof.

2.5 Life Cycle Inventory, LCI (or Water Footprint Accounting)

All three groups of authors suggest some similar inventory mechanisms, such as the *source* or type of water, in what way the water is *used* (ultimately how, where, when and if it is returned) and *where* it is used (what watershed, drainage area, country etc. but also if it is used in the stream or abstracted from it). The authors use a manifold of terms and definitions of these parameters and a brief summary of these can be found below, followed by an explanatory matrix, see Table 1 of the parameters that each group of authors suggests should be included in a LCI.

2.5.1 The Hoekstra et al approach

As mentioned in the introduction Hoekstra introduced the concept of water footprint in 2003 (Hoekstra, 2003) building on the idea of virtual water (Allan, 1998). The concept has since been refined and compiled into The Water Footprint Assessment Manual (Hoekstra et al., 2009) a comprehensive volume by the Water Footprint Network, an interest-group comprised of businesses, civil society, multilateral organizations and academia (Water Footprint Network, 2012).

Hoekstra et al identifies two different types of water *use*; Consumptive and non-consumptive (or degradative) water use, Consumptive water use refers to the following scenarios (Hoekstra et al., 2009):

1. Water Evaporates
2. Water is incorporated into product
3. Water does not return to the same catchment area
4. Water does not return in the same time period

The authors define two different *sources* of consumptive water use that make up a water footprint:

- **Blue water** is fresh surface- or groundwater
- **Green water** refers to the precipitation that does not run off into surface waters or recharge ground water, but is stored in soils and is then evaporated or transpired through plants (evapotranspiration)

Non-consumptive (or degradative) use refer to water that is returned to the same catchment and in the same time period but is of lower quality due to pollution or eutrophication. Degradative water use causes a third category of water footprint:

- **Gray water** is the amount of water required to assimilate pollutants in any water which is returned to the catchment, to a concentration where it complies with ambient water quality standards

Equations (1)-(2) and (3) below, define the method of volumetric calculation for each source of water:

$$WF_{green} = ET_{green} + Incorporated_{green} \quad (1)$$

$$WF_{blue} = ET_{blue} + Incorporated_{blue} + R_{other\ basin} + R_{other\ time} \quad (2)$$

$$WF_{gray} = \frac{L_j}{(c_{awq,j} - c_{nat,j})} \quad (3)$$

Where WF is the water footprint, ET is the evapotranspiration, R refers to return flows L is the load of pollutant j and $c_{awq,i}$ and $c_{nat,i}$ are the concentrations of pollutant j as defined in ambient water quality standards and natural background concentrations respectively.

The Water footprint assessment manual also mentions a further categorization of blue water by source, into surface water, renewable groundwater and fossil groundwater (or light blue, dark blue and black water respectively) but the precise source of blue water can often be difficult to identify, especially in studies with a large geographic scope.

When dealing with a product, the Water Footprint Network suggests the inclusion of a type of allocation principles, referred to as value fractions (economic allocation) and product fractions (mass allocations). This concept is not applied directly in this report; instead allocations are made according to LCA methodology.

2.5.2 The Milá i Canals et al approach

This approach builds on the same principles as Hoekstra et al, i.e. virtual water and a division between the water source, water use and location of use. However, the definitions of the use and source differ somewhat from Hoekstra, and are divided by water *input* and *output categories* (Milá i Canals et al., 2009). The water sources (or inputs) are:

- **Blue water** is fresh surface- or groundwater, subdivided into *flows* (rivers, lakes), *funds* (groundwater) and *stocks* (fossil water)
- **Green water** is defined in a similar way as in the Hoekstra et al approach but is not a direct part of the life cycle inventory, instead the green water footprint consists of the change in runoff and infiltration due to land use changes, called *net green water footprint*.

The types of water use (or outputs) are simply divided into:

- **Evaporative use**, water is lost and not immediately available after use (also referred to as *water consumption* (Owens, 2001)).
- **Non-Evaporative use,** water is returned and may be used by others after leaving the system (also referred to as *water use* (Owens, 2001)). It does however not need to return to the same basin, at the same time or be of the same quality, to be considered non-evaporative.

Equations (4) and (5) below represent how the footprints are calculated according to Milá I Canals et al:

$$WF_{green} = ET_{green,sys} - ET_{green,ref} \qquad (4)$$

$$WF_{blue} = ET_{blue} + Incorporated_{blue} \qquad (5)$$

The indexes *sys* and *ref* refer to the studied system and the reference system, respectively. For equation (4) it is assumed that the sum of evapotranspiration (ET), run-off (R) and infiltration (I) make up the total amount of green water in any area, thus an increase in ET, will lead to less I and R, in turn leading to less available water. Non-evaporative water use is accounted for in the life cycle inventory, but treated otherwise in the impact assessment, as the returned water will have different environmental effects than the evaporated water.

2.5.3 The Pfister et al approach

Pfister et al (2009) divide water use into two categories, similar to those of Hoekstra et al:

- **Consumptive water use**, defined as "freshwater withdrawals which are evaporated, incorporated in products and waste, transferred into different watersheds, or disposed of into the sea after usage." (Pfister et al., 2009)
- **Degradative water use**, counted as a loss of higher quality water, and a gain of lower quality water.

The sources of water used are similar to those used by Milá i Canals, except for the fact that Pfister et al do not consider any green water use, but argues for an inclusion of degradative (gray water) in the LCI without suggesting any methods of how to quantify this. The blue water footprint is the same as defined by Hoekstra et al, expressed in equation (2).

Table 1: A summary of how the three different methods account for water use from different sources, the type of water use, i.e. consumptive, degradative, evaporative or non-evaporatoratory are not explicitly specified.

	Blue water	Green water	Gray water
Hoekstra et al 2009	All types of Blue water included: Evapotranspirated, incorporated and run-off lost to another basin or returned at another point in time	All Green water included: Evapotranspirated and incorporated	Defined as the volume of freshwater required to dilute pollutants in run-off to an ambient water quality standard
Milá i Canals et al 2009	Blue water that is evapotranspirated or incorporated, along with *any* use of fossil (black) water included	Green water is seen as the difference in run-off between the new system and a reference system, similar to the concept of 'net green water'	Gray water is not included, with the reasoning that it should be considered in another section of an LCA, eutrophication, Eco-toxicity etc.
Pfister et al 2009	Same definition of blue water as Hoekstra et al.	No green water included	No gray water included

2.6 Life Cycle Impact Assessment, LCIA or Water Footprint Sustainability Assessments

As was previously mentioned, the water footprint analyses that are part of this report do not include impact assessments. The reason for this is a combination of the scope of the thesis and a lack of available data. A brief description of how the impact assessments should be conducted according to the three methods is presented below to give an indication of how the results of the supply chain and case studies could be interpreted.

2.6.1 The Hoekstra et al approach

Following a four-step process the sustainability of the calculated water footprints are assessed based on predefined criteria. These four steps are (Hoekstra et al., 2009):

1. Identify and quantify sustainability criteria
2. Identify hotspots (points in space and time where the criteria are not met) within this sub catchment or sub basin
3. Identify and quantify primary impacts in these hotspots
4. Identify and quantify secondary impacts in these hotspots

The authors use a yes-or-no method of deciding whether the water footprint is sustainable or not. Each source of the water footprint is individually evaluated, meaning for example that the green footprint could be sustainable while the blue is not etc. The environmental sustainability is evaluated by defining a scarcity factor as the ratio between the green footprints over the availability of green water. The indicator is calculated similarly for blue water, but an environmental flow requirement is also considered in this fraction. For gray water the footprint is divided by the actual run-off from the field or region in question, and this fraction represents how much of the assimilation capacity is consumed. Any values above 1 indicate an unsustainable footprint. These can then be multiplied with the corresponding footprints at each time and location to find what the authors call local water footprint impact indices. The equations used for these calculations are defined below.

The green water scarcity is calculated as:

$$WS_{green}[i,j] = \frac{\sum WF_{green}[i,j]}{WA_{green}[i,j]} \quad (7)$$

Where WA is water availability, WS is the scarcity and WF is the water footprints of the processes within each region *i* and at each time *j.* The sum of all green water footprints within region *i* at time *j* divided by the water availability within that same region.

The blue water scarcity is calculated in the same way with the same denotations:

$$WS_{blue}[i,j] = \frac{\sum WF_{blue}[i,j]}{WA_{blue}[i,j]} \quad (8)$$

Where the available blue water is calculated as run-off (R_{nat}) minus the environmental flow requirement, EFR:

$$WA_{blue}[i,j] = R_{nat}[i,j] - EFR[i,j] \quad (9)$$

The gray tolerance, or water pollution level (WPL) is calculated with the same denotations as above:

$$WPL[i,j] = \frac{\sum WF_{gray}[i,j]}{R_{act}[i,j]} \quad (10)$$

Where R_{act} is the amount of actual run-off from the studied system.

The social sustainability is only briefly discussed and builds on the assumption that unsustainable social hotspots can potentially be found where environmental hotspots are present, and should be individually assessed in those locations and at those times.
The economic sustainability is treated in a similar way, and the authors suggest that the efficiency of the water use decides how sustainable it is. The degree to which the full economic costs of the water used are charged to the user, including opportunity costs, water rents and externalities, is suggested as a way of measuring this efficiency.
These methods of handling the economic and social sustainability are based on the assumption that environmental sustainability conditions are the first to be violated.

2.6.2 The Milá i Canals et al approach

The authors suggest that freshwater need to be assessed from two different aspects: as a resource for humans, and as a habitat, a resource for ecosystems (Milá i Canals et al., 2009). These aspects give rise to four main impact pathways:

1. "Direct water use, leading to changes in freshwater availability for humans leading to changes in human health"
2. "Direct water use leading to changes in freshwater availability for ecosystems leading to effects on ecosystem quality (freshwater ecosystem impact, FEI)"
3. "Direct groundwater use causing reduced long-term (fund and stock) freshwater availability (freshwater depletion, FD)
4. "Land use changes leading to changes in the water cycle (infiltration and runoff) leading to changes in freshwater availability for ecosystems leading to effects on ecosystem quality (FEI)"

All of the above points (1-4) are direct definitions from Milá i Canals (2009) p31.

1. Effects on human health

Concerning the effects on human health, the authors suggest that this impact pathway is omitted from the LCIA, as the damages often relate to poor water quality and sanitation, and there are no statistically significant correlations between available freshwater resources and human health and well-being (Chenoweth, 2008a; Chenoweth, 2008b).

2. Change in water quantity affecting ecosystem health (FEI)

The effect on ecosystems is assumed to originate only from evaporative water uses, and water extracted and then later returned is not included. The authors exemplify this with the water intake for a city: the release of water might be localized further downstream than the intake, causing decreases in local flow. However these effects are deemed too local and are therefore not included. The authors also suggest that the quality aspect of the returned water should belong to another impact category, such as eutrophication or eco-toxicity, depending on what the pollutant is.

3. Depletion of freshwater resources (FD)

The use of groundwater is included as an impact on natural resources because it may reduce availability for future generations. Competition with ecosystems is addressed in 2 above, and the competition with humans is considered as outside the scope of an LCA.

4. Changes in the water cycle due to land use related to the production system (FEI)

The change in the balance between run-off (R) infiltration (I) and evapotranspiration (ET) due to a production system compared to a reference system is considered in this category. The sum of R and I are estimated by the difference between precipitation and ET. This will reflect decreased or increased water availability in freshwater ecosystems due to changes in infiltration and run-off. Increases are generally not seen as "negative" footprints, and are not deducted from the total footprint. This is due to the negative effects often related to increased direct runoff.

Characterization indicators for freshwater ecosystem impacts (FEI)

The authors suggest an indicator that is a fraction of the water use over the available water resources WU/WR (Raskin et al., 1997), they motivate the choice of this simple parameter by the readily available data, and the fact that it reflects the marginal impacts of water use. Another approach is also suggested where, similar to Hoekstra et al, the environmental flow requirements are subtracted from the available water (Smakthin et al., 2004), but due to large gaps in data regarding environmental flow requirements the authors do not recommend this more sophisticated method.

Characterization indicators for freshwater depletion (FD)

The indicator that Milá i Canals et al proposes is an adaption of the Abiotic Depletion Potential or ADP (Guinée et al., 2002), calculated by subtracting the replenishment rate from the extraction rate, and dividing that with the total reserve squared, see equation (11) below. This will give an indication of how long the current resources will last. The answer is then multiplied with the total resources squared and divided by the depletion rate for the reference element antimony (Sb).

$$ADP_i = \frac{ER_i - RR_i}{R_i^2} \times \frac{R_{Sb}^2}{DR_{Sb}} \qquad (11)$$

Where ER, RR and R stand for extraction rate, replenishment rate and total reserves respectively. The equation shows that for RR>ER we get a negative depletion potential, which indicates that there is no depletion of freshwater resources. This is the case for most aquifers and the FD is therefore often not an issue (Milá i Canals et al., 2009). However heavily exploited water reserves such as in California or parts of Spain will display depletion factors much higher than most abiotic resources listed by Guineé et al (2002).

2.6.3 The Pfister et al approach

The authors propose a significantly more refined method compared to the two previous LCIAs. First they suggest an initial screening assessment using the WSI, or water stress index, which is similar to what the two other approaches use. The WSI depends on a withdrawal-to-availability ratio (WTA) simply defined as the sum of all water withdrawals divided by the available resources similar to equation (8) of Hoekstra et al.

In this approach the WTA data is input to a model called WaterGAP2 that calculates the WSI. This model includes hydrological and socio-economic parts based on annual average data from the climate normal period 1961-1990 (Alcamo et al., 2003). The authors further expand this model by introducing a variation factor (VF) to account for seasonal changes and the effects of flow regulations such as dams and reservoirs (Pfister et al., 2009). The WSI calculated with this methodology is then used as a general indicator or as a separate impact category in the LCIA. The WSI is calculated as shown in equation (12). It is worth noting that the expression within parenthesis could be simplified, but the authors choose not to do so without specifying a reason for it.

$$WSI = \frac{1}{1+e^{-6,4 \cdot WTA* \cdot (\frac{1}{0.01}-1)}} \qquad (12)$$

Where the WTA* is the WTA multiplied by the variation factor (VF) for unregulated streams, and the square root of VF for regulated streams. The VF is defined by the standard deviations of monthly ($s^*_{Monthly}$) and annual (s^*_{annual}) precipitation as:

$$VF = e^{\sqrt{\ln(s^*_{monthly})^2+\ln(s^*_{annual})^2}} \qquad (13)$$

To further develop the LCIA methodology, Pfister et al suggest a damage assessment consisting of three parts as defined in the *Eco-indicator 99 methodology* (Goedkoop & Spriensma, 2001):

1. **Damage to Human Health:** unlike Milá i Canals et al, the damages to human health are evaluated in this LCIA approach. The authors use a method based on statistical health data to model the entire cause-effect-chain in the specified regions.
2. **Damage to Ecosystem Quality:** This too is assessed with the *Eco-indicator-99-method*, using water-use, precipitation and net primary production (NPP) from each studied watershed as inputs as suggested by Itsubo et al (2004), modeling ecological cause-effect-chains. This is measured in potentially disappeared fraction of species (PDF).
3. **Damage to resources:** To be able to compare the resource use of fossil blue water (or over-use of fund blue water) the *Backup-technology concept* (Stewart & Weidema, 2005) is applied. This means that the damage is expressed as: the additional energy required to replace the lost resource. In this case the authors use desalination technology, where the required energy is calculated by multiplying the total water use with the fraction that contributes to depletion (WTA-factor > 1) and then multiplying that with the energy required for desalination of the unit volume.

2.7 The CROPWAT model

The FAO, or Food and Agriculture Organization of the United Nations have developed a decision support tool called CROPWAT together with the Land and water development division. CROPWAT is a computer program for the calculation of crop water requirements, based on data on climate, crop and soil properties (FAO, 2012a). In this study the newest available version, CROPWAT 8.0 has been used. In the 8.0 version, all the calculation procedures are based on two reports by the FAO in the Irrigation and Drainage series, No. 56 *Crop evapotranspiration – guidelines for computing crop water* and No. 33 *Yield response to water* (FAO, 1998).

The first of these use the Penman-Monteith equation to calculate a reference evapotranspiration, ET_0, which is defined based for a "well watered grass" under the specified climatic conditions. The actual evapotranspiration ET_c for the studied crop in the specified climate is then calculated by adjusting the ET_0 with crop and water stress factors K_C and K_s as well as crop heights and root depths (FAO, 1998). The calculation methodology is visualized in below.

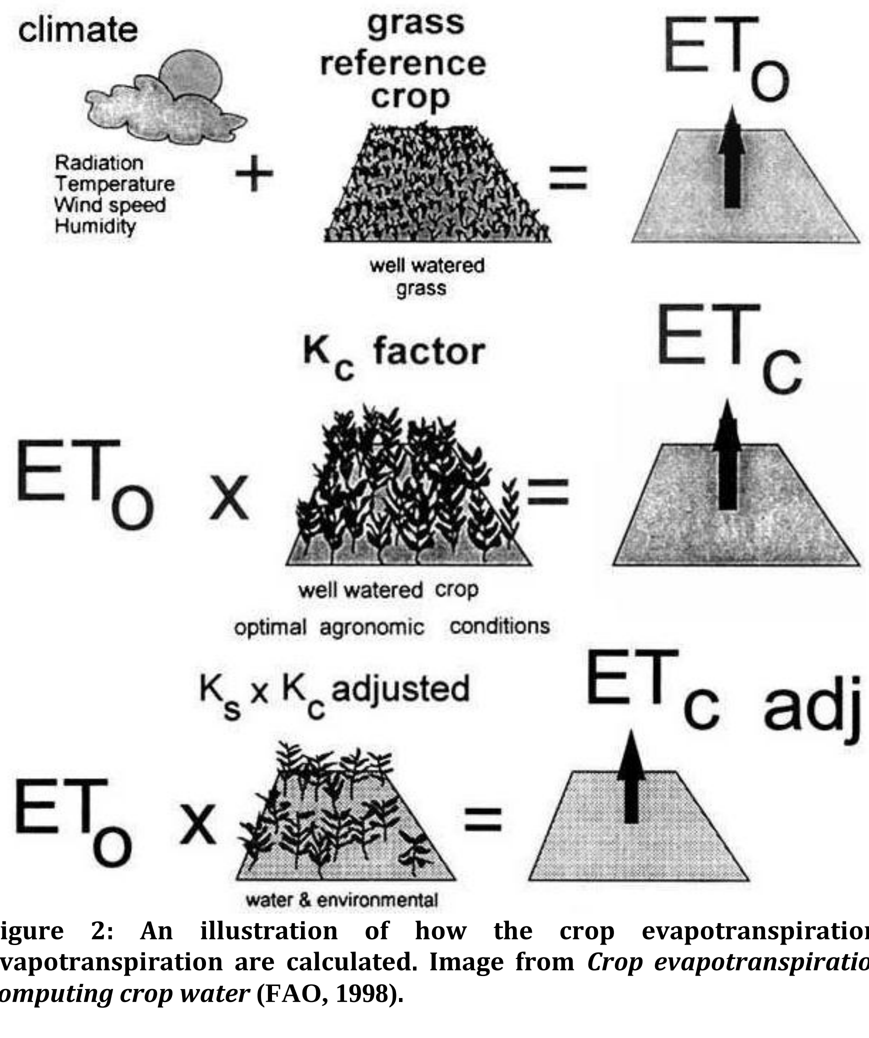

Figure 2: An illustration of how the crop evapotranspiration, and adjusted evapotranspiration are calculated. Image from *Crop evapotranspiration – guidelines for computing crop water* (FAO, 1998).

In the report *yield response to water,* the FAO suggest a calculation method to account for the effects of water deficiencies on crop productivity. This is also used in CROPWAT 8.0 to account for deficits. A yield response factor, K_y is empirically derived by comparing the actual ET and actual yield to the maximum ET and maximum yield. The K_S is then used as an input into the CROPWAT model. This model is used to calculate the green and blue water requirements as well as the evapotranspiration of winter wheat.

3 SUPPLY CHAIN SYSTEM

The supply chain water footprint study focuses on wheat, which is grown on a larger land area than any other commercial crop globally, and second only to maize in produced mass (Mekkonen & Hoekstra, 2010b). The study is limited to winter wheat and covers about 80% of the total winter wheat production of Sweden, out of which Lantmännen process or refine approximately half. The Supply chain study will be the basis on which the case studies rest. It will allow for a synoptic calculation of the water footprints of three of Lantmännens products, from the production of input materials to the cultivation process, up to the finished products at the factory gate.

3.1 Goal, Scope and Purpose Definitions

The purpose of the supply chain water footprint is to give Lantmännen an idea of the water footprints, related to the winter wheat production in Sweden, and of the winter wheat that is refined in their facilities. An additional purpose is to create the basis for a number of case studies to allow Lantmännen to evaluate the water footprint of the whole value chain for a number of finished products. The case studies and their individual scopes are described in detail in sections A, B and C.

The report attempts to quantify the water footprints of the raw materials and finished products, in general following the method of Hoekstra et al, outlined in *The Water Footprint Assessment Manual* (2009). The analysis covers the concepts of green, blue and gray water, and is presented using LCA framework.

No qualitative sustainability assessment or impact analysis of the result is attempted due to limitations in scope and data availability.

3.1.1 Scope Definition

The study will focus on the production of winter wheat in Sweden during the years 2008, 2009 and 2010.

3.1.1.1 Functional Unit

The functional unit is *one metric ton of winter wheat with 14% water content, at a storage facility.*

Due to the geographically explicit nature of water footprints, the location of the water footprint needs to be defined. This is attempted at a general scale but is not included in the functional unit. Each of the case studies in the report will have additional functional units for the refined wheat products.

3.1.1.2 Geographic, Temporal and Technological Scope

The geographic scope is Sweden, but the study is carried out on a number of geographic scales; the end result is presented for each river basin as well as on a national scale. Around 80 % of the total Swedish winter wheat production in 2008-2010 is included in the study and the results are therefore assumed to be representative for the nation as a whole during that time.

The temporal boundaries are set to the years 2008, 2009 and 2010 to account for annual fluctuations in a number of parameters, such as yield, climatic factors etc. The data for the year 2011 is not yet available in all categories so more current values could not be included. The period of three years was a compromise made to limit the amount of data processing required, while still attaining some degree of variation.

The technological scope is defined as the relevant agricultural and industrial processes in use during the defined time period, 2008-2010.

3.1.2 System Boundaries

A number of system definitions are required to describe both the supply chain processes on one hand and the case studies of the refinement facilities on the other. The system boundaries of the supply chain processes are described here, while the system boundaries for each individual case study are presented in their respective section.

3.1.3 System Description

The boundaries of the supply chain system are defined in Figure 3, which is covered cradle-to-gate, meaning that it starts with the production of the input materials and ends when the wheat reaches a storage facility.

The included input materials to the cultivation stage are confined to fertilizers and seed, for the latter no further processing is included as it is assumed to have no impact on the overall result following (Flysjö et al., 2008). The water footprint of each component is calculated and then they are added to generate the result. These footprints are indicated by the green, blue and gray arrows entering or leaving each process box in Figure 3. Water footprint components without geographic information, such as electricity and fuel production, are assumed to occur in the same watershed as the process to which they belong. The components of the supply chain system are described in detail under headings 3.1.3.1 - 3.1.3.7 below. The production and pollution from pesticides and herbicides are assumed to have no effect on the system, as they are used in relatively small amounts, which mean that the energy use is low in production, and the gray water footprint of nitrogen is significantly higher.

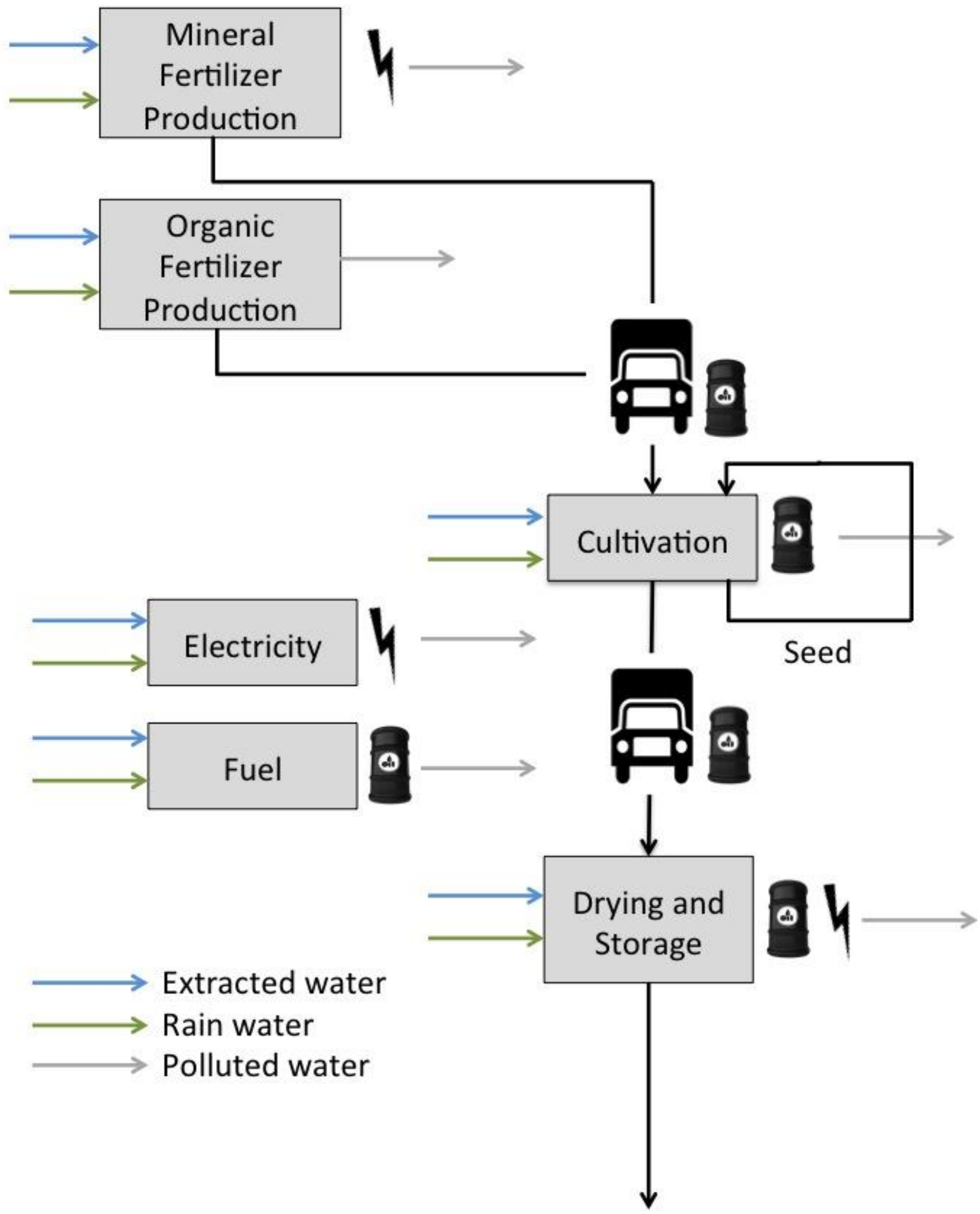

Figure 3: An abstraction of the supply chain system, when support components such as fuel and electricity production are used this is represented by an oil barrel or bolt of lightning respectively.

3.1.3.1 Mineral fertilizer production

Mineral fertilizers are produced by fixating nitrogen into a number of compounds that can be applied to the wheat fields. The water footprint associated with this comes from the energy used in the fixation processes, mainly from natural gas and some electricity.

3.1.3.2 Organic fertilizer production
Organic fertilizers, assumed to be manure from beef cattle, have water footprints associated with the raising of cattle, and the cultivation of the feed for the animals. It is worth noting that in the main body of this report there is no allocation of the water use associated with the manure production to manure. The effects of this assumption are evaluated in a sensitivity analysis in section 3.4.2.2.

3.1.3.3 Cultivation
The cultivation component include the water footprints of the crops as they grow, such as the evapotranspiration of rain or irrigation water, as well as the gray water footprint of any leaching pollutants or fertilizers. It also includes the fuel used in any agricultural activities, such as sowing, plowing, harvesting etc. The amount of grain that is required for reseeding the fields is accounted for by subtracting it from the total yield. Any processing or handling of the seeding grain is assumed to have no impact on the outcome of the study.

3.1.3.4 Drying and Storage
After the grain is transported from the fields it is dried to reduce the water content to 14%. The drying process uses oil and electricity. Storage is assumed to take place in the same location as the drying, a simplification for calculation purposes.

3.1.3.5 Fuel production
Liquid fuel in the form of diesel is used in many of the system components and consists of both fossil and bio-based diesel. The production of these differs enormously, and the water footprints associated with fossil diesel occur in extraction and refinement while the water footprint of bio-diesel originates in the cultivation of the energy crop.

3.1.3.6 Electricity production
Much like the fuel production component, the different sources of Swedish electricity production have water footprints originating from a range of processes. Evaporation from water reservoirs for hydroelectric power production contributes to about 65% of the water footprint of electricity production in Sweden, while biomass based power production contribute to almost 30%, originating in the cultivation of the energy crops.

3.1.3.7 Transports
The transportation of wheat between the different fields and facilities contribute to the water footprint through the fuel use, and the sources depend on the composition of the diesel.

3.1.4 Cut off criteria
No explicit definition of cut off criteria is applied to the supply chain system, but processes that contribute less than 0.1% of the total water footprint, are deemed to be insignificant, they are however still presented for the sake of interest.

3.1.5 Allocation
In the main report, there is no allocation of water footprints to any byproducts of the supply chain system. The effects of this simplification are evaluated in a sensitivity analysis in section 3.4.2 by adding a number of allocations and assessing the degree to which they impact the final result.

3.1.6 Data Quality

The data quality is divided into a number of classes according to Table 2. The classification is based on:

- *Spatial quality* showing the level of location-specific detail, represented by numbers (1-4).
- *Source quality* referring to the origin of the data, represented by letters (A-D).
- *Temporal quality* referring to the age of the data.

The temporal quality is binary and if the data is older than 2008 a negative sign (-) is added at the end of the quality indicator.
An example: Climatic data from SMHI referring to the year 2010 in a specific climate region (county equivalent) would have the quality indicator B2, while FAO world-wide crop-parameter data from 1994 would be of C4- quality.

Table 2: Quality classes, based on source and spatial data quality. A binary temporal dimension is included as well, where any data older than 2008 is given a negative sign (-). The colors indicate levels of quality: green - good, yellow – intermediate and red –bad quality.

Source Quality / Spatial Quality	A Specific to Lantmännen	B Swedish national statistics	C Scientific, from other sources	D Estimated or calculated
1 – Drainage Basin				
2 – County				
3 – Sweden				
4 – Other				

All data that is used in the supply chain system is described and rated in Table 3. Further details of the acquired data, and how the calculations are conducted will be presented in the inventory section.

Table 3: Data sources and quality ratings for the supply chain inventory.

% of Result	Category	Component	Source	Data Quality
0.294%	**Transport**	Distances	GIS and Google maps 2012	D4-
		Fuel composition	(Energimyndigheten, 2011b)	B3
		Water footprint, Biodiesel (L/ton-km)	(Hoekstra & Gerbens-Leenes, 2010)	C4
		Water footprint, Fossil diesel (L/ton-km)	(Gleick, 1994)	C4-
		Filling degree	Rough estimate	D4-
N/A	**Electricity**	Swedish average electricity composition (Svensk medelel)	(Energimyndigheten, 2011b)	B3
		Water footprint of primary energy carriers	(Gerbens-Leenes et al., 2009)	C4-
0%	**Organic Fertilizer Production**	Water footprint of beef production	(Gerbens-Leenes et al., 2011)	C4
		Average manure production of beef cattle	(Jordbruksverket, 1995)	B3-
		Weight of slaughtered beef cattle	(Cederberg & Nilsson, 2004)	B3-
		Nitrogen content of beef cattle manure	(Greppa näringen, 2011)	C3
		Fertilizer application rates, county level	(Statistiska Centralbyrån, 2009)	B2
0.008%	**Mineral Fertilizer Production**	Energy use in fertilizer production	(Jenssen & Kongshaug, 2003)	C4-
		Water footprint of primary energy carriers	(Gerbens-Leenes et al., 2009)	C4-
		Fertilizer application rates, county level	(Statistiska Centralbyrån, 2009)	B2
39.9%	**Cultivation, Gray Water**	Ambient water quality standards	US-EPA and WHO	C4
		Leaching fraction	Assumption following (Chapagain et al., 2006)	D4
		Natural background concentration	Assumption following (Chapagain et al., 2006)	D4
		Fertilizer application rates, county level	(Statistiska Centralbyrån, 2009)	B2

% of Result	Category	Component	Source	Data Quality
59.6 %	**Cultivation, Blue and Green Water**	Fuel Use in agriculture	(Lindgren et al., 2002)	C3-
		Climatic Data	(SMHI, 2012), (SMHI, 2010) (SMHI et al., 2012)	B2
		CROPWAT model	(FAO, 1998), (FAO, 2012a)	D4-
		Winter wheat yield	(Statistiska Centralbyrån, 2011)	B2
		Cultivated areas	(Jordbruksverket, 2010)	B1
		Crop parameters	(FAO, 2012b)	C4
		Swedish irrigation practices	(Brundell et al., 2008)	C3
		Amount of Seed applied	(Flysjö et al., 2008)	D3
0.143%	**Drying and Storage**	Energy requirement per ton wheat	(Edström et al., 2005)	C3-
		Water content at Harvest	(Edström et al., 2005)	C3-
N/A	**Net Green Water**	Reference system	(Milá i Canals et al., 2009)	C4-
		Absorbed precipitation for different land uses	(Zhang et al., 1999)	C4-
N/A	**Required irrigation**	CROPWAT model output	(FAO, 1998), (FAO, 2012a)	B3
N/A	**Allocation principles**	Sensitivity analysis	(Börjesson et al., 2010)	C3
N/A	**Share of straw retained**	Sensitivity analysis	(Statistiska Centralbyrån, 1997)	B3

3.2 Inventory

The data collection and calculation methods for each unit process are described below, along with any assumptions, allocations or validations that are necessary.

3.2.1 Liquid/Transport fuels

According to the 2010 annual energy use statistics of the Swedish energy department 7.9% of the fuel used in Swedish road transportation was renewable, out of this, 48% was ethanol, 41% biodiesel, and the rest biogas (Energimyndigheten, 2011a). In a water footprint assessment report for UNESCO by the water footprint network, the water footprint of a truck burning biodiesel made from rapeseed oil is stated as 133-227 liters per ton-km of green, and 103-175 liters per ton-km of blue water(Hoekstra & Gerbens-Leenes, 2010). The water footprint of the production and refinement of fossil fuel, in this case fossil diesel, has been estimated by Peter Gleick (1994). That study does not include the gray water footprint, which is instead estimated to be equal to the polluted water volumes included in the fossil fuel life cycle.

It is assumed that the fuel distribution of Lantmännen´s domestic transports is the same as Sweden in general. The share of biodiesel is therefore 3.2%, leaving 96.8% fossil diesel. It is also assumed that the rapeseed-based biodiesel is representative for the biodiesel used in Sweden. As a conservative estimation the high end of the presented range is used in the study. The data is presented in Table 4 below. It should be noted that the data quality suffers from the large number of assumptions and estimations, which is apparent from the data quality ratings of transport in Table 3.

Table 4: Water footprint data on biofuel transport (Hoekstra & Gerbens-Leenes, 2010), and fossil diesel (Gleick, 1994). The footprints are from the production and refinement stages, values for usage is not included. Swedish average is 3.2% of the liquid fuels that is biofuel in the transportation sector. The gray water footprint of fossil diesel is not calculated by the authors, but instead assumed to be 10% of the total blue, following Gerbens-Leenes et al. (2009). This serves as an estimation of the total polluted water volumes in the fossil fuel life cycle.

	Green WF (L/km and ton)		**Gray WF (L/km and ton)**		**Blue WF (L/km and ton)**		**Total WF (L/km and ton)**	
	Pure	Swedish average	Pure	Swedish average	Pure	Swedish average	Pure	Swedish average
Biodiesel	227	7.35	22.7	0.18	175	5.67	402	13.02
Fossil Fuel	0	0	2.62	2.41	3.20	2.95	5.82	5.36
Total WF for average transport	**7.35**		**2.59**		**8.62**		**18.56**	

3.2.2 Electricity

The average water footprint of a number of primary energy carriers are calculated in a water footprint assessment by Gerbens-Leenes et al (2009) and these are used in this report to estimate the water footprint of Lantmännen´s electricity and energy use. Gerbens-Leenes et al. have used values estimated by Gleick (1994), and added gray water footprints equal to the volume of polluted water for all degradative uses of freshwater. That is probably an underestimation of the gray water footprint, but it is used due to lack of more reliable data. The footprints are combined with statistics of the total energy distribution to calculate the water footprint of Swedish average power (Svensk medelel), shown in Table 5 below. Similar to the fuel component, the data quality of electricity generation is low.

Table 5: Water footprints of major energy carriers (Gleick, 1994) (Gerbens-Leenes et al., 2009). Composition figures for different sources of electricity from the Swedish energy agency (Energimyndigheten, 2011b). Other energy carriers such as waste and peat are also used, but not included in this study due to a lack of available data, the share of electricity therefore reaches only 95% in total.

Primary Energy carrier	**Average water footprint (m^3/GJ)**			**Share of Swedish electricity**	**Contribution to total WF (m^3/GJ)**		
	Green	Blue	Gray		Green	Blue	Gray
Wind	0	0	0	2%	0	0	0
Nuclear	0	0.1	0.08	38%	0	0.04	0.03
Natural gas	0	0.1	0	0%	0	0	0
Coal	0	0.2	0.1	0%	0	0	0
Solar	0	0.3	0	0%	0	0	0
Oil/Diesel	0	1.1	0.9	0%	0	0	0
Hydropower	0	22	0	46%	0	10.12	0
Biomass	56.7	14.4	7.1	9%	5.10	1.30	0.64
Total					**11.45**	**5.10**	**0.67**

3.2.3 Mineral fertilizer production

The water use related to the production of mineral fertilizers comes mainly from energy use, in nitrogen fixation and fertilizer processing. In a modern ammonia plant the energy used is approximately 34.2 GJ/ton NH_3-N out of which 0.2 GJ is electricity and 34 GJ is natural gas (Jenssen & Kongshaug, 2003). This will give a water footprint of 1.02 m^3 green, 2.29 m^3 blue and 0.134 m^3 gray water per ton of NH_3-N. Mineral fertilizers refer only to the nitrogen component while sodium and potassium are assumed to have an insignificant contribution to the energy use, following (Jenssen & Kongshaug, 2003). The electricity is assumed to be Swedish average. It is also assumed that the nitrogen that leaches off the fields have the largest gray water footprint. This assumption is used in most water footprint analyses and is not evaluated further in this report.

3.2.3.1 Relating data to functional unit

The amount of fertilizer used differs within the country and is averaged over a large number of fields in the calculations. The fertilizer application data is from Statistiska Centralbyrån on a county-level. This applies for both mineral and organic fertilizers.
The final average values are 0.046 m^3 of green water, 0.003 m^3 of blue water and 0.069 m^3 of gray water per ton of wheat.

3.2.4 Organic fertilizer production

An estimation of the water footprint associated with the production of organic fertilizers, in this case cattle manure, is made using a water footprint assessment by the water footprint network for UNESCO (Gerbens-Leenes et al., 2011). In the UNESCO report the water footprint of beef, pork and poultry is calculated for three different production systems (grazing, mixed and industrial) and for four countries (Brazil, China, Netherlands and USA) along with a global average. The global average is used as the best approximation of similar production in Sweden.

The water footprint of the production of meat is related to the manure production by following a study of manure output from beef and dairy cattle by the Swedish agricultural agency (Jordbruksverket, 1995). The average manure output from beef cattle (vallfodertjur) is 15 652 kg for a 26 month breeding period, after which the cattle is slaughtered. On average a carcass for slaughter in Sweden weighs about 590 kg (Cederberg & Nilsson, 2004) and the nitrogen content of manure from beef cattle is about 5kg N/ton of manure (Greppa näringen, 2011). From this an estimation of the water footprint of manure can be calculated following the order presented in **Error! Reference source not found.** below, together with the sources and the final water footprint per kg of organic nitrogen fertilizer. As in the two previous components, the data quality is low, suffering from a number of assumptions and simplifications.

Table 6: Conversion factors and estimations for the water footprint of beef manure.

Source and type of conversion	Conversion factor and unit	Green (m^3)	Blue (m^3)	Gray (m^3)
WF of Beef (Gerbens-Leenes et al., 2011)	Water footprint **(m^3/ton carcass)**	14 803	508	401
Average weight (Cederberg & Nilsson, 2004)	590 kg /animal **(m^3/animal)**	8 734	300	237
Manure Production (Jordbruksverket, 1995)	15 652 kg manure/animal **(m^3/ton manure)**	558	19.2	15.1
Nitrogen content (Greppa näringen, 2011)	5 kg Nitrogen/ton manure **(m^3/kg Nitrogen)**	112	3.83	3.02

3.2.4.1 Allocation

The manure that is attained from beef cattle production is normally not considered a byproduct; it is usually treated as waste. To avoid double counting in the production system it is assumed that none of the environmental impacts, including water use, is allocated to the organic fertilizer. The production of manure is still included in the study, and the impact an inclusion of manure would have on the final result is evaluated in a sensitivity analysis in section 3.4.2.2.

3.2.5 Cultivation

The water footprints associated with cultivation are determined in two steps; the green and blue footprints are calculated using the CROPWAT-model developed by the United Nations Food and Agricultural Organization (FAO, 2012a). For more details on CROPWAT see the appendix. The CROPWAT model requires an input of climate data and crop-specific parameters. The data collection and calculations required for the climatic data are described below and the crop parameters can be found in Table 8. The gray water footprint is calculated using the method described under heading 3.2.5.4.

3.2.5.1 Climatic data

The climatic parameters required as inputs in the CROPWAT model are: elevation, coordinates, precipitation, wind speed, min & max temperature, relative humidity and sun hours. The required data is collected from 18 climate stations belonging to the Swedish meteorological and hydrological institute (SMHI). Some of the stations do not record precipitation, and in those cases the data is from SMHI's Luftwebb model, and all the data on the sun hours are from SMHI's STRÅNG-model (SMHI et al., 2012). The inputs to the model are monthly averages of 3-hour data for the years 2008, 2009 and 2010. To keep data processing at a level that is appropriate for this project, averages of the climatic conditions during the studied years were used. The effects of this on the final outcome are evaluated in a sensitivity analysis in section 3.4.2.7.

Table 7: Description of the 18 climate stations used to acquire the input data for CROPWAT. The climatic data is taken from SMHI measurement series (SMHI, 2010), with the exception of solar radiation, which is from the STRÅNG solar model (SMHI et al., 2012) and in some cases precipitation from Luftwebb, a precipitation model (SMHI, 2012).

Station Name	Elevation (m.s.l.)	Station Number	Precipitation from	RT-90 Coordinates	
				Y	X
Borlänge flp	152	10526	SMHI measurements	6701250	1483460
Bredåkra	58	6516	Luftwebb model	6237210	1466910
Falsterbo	5	5223	SMHI measurements	6143370	1310670
Films Kyrkby A	33	10714	SMHI measurements	6681560	1616290
Göteborg A	5	7142	SMHI measurements	6405400	1272800
Jönköping flp	226	7446	Luftwebb model	6404250	1396720
Karlstad flp	107	9322	SMHI measurements	6594120	1359860
Kisbergen-Suttarboda A	219	9419	SMHI measurements	6575760	1448180
Målilla A	95	7525	SMHI measurements	6362110	1499730
Malmö A	20	5235	SMHI measurements	6163610	1327530
Malmslätt	93	8524	Luftwebb model	6475240	1483890
Malung	308	10341	SMHI measurements	6731150	1384800
Nidingen	2	7119	Luftwebb model	6359850	1264920
Såtenäs	54	8226	Luftwebb model	6483330	1318940
Stockholm-Bromma	14	9720	Luftwebb model	6583350	1621880
Torup A	130	6359	SMHI measurements	6317010	1332960
Tullinge A	45	9710	SMHI measurements	6563810	1620290
Åmot A	162	10657	SMHI measurements	6760720	1533740

3.2.5.2 The CROPWAT model in- and outputs

For a number of crops the water stress factor K_s is available on FAO.org and the data used in this report is from here and is presented in Table 8. The output from the CROPWAT model is a required evapotranspiration ET_c and the effective rain, divided into 10-day periods, called decades. Whenever the effective rain does not cover the crop water requirement, the difference between the two becomes the irrigation requirement. These three are plotted in Figure 4 below for the climatic station at Borlänge airport, one of the 18 stations from Table 7.

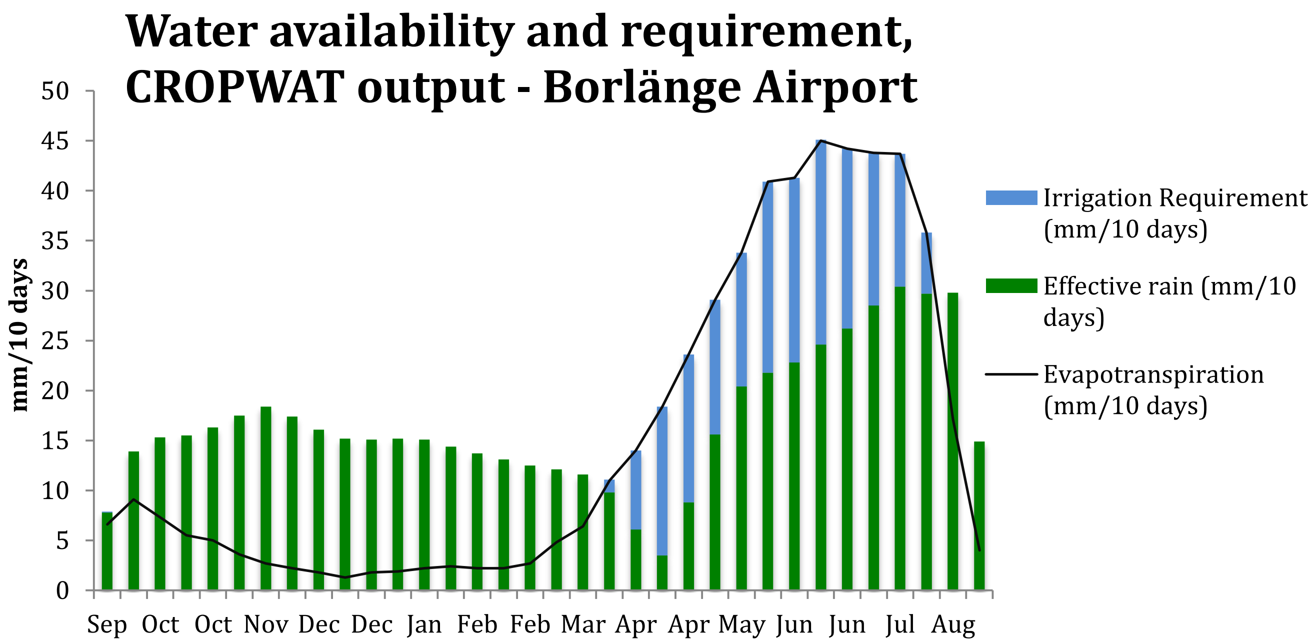

Figure 4: CROPWAT model output from the Borlänge Airport Climate station.

The crop parameters, specific to winter wheat under climatic conditions similar to those of Sweden are presented in Table 8.

Table 8: Crop parameters for winter wheat. Input into the CROPWAT model. The data is from the FAO crop water information website (FAO, 2012b).

Parameter	Initial Stage	Development Stage	Mid Stage	Late Stage	Total
K_c (-)	0.7	-	1.15	0.25	-
K_s (-)	0.2	0.6	0.5	0.5	-
Critical Depletion Factor (-)	0.6	-	0.6	0.9	-
Root Depth (m)	0.3	-	-	1.4	-
Growth Time (days)	160	75	75	25	335

3.2.5.3 *The Green and Blue Water Footprints of Cultivation*

Based on the provided climatic and crop specific parameters, the CROPWAT model calculates the evapotranspiration of the crops, and the available precipitation as well as the required irrigation. The size of the required water footprint within each of the 18 climatic regions is presented in Figure 5.

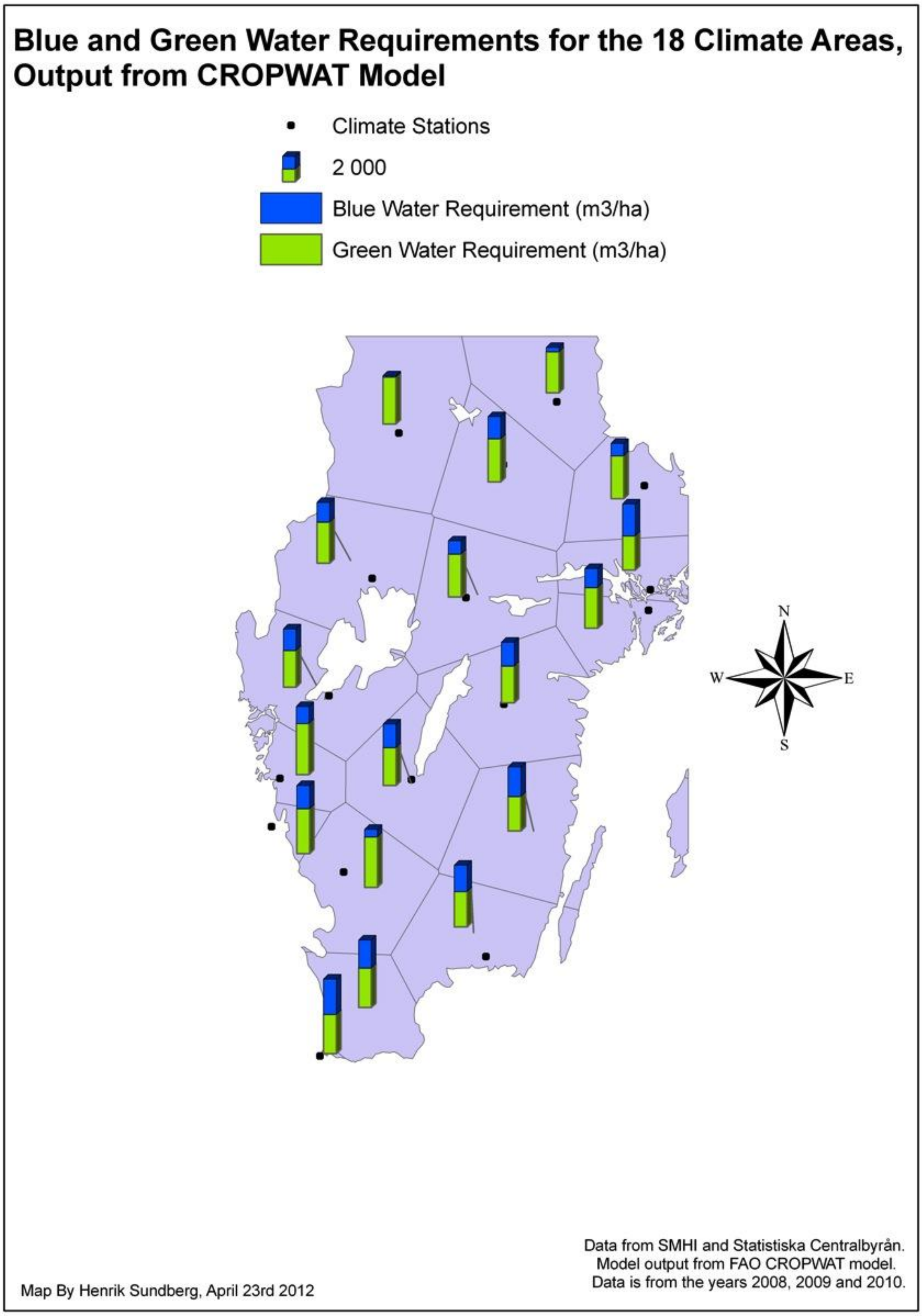

Figure 5: The output from the CROPWAT model showing the Green and Blue crop water requirements as calculated by the model, as well as the geographic extent of each of the 18 stations.

The actual blue water footprint differs from the requirement calculated by CROPWAT due to the irrigation practices of Swedish farmers. Sources at Jordbruksverket indicate that irrigation of wheat occur only on light and sandy soils, and a report by Brundell et al. (2008) for the Swedish Central Bureau of Statistics (SCB) suggest that 1% of the area used for cultivating grains is irrigated. These results are assumed to be accurate for winter wheat, giving a blue water footprint 1% of what the CROPWAT model suggests. This is a rough estimate, as the irrigation is more likely to occur in areas which have less of its water requirements filled by precipitation. The lack of available data and time constraints makes it impossible to further refine this assumption. The 1%-assumption will be subject to a sensitivity analysis in section 3.4.2.6.

3.2.5.4 The Gray Water Footprint of Cultivation

The gray water footprint is calculated by multiplying the amount of pollutant added with a specific leaching fraction, which gives the total amount of pollutant that reaches the receiving water body. This is then divided by the ambient water quality standard that applies for the pollutant in question. Only the pollutant with the highest gray water footprint is then used, as the same water volume will dilute other pollutants as well. It is assumed that the nitrogen present in the applied fertilizers will produce the largest gray water footprint and therefore this study only considers nitrogen pollution, i.e. eutrophication.

An ambient water quality standard of 10 mg/L (NO_3-N) has been established by the United States environmental protection agency (USEPA), and this is often used in water footprint assessments. The world health organization (WHO) and the EU use another standard of 50 mg NO_3/l, which translates to about 11.29 mg/L (NO_3-N) (Chapagain & Orr, 2010), (FAO, 2012a).

The amount of nitrogen that leaches off without being absorbed depend on a number of factors, and an estimation is required. In line with Chapagain et al (2006) a leaching fraction of 10% is used. The 10% fraction is commonly used in water footprint analysis and life cycle assessments, and is deemed to be adequately accurate for the purposes of this study.

The Swedish Central Bureau of Statistics (SCB) carries data on the fertilizer application rates for grains in the different counties of Sweden (Statistiska Centralbyrån, 2009). Natural background concentrations for nitrogen are assumed to be zero as a conservative estimation, again following Chapagain (2006). Assuming that the fertilizing practices, and thereby leaching fractions, are similar for wheat in each county the water footprints are calculated and shown in Table 9 below. The values in italic for 2008/2009 using the USEPA water quality standard are used to comply with data requirements and to follow previously quoted studies as a simplification and to allow for comparisons to the results of other studies.

Table 9: The gray water footprints for grain production in a number of Swedish counties. The table shows the calculated water footprints using both the US and European standards. Averages of the years 2004-2009 are presented along with values only for the years 2008 and 2009. NOTE: Only the counties relevant to this study are presented.

		Average		**Only 2008/2009**	
County number	**County Name**	Gray WF - US (m^3/ha)	Gray WF – EU (m^3/ha)	*Gray WF – US* (m^3/ha)	Gray WF – EU (m^3/ha)
1	**Stockholm**	1507	1335	*1080*	957
3	**Uppsala**	2020	1789	*1970*	1745
4	**Södermanland**	2250	1993	*2110*	1869
5	**Östergötland**	2350	2081	*2200*	1949
6	**Jönköping**	1890	1674	*1800*	1594
7	**Kronoberg**	1700	1506	*1880*	1665
8	**Kalmar**	1953	1730	*1910*	1692
9	**Gotland**	1910	1692	*1800*	1594
10	**Blekinge**	1620	1435	*1690*	1497
12	**Skåne**	2423	2146	*2430*	2152
13	**Halland**	2070	1833	*1890*	1674
14	**Västra Götaland**	2093	1854	*2040*	1807
17	**Värmland**	1863	1650	*1790*	1585
18	**Örebro**	2013	1783	*1880*	1665
19	**Västmanland**	1380	1222	*1040*	921
20	**Dalarna**	1340	1187	*370*	328
21	**Gävleborg**	1747	1547	*1840*	1630

3.2.5.5 Fuel use in cultivation
The fuel required by agricultural machinery is estimated to be 2988 MJ of diesel per ha of wheat (Lindgren et al., 2002). Applying the same methodology as in fuel and electricity production, this translates to about 1027 ton-km of road transport, assuming that one ton-km requires approximately 2.91 MJ. The fuel use per ton of wheat is then calculated for each field.

3.2.5.6 Seed
The grain needed for seeding purposes is deducted from the amount produced, to account for the impacts of this use. It is assumed that 200 kg of seed is required per ha, following Flysjö et al. (2008), and that any transportation or processing associated with the seed has a negligible impact.

3.2.6 Drying and storage
The water content at harvest is estimated to 19% on average and the energy required to dry one ton of wheat down to 14% water content is 0.195 MJ of oil and 19kWh of electricity (Edström et al., 2005). This will result in a water footprint of 0.370 m^3 green, 0.832 m^3 blue and 0.0488 m^3 gray water per ton of 14%-wheat.

3.2.7 Transportation distances
The transportation distances of the various components will vary from field to field and therefore a simple estimation of these had to be made using the map tools ArcGIS and Google maps. A life cycle analysis of wheat flour made for Lantmännen by Tynelius

(2008) estimate the average distance from field-to-facility to 200 km which corresponding well to the distances measured in GIS. The average distances for each component is presented in Table 10 below.

Table 10: Transportation distances for the supply chain study and for the three case studies. In case C: Järna, initial processing takes place in Malmö, and the flour used in the production of the pasta is the transported by train to Järna. This is not included in this table, but described in detail in the Järna case study.

***The distance from drying to storage is assumed to be zero.**

Route (from – to)	Carrying	Distance (km)	System
Organic fertilizer - Field	Manure	50	Supply chain
Mineral fertilizer - Field	Mineral fertilizer	200	Supply chain
Field – Drying facility	Wheat (19% moisture)	100	Supply chain
Drying facility – Storage	Wheat (14% moisture)	0*	Supply chain
Storage – Ceralia, Malmö	Wheat (14% moisture)	100	Case A
Storage – Agroetanol, Norrköping	Wheat (14% moisture)	100	Case B
Storage - Malmö	Wheat (14% moisture)	100	Case C

The drying and storage facilities are assumed to be one and the same, and therefore no transportation between them is required. The filling degree of the trucks transporting the grain is assumed to be 80% throughout all the transportation stages of this analysis. The effects of these assumptions are estimated in a sensitivity analysis in section 3.4.2.3.

3.3 Results

The results of the supply chain study are presented in Table 11 followed by graphical representations in Figure 6 and Figure 7. All three show that the cultivation component is by far the largest contributing factor, with 99.55% of the total 875 m^3 of water per ton of wheat. A breakdown of the cultivation component into crop water use and fuel production water use presented in Figure 8, show that 99.59% of the cultivation water footprint originates in the crop water use. This means that crop water use alone represent 99.14% of the entire supply chain water footprint.

Table 11: The results of the supply chain study, an average of the Swedish production conditions.

	Green (m^3/ton)	Blue (m^3/ton)	Gray (m^3/ton)	Total (m^3/ton)	Percent of total
Mineral Fertilizer production	0.020	0.046	0.003	0.069	0.008%
Organic fertilizer production	0.000	0.000	0.000	0.000	0.000%
Cultivation	519	4.8	347	871	99.555%
Drying & Storage	0.37	0.83	0.049	1.25	0.143%
Transports	1.02	1.20	0.36	2.58	0.294%
Sum	520.0	6.9	348	875	100%

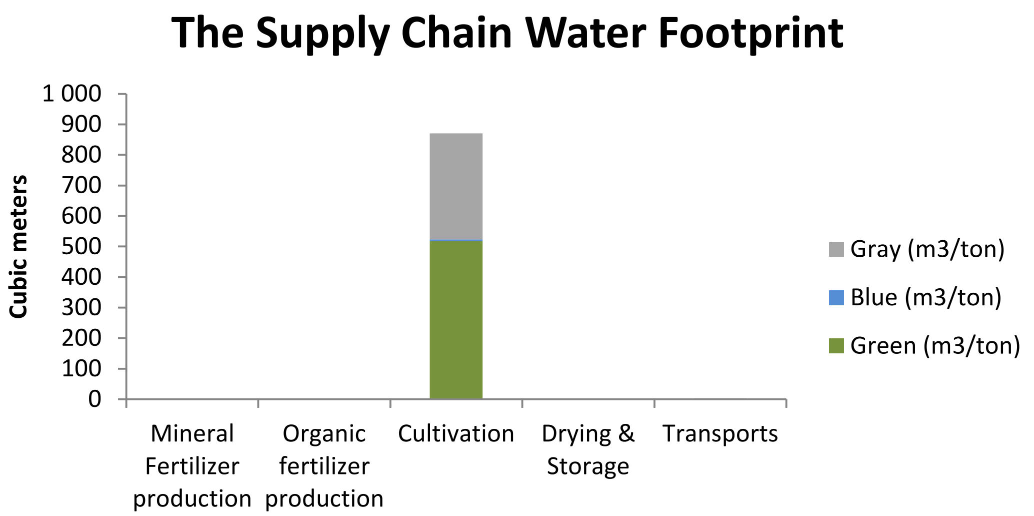

Figure 6: The chart shows the components of the supply chain systems and their respective water footprints. The exact values for each component can be found in Table 11.

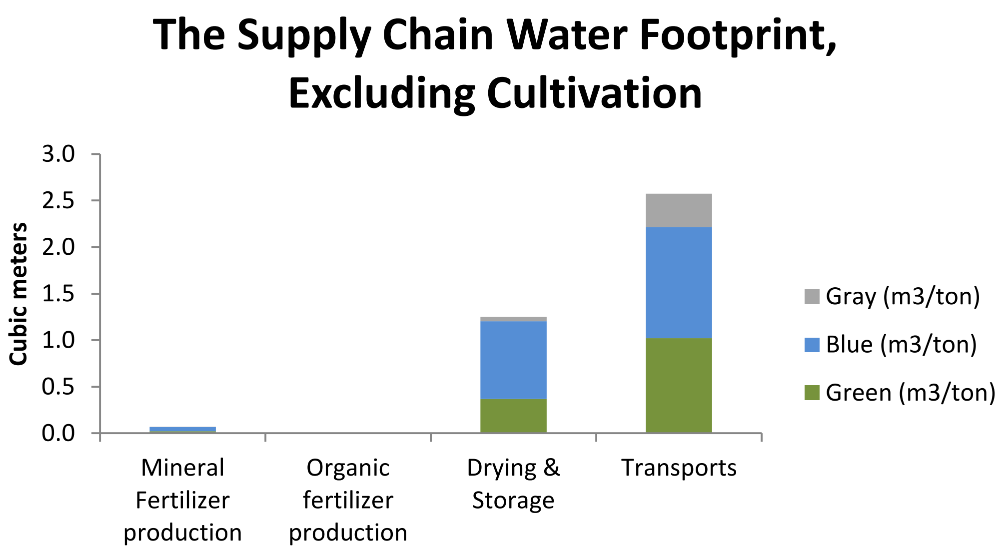

Figure 7: Four components out of the supply chain system, the cultivation component is excluded to allow the other components to be viewed in detail.

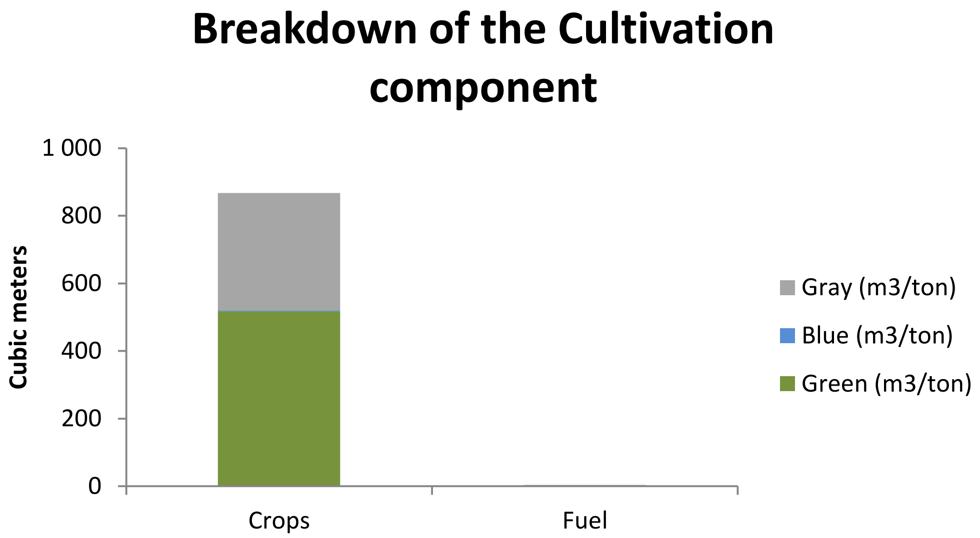

Figure 8: Breakdown of the cultivation component into fuel and crops water requirements. Crops represent 99.59% of the water footprint in the total cultivation component and 99.14% of the total supply chain water footprint.

3.3.1 Geographic distributions

The geographic distribution of the water footprint of wheat production in Sweden is presented in Figure 9 below. The total water footprints of each basin are divided by the basin area, to produce an indication of the share of available water that is used for the cultivation of winter wheat. However, the map does not include actual available water, or any other crops. It should not be interpreted as a map of hotspots or sensitive areas, but instead as an indication of where water is used for wheat cultivation, and to what extent. The study includes an average of about 80% of the total winter wheat production in Sweden and covers only the river basins that are not gray in Figure 9.

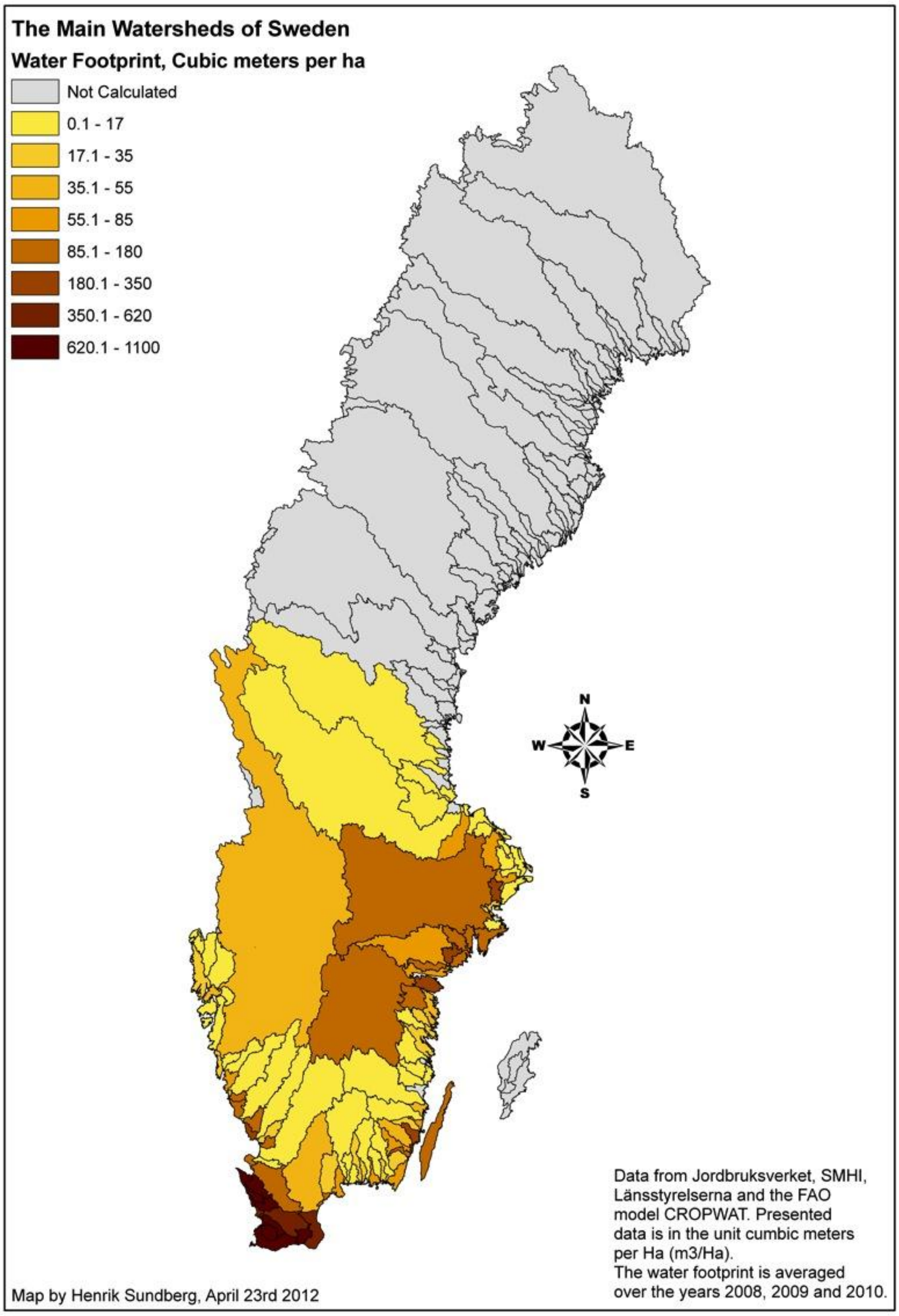

Figure 9: Geographic distribution of the water footprints of wheat cultivation in Sweden. The total water footprint of each river basin is divided by the basins total area to produce a per-ha water footprint within it, ranging from 0 – 1 100 m^3. The map should not be interpreted directly to identify water footprint hotspots, as it covers only the production of winter wheat and is normalized by each basins area and not available water resources.

3.4 Discussion and Analysis

3.4.1 Consistency Check

To evaluate the consistency of the results in this study compared to previous calculations, a table has been extracted from Mekkonen and Hoekstras: *water footprint assessment of global wheat production* (2010a). The table is presented (Table 12) in a modified form, along with the result of the cultivation component from this study. It is the only component of the reference study, and the inclusion of additional parts of the supply chain study would be misleading and mismatch the scope of the reference study.

The values obtained in this study are similar to relevant water footprints in the reference study. The overall water footprint of cultivation in this study is off by only a few m^3 per ton for blue and green water, compared to Denmark, and line up well with other European countries such as France, Germany and Czech Republic. In Figure 10 the contents of Table 12 are presented graphically.

Table 12: Water footprints of wheat cultivation for the major wheat producing nations from (Mekkonen & Hoekstra, 2010a), and the result for the cultivation step of this study.

Country	Contribution to global wheat	Water footprint per ton (m^3) Green (m^3/ton)	Blue (m^3/ton)	Gray (m^3/ton)	Total (m^3/ton)
Argentina	2.5%	1777.00	11.00	110.00	1898.00
Australia	3.6%	2130.00	18.00	109.00	2257.00
Canada	3.9%	1358.00	5.00	204.00	1567.00
China	17.4%	820.00	466.00	311.00	1597.00
Czech Republic	0.6%	726.00	0.00	231.00	957.00
Denmark	0.8%	530.00	6.00	114.00	650.00
Egypt	1.1%	216.00	907.00	412.00	1535.00
France	6.0%	584.00	1.00	6.00	591.00
Germany	3.5%	602.00	0.00	185.00	787.00
Hungary	0.7%	973.00	2.00	331.00	1306.00
India	11.9%	635.00	1173.00	296.00	2104.00
Iran	1.8%	2412.00	988.00	290.00	3690.00
Italy	1.2%	1200.00	16.00	189.00	1405.00
Kazakhstan	1.7%	3604.00	26.00	0.00	3630.00
Morocco	0.5%	3291.00	292.00	126.00	3709.00
Pakistan	3.2%	644.00	1478.00	426.00	2548.00
Poland	1.5%	1120.00	0.00	518.00	1638.00
Romania	0.9%	1799.00	49.00	85.00	1933.00
Russian Fed.	6.5%	2359.00	31.00	89.00	2479.00
Spain	1.0%	1441.00	49.00	289.00	1779.00
Syria	0.7%	1511.00	457.00	215.00	2183.00
Turkey	3.3%	2081.00	131.00	196.00	2408.00
UK	2.5%	413.00	0.00	153.00	566.00
Ukraine	2.5%	1884.00	21.00	82.00	1987.00
USA	10.2%	1879.00	92.00	230.00	2201.00
Uzbekistan	0.7%	939.00	101.00	0.00	1040.00
World	90%	1297.00	343.00	208.00	1848.00
This study		**517.00**	**3.16**	**347.00**	**867.16**

The overall concurrence of the results of this study with that of the reference study implies that the consistency of the two is good, in countries with similar agricultural practices and climatic conditions the water footprints of wheat cultivation are well aligned with the results in this study.

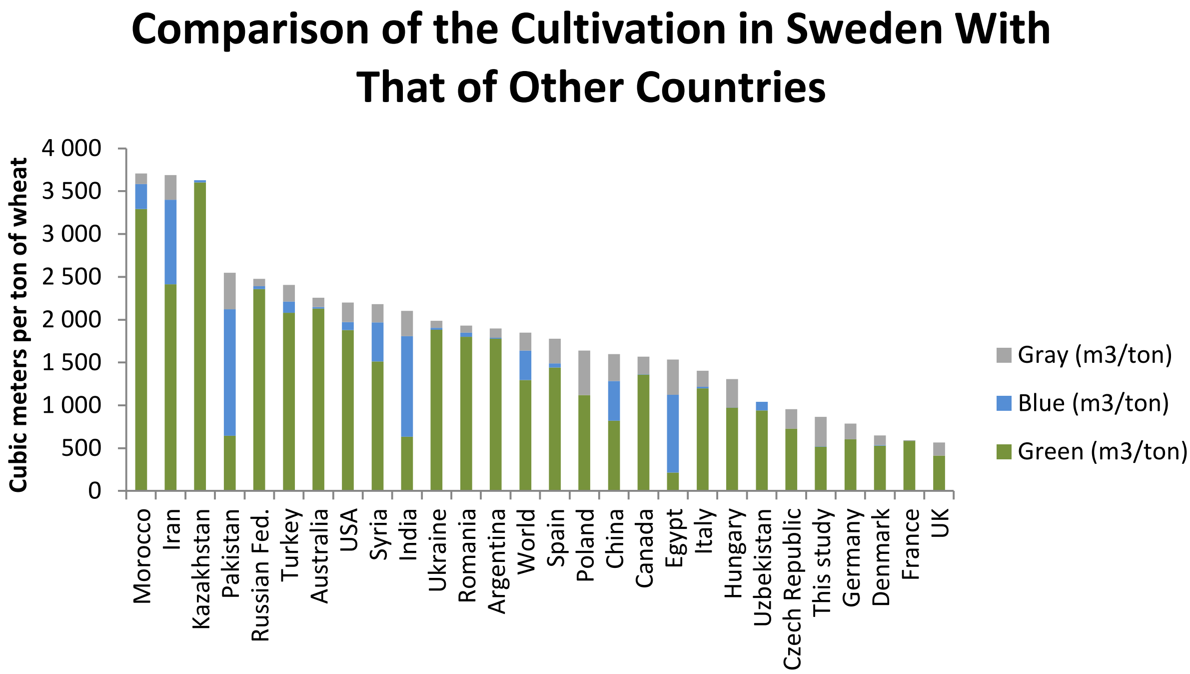

Figure 10: The water footprint of wheat cultivation in a number of countries. This study is included in the figure, fifth from the right. Data on the compared water footprints from Mekkonen and Hoekstra (2010a).

In a follow up study where the same authors calculate the water footprints of a number of crops and derived crop products, the average footprint of Swedish wheat production is 603 m^3 (77.4% green 0% blue and 22.6% gray) (Mekkonen & Hoekstra, 2010b). Obviously this does not correspond very well to the result of this study, being about 31% lower. The water footprints of the derived wheat products in the case studies are compared to the results of this study and the disagreement between the results are continued there, as the cultivation component dominate those studies as well.

In the opinion of the author the results of this study are a more accurate representation of the water use related to winter wheat cultivation in Sweden than the reference study. There are a number of factors behind this:

- This study focus solely on winter wheat while Mekkonen and Hoekstra include other wheat grains as well
- The level of detail in climatic factors, cultivated area, yields and fertilizer application is better in this study, and the data is more recent

It is worth noticing however that this study is based on calculations by the CROPWAT model, while Mekkonen and Hoekstra have developed a water balance model specifically for the purpose of water footprints. The extent to which these factors individually affect the result is not further elaborated on here.

The comparison does not confirm or refute the validity of the conclusions of the study, but gives an indication that the size and composition of the resulting water footprint is within a reasonable range.

3.4.2 Sensitivity Analysis

The sensitivity analysis is done to evaluate the impact of a number of variables on the final outcome and conclusion of the study. The variables that are tested here include: allocation principles, transportation distances, fuel composition, climatic conditions, irrigation practices and net green water.

3.4.2.1 Allocation to Straw

In LCA contexts it is not uncommon to allocate some of the environmental impacts to the straw that is produced along with the wheat. There are a number of methods available for this based on physical relationships such as mass or energy contents, economic value and system expansions. The allocation factors that will be used here are energy contents and economic value. Following (Börjesson et al., 2010) the values in Table 13 are used. A significant share of the straw is not removed from the fields, and this has to be taken into consideration when allocating. An average of 28% of the straw is removed from the fields and made available for other uses (Statistiska Centralbyrån, 1997), which means that the allocation to straw needs to be adjusted to 28% of the total available. The rest of the straw is plowed into the fields to replenish carbon stocks.

Table 13: Allocation principles and the percentages associated with each product.

	Wheat (Suggested / Adjusted)	Straw (Suggested / Adjusted)
Energy content	58% / 88.2%	42% / 11.8%
Economic value	90% / 97.2%	10% / 2.8%

The results of the applied allocation principles can be seen in Figure 11 below.

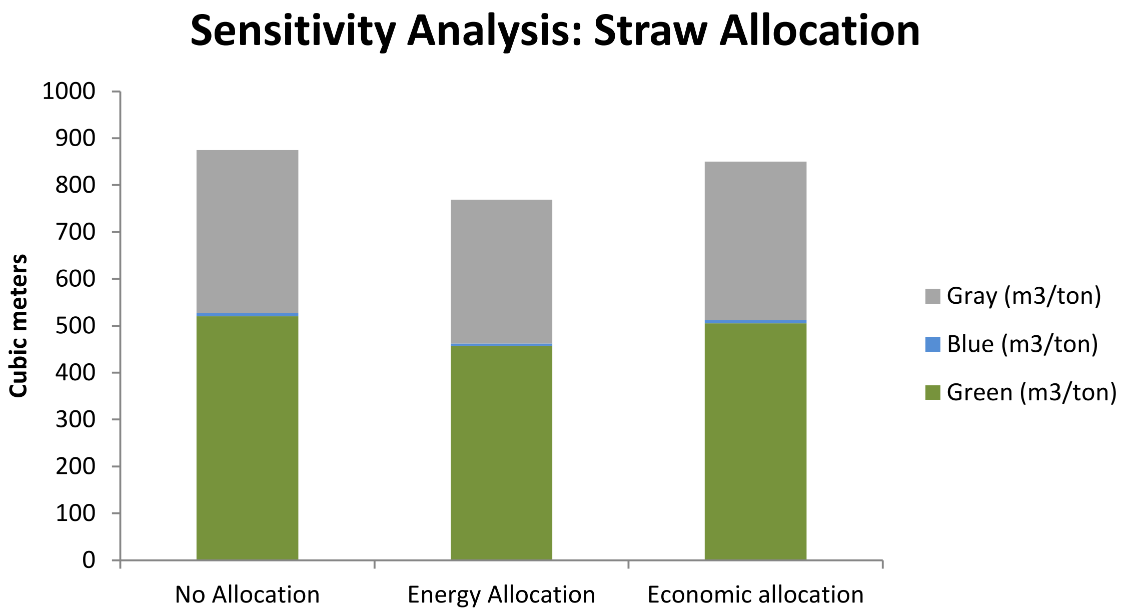

Figure 11: Results of the different allocation methods after adjustment. The allocations where applied to the two fertilizer production components and the cultivation, transport and energy uses associated with these. The storage and drying components were not altered as they only apply to the wheat kernels.

By allocating some of the water footprint to the straw the final result varies from 875 m^3 with no allocation, to 772 m^3 and 850 m^3 or -11.7% and -2.8% with energy and economic allocations respectively.

3.4.2.2 Allocation in the Production of Manure for Organic Fertilizer

As was previously mentioned, the manure is a byproduct of animal production, in this case assumed to be cattle. The water footprint of that cattle production is allocated onto the byproducts according to a predefined allocation principle, similar to the case of straw mentioned in section 3.4.2.1 above. It is not common practice however, to allocate environmental impacts to the manure in meat production systems. Economic allocations are commonly used, where 90% of the impact is allocated to the meat and 10% to byproducts such as leather and intestines. As an evaluation of the effect that an allocation to the manure would have on the final result of this study a sensitivity analysis is conducted based on an assumed economic allocation of 1% and 5% of the total water footprint onto the manure. The result of this is presented in Figure 12.

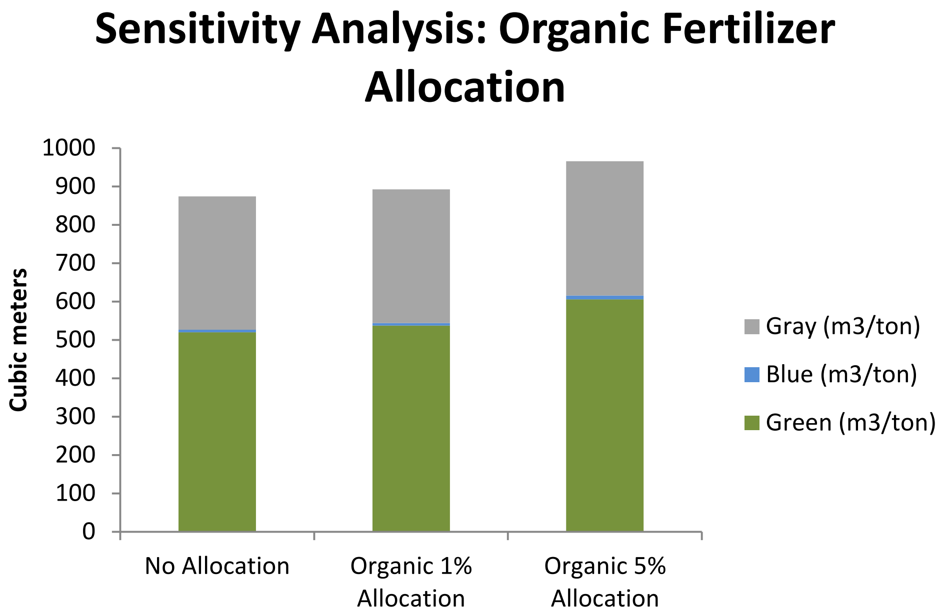

Figure 12: Results of the sensitivity analysis of different allocation percentages for the production of manure, used as an organic fertilizer.

The two suggested allocation levels of 1% and 5% increase the total supply chain water footprint by 2.1% and 10.5% respectively.

3.4.2.3 Transportation distances and filling degree

The transportation distances presented in Table 10 are all estimates based on approximations from Google maps, ArcGIS and previous studies. The effects of potential underestimations are evaluated in this sensitivity analysis. Three alterations to the original study are tested at once:

- The transport distances are doubled
- The filling degree is decreased to 70% and,
- The distance from drying to storage is set to 100km

The result is presented in Figure 13 below.

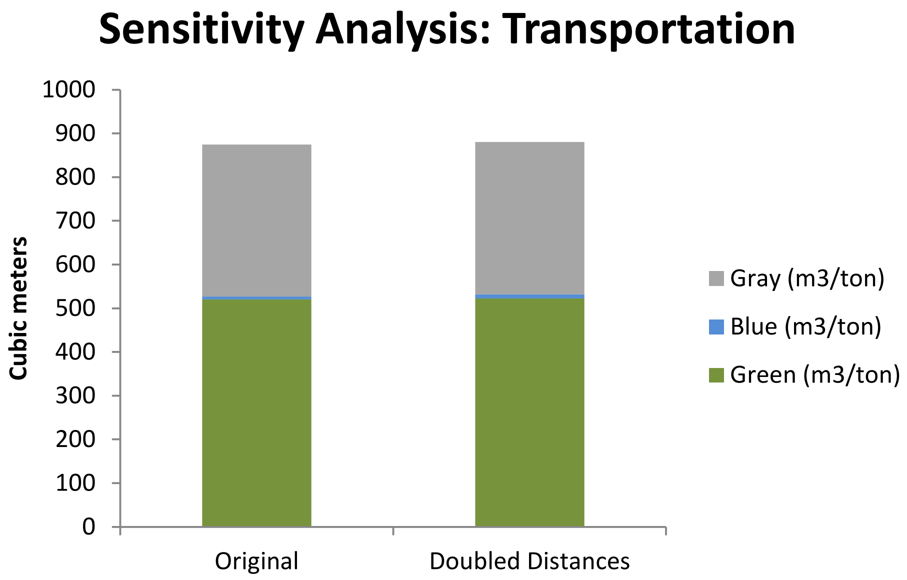

Figure 13: Result from sensitivity analysis on transportation. All the supply chain distances from Table 10 are doubled, the distance from drying to storage is assumed to be 100 km and the filling degree is decreased to 70%.

The combined effect of the three changes is an increase in the total supply chain footprint by 0.68% to about 881 m^3 per ton. The sensitivity analysis clearly shows that the poor quality of the transportation data do not affect the outcome in a significant way, and even doubling the distances and further decreasing the filling degree changes the result by less than 1%.

3.4.2.4 Pure Biofuel in Transportation and Cultivation

As can be seen in Table 4, biodiesel based transport has a significantly higher water footprint than fossil fuel based transport, due to the cultivation of the crops required for biofuel production. In the original study it is assumed that the Swedish average fuel composition, about 3.2% biodiesel, is valid for the transports. However there are plans and initiatives in place to increase the share of biofuel in Sweden, as well as in Europe. This makes it interesting to look at what effect a pure biofuel based transportation system would have on the overall result.

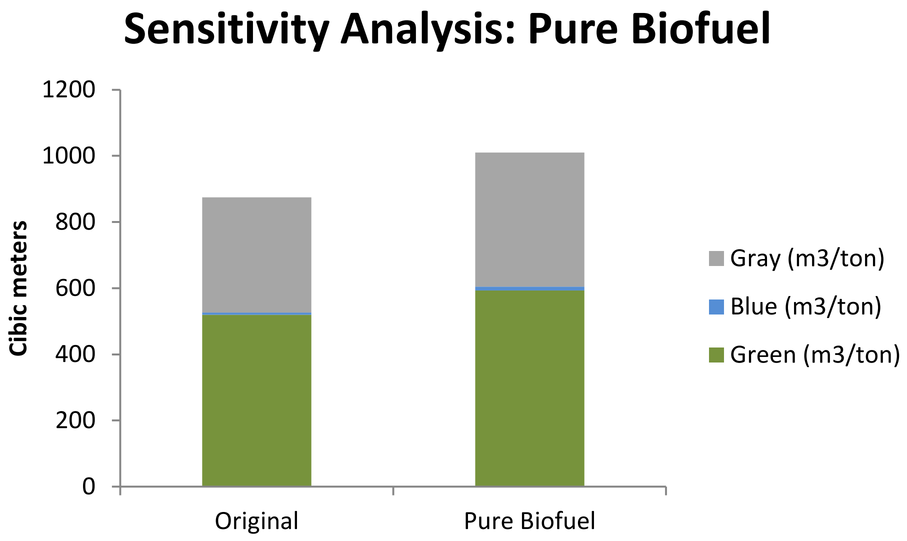

Figure 14: The result of the sensitivity analysis of a pure biofuel based transportation and cultivation components.

The total water footprint increases by 15.5% of which transportation is 5.8% compared to 0.29% in the original case, when the fuel used is assumed to be 100% biodiesel. This is a significant change, and would obviously have even greater impacts on a more transportation-intensive system. The more realistic Swedish and EU environmental goals of 10% biofuels would increase the overall result by approximately 1.6%.

3.4.2.5 The Net Green Water Method and the Exclusion of Gray Water

The idea of a net green water footprint has been described in the literature study and a sensitivity analysis is done here to assess the impact on the overall result and conclusion that this concept would have. The rainwater that would be absorbed by a theoretical reference crop (forest, permanent crops such as fruit orchards, and shrub land) is compared to water absorbed by a wheat field to calculate the additional water that the arable land absorbs. The results of this analysis are presented in Table 14 and Figure 15 below.

Table 14: The supply chain water footprint when considering the net green water concept. Data on absorbed rain from Milá í Canals et al (2009) and Zhang et al (1999).

Land occupation type	Share of precipitation Evapo-transpirated	Difference from Original (Net green water)	Total WF (m^3/ton)	Percent of original study
Arable Land, Original	73 %	100%	875	100.0%
Forest as reference	67%	6%	386	44.1%
Permanent Crop as Reference	67%	6%	386	44.1%
Shrub Land as Reference	64%	9%	401	45.9%

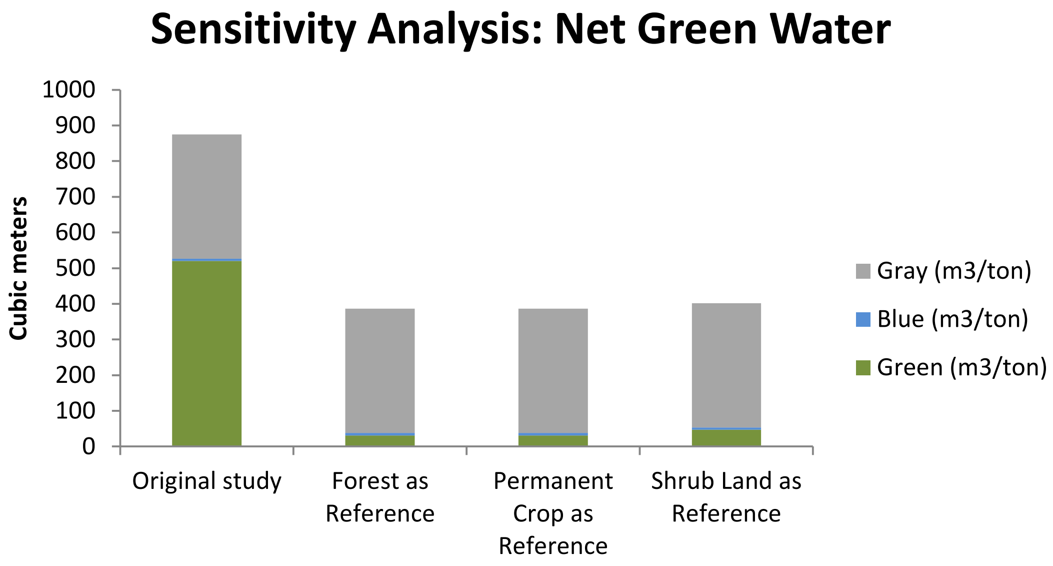

Figure 15: The results from Table 14 presented graphically. The net green water concept is applied only to the cultivation component of the supply chain system.

The net green water method decreases the water footprints by up to 65% as shown in Table 14, a significant alteration of the composition and magnitude of the result. Instead of the green water dominating, the gray water constitutes almost the entire footprint.

As was concluded in the literature study, the inclusion of the gray water component is debated, and the Water Footprint Network is the only entity that suggests it. If the water footprint analysis were a part of a life cycle assessment, the nutrients that make up the gray water would already be accounted for, and might be excluded from the water footprint. The result of applying both the net green water method and excluding the gray water footprint is presented in Figure 16 below. There would probably be a gray water footprint associated with another pollutant in place of nitrogen, but no attempt is made here to calculate it.

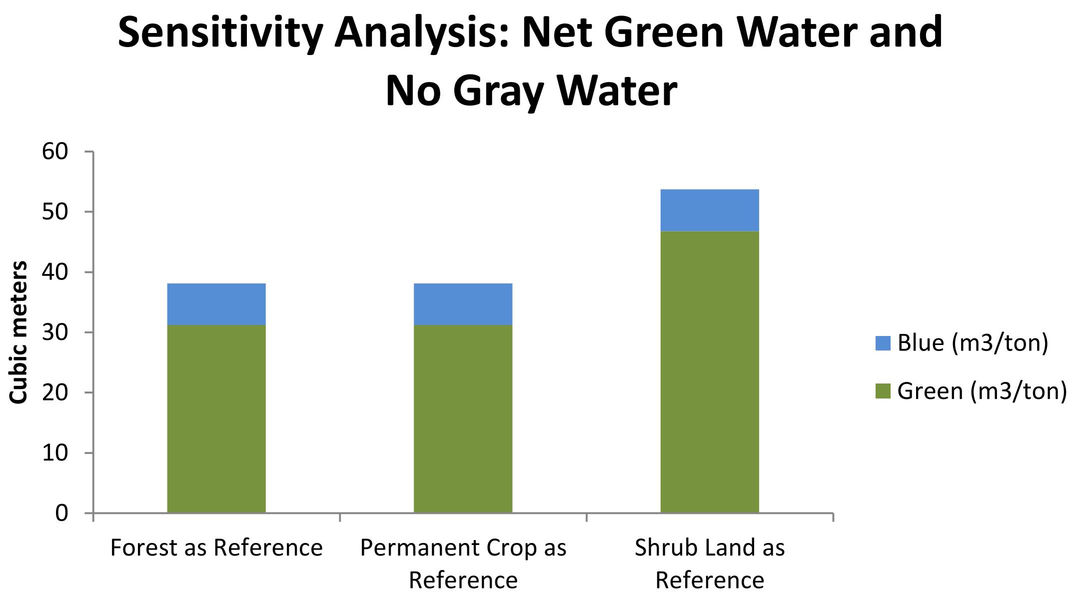

Figure 16: The water footprint per ton winter wheat, when the net green water method is applied and the gray water is considered in the eutrophication category of a traditional LCA.

The exclusion of the gray water significantly decreases the total water footprint, from 875 m^3 to 38 m^3 and for forest or permanent crops, and 53 m^3 for shrub land. This decrease, to between 4-6% of the original result, might be considered the *actual* change in water availability as a result of the cultivation, compared to the 875 m^3 when considering all virtual water.

3.4.2.6 Irrigation Practices

The original supply chain system use an evenly distributed irrigation factor of 1% of the winter wheat cultivated area. The 1% value is surrounded by uncertainty as it originates from a survey of a small percentage of Swedish farmers, and is not specific to winter wheat or even wheat, but grains in general. In addition to this, changing climatic conditions could potentially influence the amount of irrigation that is applied or required. The sensitivity analysis is run for three scenarios in addition to the original 1% value: a slight increase from 1 to 5% a large increase from 1 to 20% and finally the full 100% of what is suggested by the model as required irrigation.

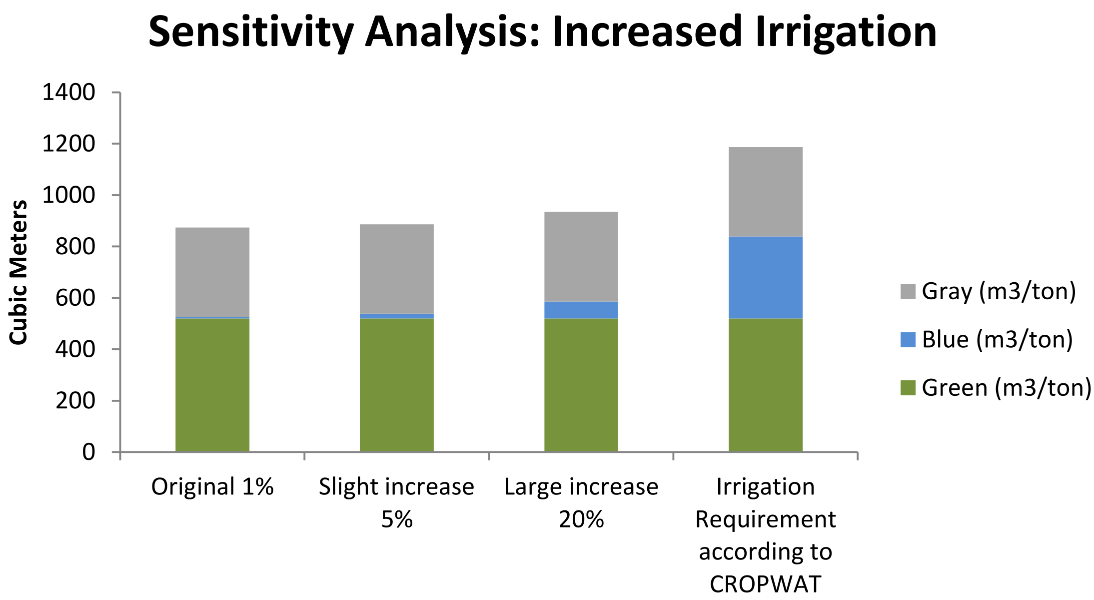

Figure 17: The result of the sensitivity analysis estimating the effects of increased irrigation. The increased irrigation is only applied to crop water requirement, and not to any of the other components.

By increasing the irrigation from 1% of the area to 5%, 20% and 100% of the volumes suggested by the CROPWAT model, the total supply chain water footprint increases by 1.4% and 6.9% and 35.8% respectively. Assuming that the 1% suggested by the survey is somewhat realistic as sources at Jordbruksverket indicate it might be, a 100 fold, or even 20 fold increase in the amount of winter wheat being irrigated does not seem probable within the foreseeable future, and the 1.4% increase in the water footprint of a five fold increase in irrigation is negligible compared to other effects of short term climatic variations, shown in the section below.

3.4.2.7 Non-Linearity within the CROPWAT model

The climatic input data for the CROPWAT model are averages for the years 2008-2010, which mean that dry and wet periods during these years could potentially cancel each other out, resulting in lower water footprints than if annual data would have been used. The decision to use average data was based on the large amount of work that would be required to make simulations for all three years, for all 18 stations.

Due to the non-linear nature of the calculations involved in the CROPWAT model, the effects of changes in climatic factors cannot be accurately predicted, instead the model was run for three climate stations, and the results compared to the average data from the main study. The three stations chosen were Malmö, Såtenäs and Malmslätt, a choice based on the total cultivated area, and these three regions contain more than 67% of the winter wheat fields in the study. The differences in the outcome of the study are presented in Table 15.

Table 15: A comparison of the annual values to the three-year averages. The percentage shows the annual/average fraction, i.e. greater than 100% means that the annual value is greater than the average and vice versa.

	Green Water Requirement			Blue Water Requirement		
	2008	2009	2010	2008	2009	2010
Såtenäs	96.9%	100.3%	99.2%	35.6%	27.0%	19.1%
Malmslätt	91.0%	111.8%	103.6%	57.7%	24.3%	15.1%
Malmö	103.3%	118.4%	97.4%	66.0%	26.5%	32.1%

As can be seen in Table 15 the Green water requirements are similar between the average and the annual values, while the blue water requirements are drastically decreased when annual values are taken into consideration. The effects of this on the final result is limited, as the blue water footprint, contributing to 0.78% of the total, is insignificant compared to the green and gray water footprints. The effects on the blue water requirement are however, an important observation and should be taken into consideration in future studies where blue water might constitute a larger share of the final water footprint. It should be noted that the averaged values may have been smoothed out in a number of ways, the combination of which lead to a significantly larger blue water requirement, than in the annual cases. In Figure 18 below, the changes have been averaged over the three stations and extrapolated to the whole study, to simulate what the final result would be if the differences in Table 15, were universally valid.

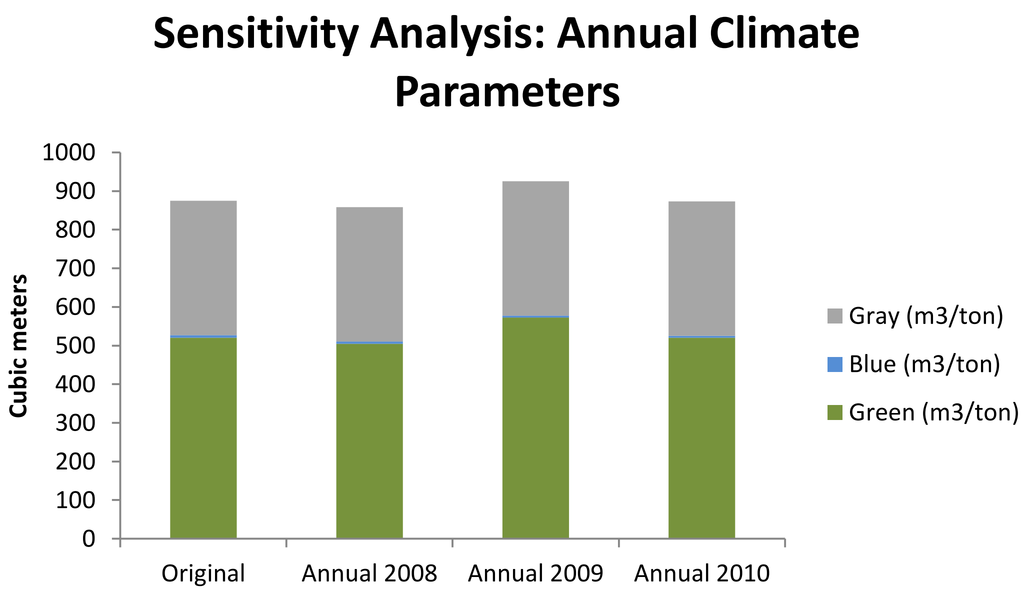

Figure 18: Result from sensitivity analysis of annual versus average climate parameters as input to the CROPWAT model. Results from partial re-simulation presented in Table 15 were extrapolated to apply for the study as a whole.

The total water footprints from the three annual values differ by -1.9%, 5.8% and -0.2% for the years 2008, 2009 and 2010 respectively. This indicates that even if the entire study had been made based on annual values instead of average the differences would have been marginal.

3.4.3 Discussion

The cultivation is by far the most important component for the result, as it constitutes all but a fraction of a percent of the total supply chain water footprint. The data quality of the cultivation component is good but not great, and using a model to estimate the evapotranspiration introduces uncertainty to an unknown degree. The Water Footprint Network use a grid based water balance model in similar studies quoted in the completeness check, and their results are significantly lower than the result from this study. However, a number of other factors are different between the two studies, so the effect of the differences in the water footprint models cannot be directly evaluated.

The data quality of the other components: transport, energy, fertilizers and storage is not satisfactory, but considering the miniscule impact these components have, that does not alter the composition or magnitude of the result. To verify this, a number of sensitivity analyses are done on some of the key parameters, but without radically altering some of them the effects are negligible. The analyses were discussed in detail under the sensitivity headings in section 3.4.2.

If the net green water concept becomes the norm, and the gray water is considered to belong to a different category of environmental degradation than water footprint, the result is decreased to 4-6% of the original, or 40-50 m^3 per ton. This type of footprint might be considered more tangible and direct, but does not give a complete picture of the volumes of water that are involved.

3.4.4 Improvement analysis

The analysis could be improved in a number of ways; primarily the data quality and model data for the cultivation component should be improved as it makes up almost the entire footprint. The development of a Swedish model, or crop parameters adjusted to Swedish conditions could be used to improve the accuracy of the result. More and better data on irrigation practices and winter-wheat specific values on irrigation could potentially be another important improvement. If the introduction of a net green water footprint is relevant, then reference land uses and the infiltration, runoff and evapotranspiration factors of these need to be established.

To improve the quality of the geographic and Lantmännen-specific data, the individual fields from which Lantmännen purchase their winter wheat could be defined and analyzed. This was initially intended to be a part of this report, but due to data inaccessibility and the scope of the analysis, the idea was abandoned. It would also have been interesting to examine the accuracy of the CROPWAT model output by attempting measurements of the evapotranspiration and irrigation requirements at a number of locations, as a verification of the result.

3.5 Conclusions

It is the opinion of the author that the water footprints are within the expected range. The total domination of cultivation component confirms what other studies have shown and the initial expectations in this study.

The results compare well to that of neighboring countries in the first reference study in the consistency check, they do not compare as well to the second reference, probably due to large differences in methods and models between the two.

The fact that a small share of the footprint is blue water is positive for the sustainability aspects of water availability versus extraction. The concepts of green and gray water are somewhat diffuse and not as established as that of blue water and as seen in the literature study, other methods do not include them fully or at all. Therefore, the result from the viewpoint of Milá i Canal et al, or Pfister et al. looks radically different.

The sensitivity analyses showed that the result was quite robust, and even with a 20-fold increase in irrigation, the result remained within 7% of the original, while the influence of climatic variation within the temporal scope remained within 5.8%. The applied allocation principles did make a more significant impact but the results still did not vary by more than 12%. When the climatic conditions of the base study were altered, it had a small effect of the green water, while the blue water varied significantly. This suggests that more extreme shifts in water availability such as periods of drought might drastically affect the composition and magnitude of the water footprint.

The attempt to use LCA methodology, and include other components as well as cultivation, did not influence the final result to any significant extent, but was not completely in vain, as it highlighted some gaps in the data available. It is recommended however, that future studies focus more in detail on the cultivation and especially the specific geographic extent of the water footprints.

It should be noted that the water footprints calculated here are not compared to the total water availability or total water footprints within the river basins and therefore no conclusion on the sustainability of the water footprints can be drawn. In order to assess the sustainability of the results, a total water footprint as well as the environmental flow requirements and available water within each basin need to be calculated. A sustainability assessment of the winter wheat cultivation could potentially help identify hotspots within which Lantmännen should consider amendments to their water use.

The comparison to the results from the global study show that the water footprint of Swedish winter wheat is comparatively low, and because water availability is generally good, this indicates that the water footprint would fare well in a global sustainability assessment. However this statement needs to be verified before any further elaborations are made.

It is also concluded that the calculation tools and methods of water footprinting need to be improved. The CROPWAT model is developed for other purposes and the results are difficult to verify, as accurate measurements of evapotranspiration are complicated. Further refinement of the methods and development of water footprint databases similar to those of LCA could drastically improve the quality and availability of water footprint data.

4 Case Study A: Ceralia Mill Malmö, Wheat Flour

Lantmännen Cerealia develops, produces and markets primarily grain based products under well known brands such as AXA, Kungsörnen, Start, Gyllenhammars, Gooh, GoGreen, Sopps, Amo, Kornkammeret and Regal. The Cerealia mill in Malmö produces a number of consumer and wholesale items as well as processed raw materials. This case study will concentrate on a single product produced there: the *Kungsörnen kärnvetemjöl*, which consists of 100% processed winter wheat. In the Järna case study another wheat flour called D0 flour produced in Malmö will also be included.

4.1 Goal, Scope and Purpose Definitions

The goal of the Malmö case study is to calculate the water use and water pollution i.e. the water footprint associated with the production of wheat flour at the Ceralia mill in Malmö. The result is presented in conjunction with the supply chain water footprint of winter wheat cultivation. The purpose is to allow a comparison between the water footprints of the different steps within the value chain of winter wheat and winter wheat products and to calculate a total water footprint of the entire wheat flour production system. The case study is meant to provide an indication of what the water footprint of wheat flour could be and is therefore not as detailed as the supply chain study.

4.1.1 Scope Definition

This case study is limited to the production of "*Kungsörnen kärnvetemjöl*" or wheat flour, at the Ceralia mill in Malmö during the years 2009 and 2010, from Swedish winter wheat raw material, as defined in the supply chain study. The temporal scope is limited to two years instead of three, the reason for this being that the data for 2008 has been archived and is not readily available.

4.1.2 Functional Unit

The functional unit in the case study is *1 kg of wheat flour with a water content of 14.9% at the factory gate in Malmö*.

4.1.3 System Boundaries

The case study is conducted on a gate-gate basis, but includes the supply chain water footprint as a parameter, and therefore the result is a cradle-to gate analysis. This means that the study includes the required inputs from the cultivation of the raw material, up until the wheat is completely processed into wheat flour. The packaging of the product is not included.

4.1.4 System Description

The production system consists of two components, transportation and processing. The production of fuel and electricity are support components to the case system in the same way as for the supply chain system, and are not treated in detail here.

4.1.4.1 Transportation

The transportation component consists of a single transport, from each storage facility to the mill in Malmö. In the same way as in the supply chain system, the water footprint associated with transportation originates from the production of the used fuel, as well as the composition of it.

4.1.4.2 Processing

The processing component includes a number of processes, from when the wheat raw material reaches the mill, to the finished wheat flour-product. The water footprint related to the processing is mainly found in the use of electricity and natural gas, but also in the water added during processing. Figure 19 below, show a simplified description of the process steps in which the grain seed is processed into flour, broken down into the process elements that are relevant for this study. The hygiene water that is used at the facility is returned to the municipal waste water system and then treated before it enters natural water systems again. Therefore there is no gray water footprint related to the processing at the mill in Malmö.

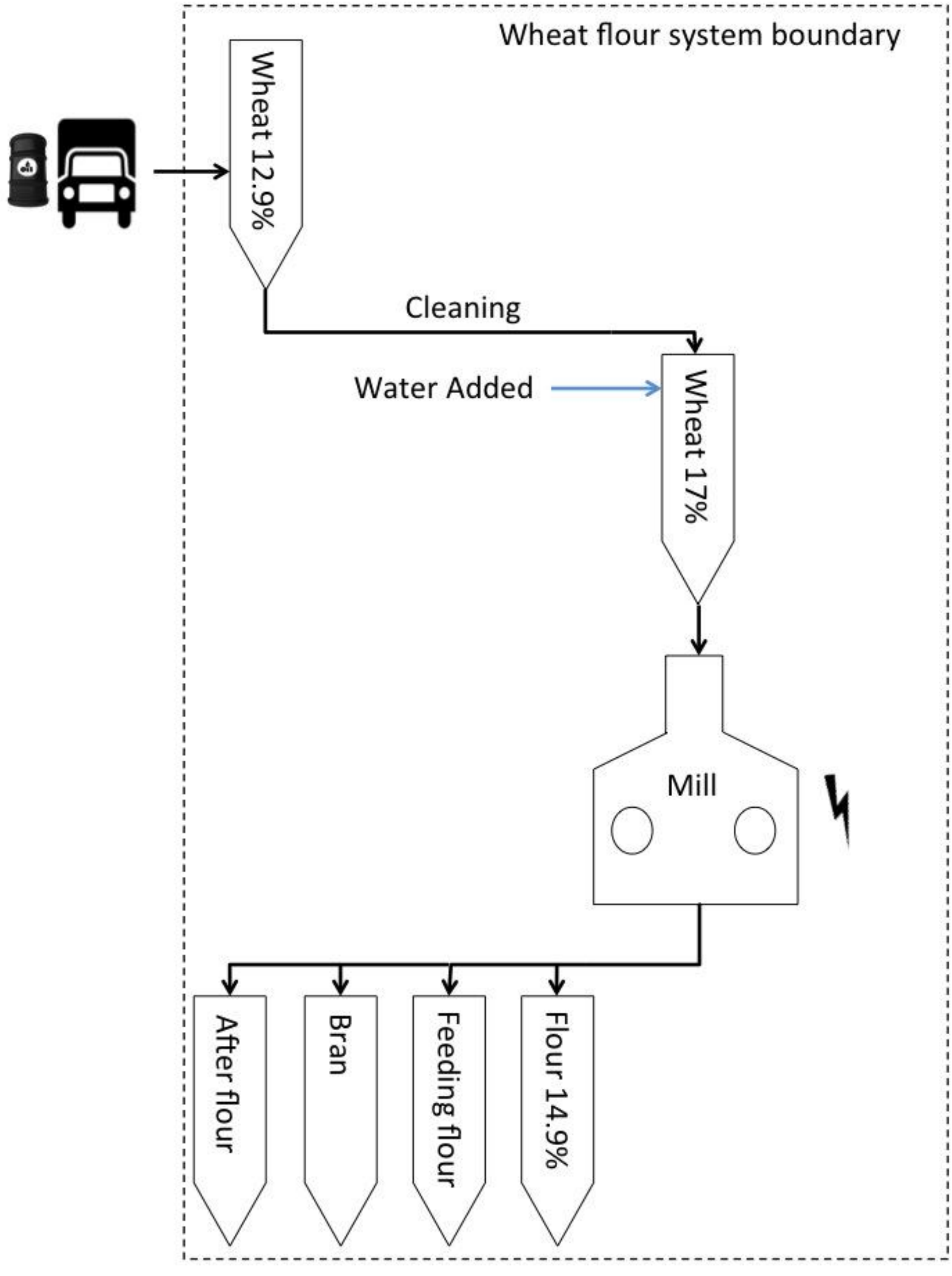

Figure 19: Simplified overview of wheat to flour processing at the Ceralia mill in Malmö. The percentages show the water content of the product at each stage.

4.1.5 Cut off criteria

Like the supply chain system, no explicit definition of cut off criteria is applied to the case study systems, but processes that contribute to less than 0.1% to the total water footprint, are deemed to be insignificant. They are however still presented for the sake of interest.

4.1.6 Allocation

The facility in Malmö process approximately 180 000 tons of grains annually, of which the winter wheat used in the production of wheat flour represent about 8.9% by mass. The use of energy in the form of electricity or natural gas, as well as the hygiene water, used for showers, toilets etc. is defined on a facility-wide scale and therefore the water footprint of these need to be allocated in order to produce a reasonable result. The allocation is made based on mass and therefore 8.9% of the hygiene water and energy use are allocated to the production of wheat flour. It is assumed that the energy and process water use are relatively homogenous for all the products, so that the mass based allocation is valid for the wheat flour.

4.1.7 Data Quality

The data quality requirements are the same as in the supply chain system, and follow the classification described in section 3.1.6 and Table 2. The data required for the calculations in this case study are described and classified in Table 16. Data for the supply chain system is not described here, but can be found in Table 3

Table 16: Data sources and quality ratings for data in the Malmö mill case study. Data for the mill such as processing and energy use data is from the environmental report and from extracts of the production software. This is referenced to Erling Koch, who is the factory manager in Malmö.

% of Result	Category	Component	Source	Data Quality
0.26%	**Transport**	Distances	GIS and Google Maps	D4-
		Fuel composition	(Energimyndigheten, 2011b)	B3
		Water footprint, Biodiesel (L/ton-km)	(Hoekstra & Gerbens-Leenes, 2010)	C4
		Water footprint, Fossil diesel (L/ton-km)	(Gleick, 1994)	C4-
		Filling degree	Estimation	D4-
0.79%	**Electricity and energy**	Swedish average electricity composition (Svensk medelel)	(Energimyndigheten, 2011b)	B3
		Water footprint of primary energy carriers	(Gerbens-Leenes et al., 2009)	C4-
		Energy Use	(Koch, 2012)	A1
0.01%	**Processing**	Total mass of winter wheat used in wheat flour production	(Koch, 2012)	A1
		Wheat-to-flour conversion	(Koch, 2012)	A1
		Water use and water content	(Koch, 2012), (Lantmännen Ceralia, 2011)	A1
N/A	**Allocation Principles**	Economic allocation percentages	(Tynelius, 2008)	A1-

4.2 Inventory

The calculation methods and assumptions necessary for each component of the water footprint are described in detail in this section. Any processes shared with the supply chain system are referred back to the relevant section there.

4.2.1 Transportation

The transportation distance from the storage facility to the mill in Malmö is assumed to be 100 km as stated in Table 10 in the supply chain study. The mass of 14% wheat that is transported to the processing plant is 15 846 tons, recalculated from 15 348 tons 12.9% wheat arriving at the facility annually. With a filling degree of 80% this gives a total transportation water footprint of 14 600 m^3 green, 17 100 m^3 blue and 5 130 m^3 gray water annually.

4.2.1.1 Relating data to functional unit

The production of 1 kg of wheat flour require about 1.29 kg of 14% wheat, calculated using a conversion rate of 76.7% acquired from Table 17, to be transported to the mill. This gives a transport water footprint of 0.89 L green, 1.05 L blue and 0.314 L of gray water per kg of wheat flour.

4.2.2 Processing

The mill process an average of 15 384 tons of 12.9% wheat annually, or 15 846 tons of 14% wheat, into 12 156 tons of 14.9% wheat flour. These numbers are averages of the years 2009 and 2010 and all the data is presented in Table 17 below.

Table 17: Processed raw material, produced wheat flour and conversion rates. Data is for the years 2009, 2010 and an average of the two.

	2009	2010	Average
12.9% wheat (tons annually)	15 044	15 724	15 384
14% wheat (tons annually)	15 495	16 196	15 846
Wheat flour (tons annually)	11 649	12 663	12 156
Conversion: 14% wheat-to-14.9% flour	75.18%	78.19%	76.72%

The direct water use at the facility is divided into two categories; hygiene water, which is used for showers, toilets etc. and process water which is used in the production process itself. The amount of water used in the processing is calculated using a water balance of the incoming wheat kernels, the added water and the outgoing flour according to Table 18. This results in a total processing water footprint of 744 m^3 of blue water annually.

Table 18: The masses and water contents in the different process steps at the mill in Malmö. In step three, 22% of the mass is removed as byproducts of the process, but no water footprint is allocated to these. The total water use per ton of flour in the process can be found by subtracting the input water (162.1 kg) from the total water after the addition (223.5 kg).

	Water content	Dry mass (kg)	Total mass (kg)	Total water (kg)
Winter Wheat	12.9%	1 091	1 253	162
Added water	17.0%	1 091	1 314	223
By-products, 22% of mass	17.0%	851	1 025	174
Kärnvetemjöl	14.9%	851	1 000	149

In addition to the water used directly in the process there is some hygiene water used by the employees at the facility. This amount is allocated by mass, 8.9%, to the wheat flour, resulting in an additional 276 m^3 of blue water added to the processing component, to a total of 1 022 m^3 of blue water. The wastewater is sent to a treatment facility, and does not contribute to the gray water footprint of the wheat flour production. It is assumed that the water is kept out of the natural system for a significant amount of time and the release of treated wastewater is therefore not seen as occurring in the same time period, and do not decrease the water footprint.

Table 19: Total annual direct water use of the facility in Malmö.

	2010	2009	Average
Process Water (m^3)	8 774	8 395	8 585
Hygiene Water (m^3)	3 107	3 092	3 100
Total Water (m^3)	11 881	11 487	11 684

4.2.2.1 Relating data to functional unit

The process water footprint is related to the functional unit by dividing the annual total with the annual production, which gives a total of 0.000084 m^3 or 0.084 liters of blue water per kg of wheat flour.

4.2.2.2 Data Validation

The annual processing water footprint of 746 m^3 calculated in Table 18 represents about 8.7% of the total process water use at the facility presented in Table 19. This corresponds well with the mass share of 8.9% of the annual grain that is used for the production of flour. The conversion factor of 77.5% also compares well with the overall values in Table 17.

4.2.3 Energy use

The Malmö mill uses about 72 240 GJ, or about 20.07 GWh of electricity and 9 419 GJ of natural gas annually, and 8.9% of this is allocated to the production of wheat flour by mass allocation. Using the same method and values as in the supply chain system under heading 3.2.2 the water footprints related to electricity and natural gas use are calculated and presented in Table 20 below.

Table 20: The water footprints associated with the energy use at the mill in Malmö, facility total and per functional unit values are presented. The values are allocated by mass at a total of 8.9% allocated to the wheat flour.

	Green (m^3)	Blue (m^3)	Gray (m^3)
Electricity	32 780	73 595	4 306
Natural gas	0	84	0
Facility total	32 780	73 679	4 306
Per kg Wheat Flour	0.003	0.006	0.0004

4.2.4 Supply Chain

The total annual use of winter wheat for input to the production of the wheat flour was 15 845 tons, an average of 2009 and 2010. Using the average water footprint of winter wheat, the total annual supply chain water footprint is about 8 220 000 m^3 green 76 500 m^3 blue and 5 510 000 m^3 of gray water for the annual wheat flour production at the mill.

4.2.4.1 Relating data to functional unit

A total of 12 156 000 kg of wheat flour was produced annually, an average of 2009 and 2010, which gives a supply chain water footprint of 0.676 m^3 green 0.0063 m^3 blue and 0.453 m^3 of gray water per kg of wheat flour.

4.3 Results

The results of the case study are presented in Table 21 and Figure 20-Figure 23 below.

Table 21: Result of the wheat flour case study. The supply chain water footprint dominates the result, constituting almost 99% of the total water footprint.

	Green (m^3)	Blue (m^3)	Gray (m^3)	Total (m^3)	Percentage of total
Process Water	0	1256	0	1256	0.01%
Energy – Electricity	32 780	73 680	4 310	110 760	0.79%
Supply Chain	8 216 780	76 500	5 506 880	13 800 160	98.93%
Transport	14 560	17 070	5 130	36 760	0.26%
Total	**8 264 120**	**168 510**	**5 516 320**	**13 948 950**	**-**
Per kg of Wheat Flour	**0.680**	**0.0139**	**0.4538**	**1.15**	**-**

The supply chain component completely dominates the water footprint, contributing to almost 99%, and is in turn made up almost entirely of the cultivation component, as seen in the supply chain study. This means that the cultivation is by far the largest contributing factor to the case study, while the energy and transportation components together barely make up 1%. The domination of the supply chain component is visualized in Figure 20 and the composition and relative sizes of the other components are shown in Figure 21 below.

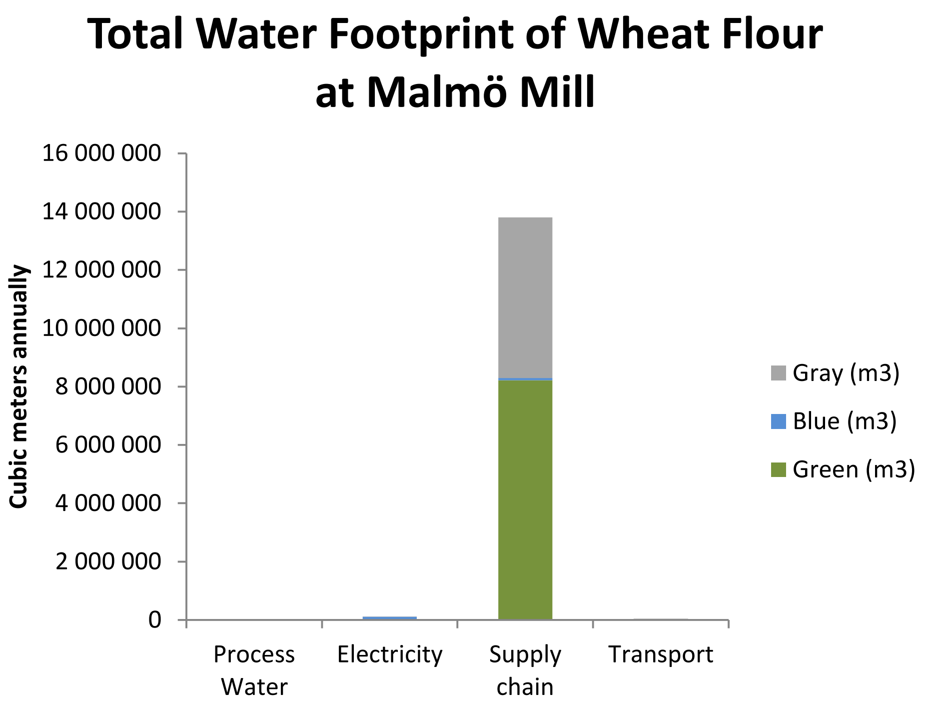

Figure 20: The total water footprint of the mill in Malmö, almost 14 000 000 m³ annually, where the supply chain component makes up 99% of the total water footprint, and is in turn made up of 99% of the cultivation component of the supply chain system. The data is presented in Table 21.

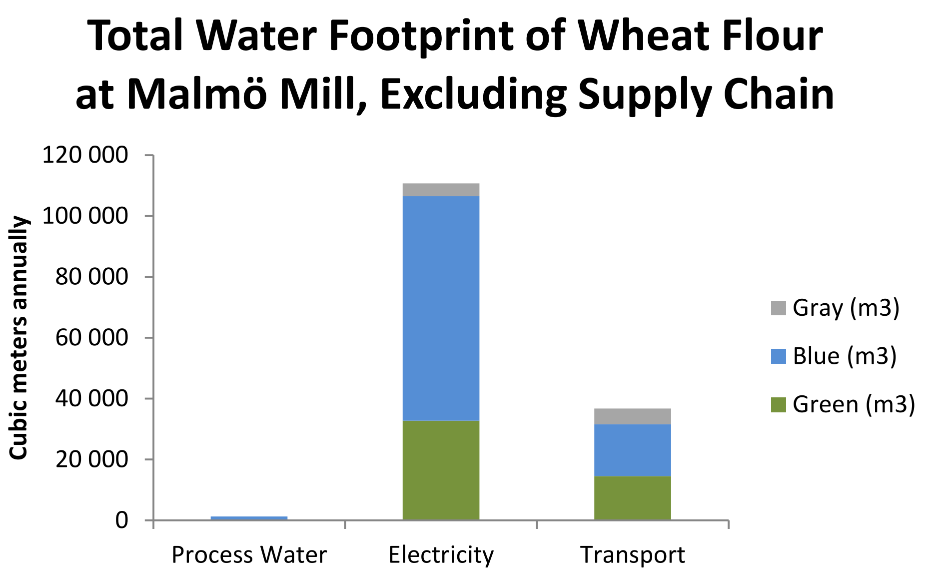

Figure 21: The total annual water footprint of the Malmö mill. The supply chain component is suppressed to show the contribution and composition of the other entities.

As Figure 21 clearly show, the electricity and energy, along with the transport components make up most of the remaining 1%. Figure 22 and Figure 23 show the water footprint per kg of wheat flour at the Malmö mill, the internal composition is of course identical to that of the two previous figures. As stated in Table 21 the total water footprint per kg of flour is about 1150 liters.

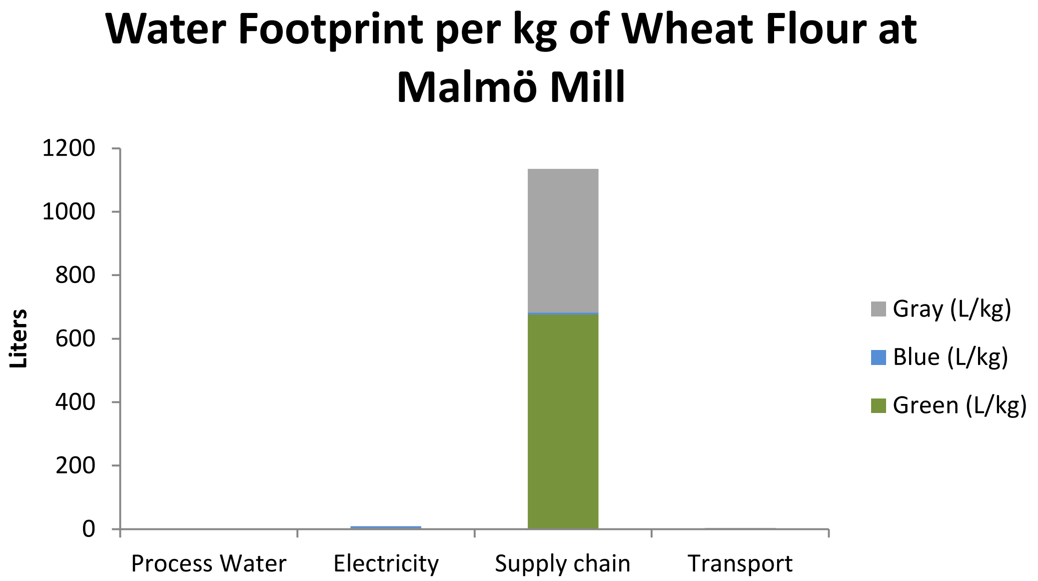

Figure 22: The water footprint of a kg of wheat flour at the mill in Malmö, data from Table 21.

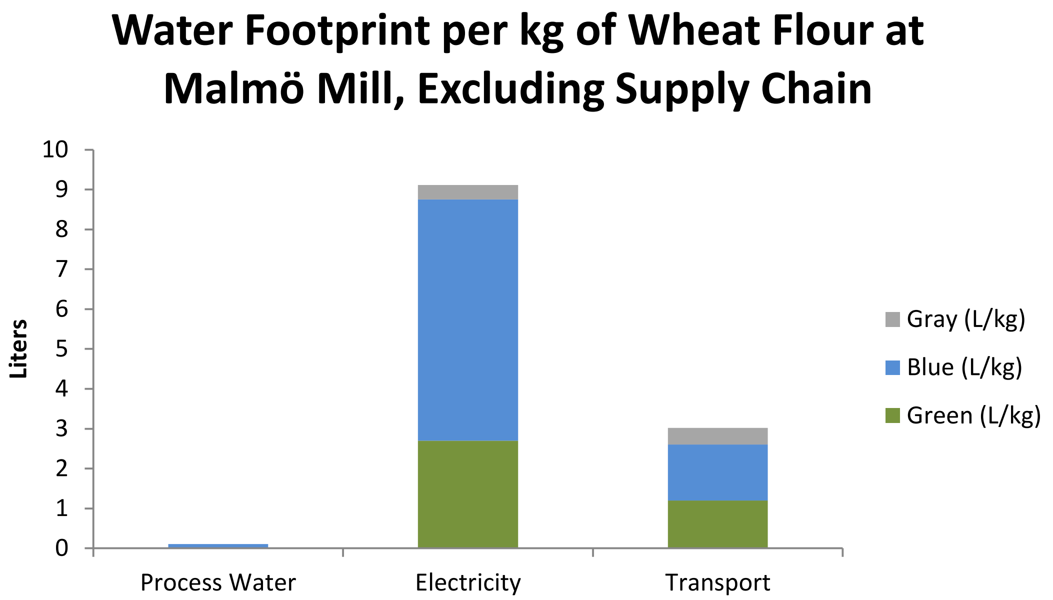

Figure 23: The water footprint of a kg of wheat flour at the Malmö mill. The supply chain component is suppressed to show the other components in detail.

4.3.1 Geographic Distribution

To estimate the geographic extent and distribution of the water footprint of the Malmö facility a number of assumptions are necessary. These are:

- The wheat is sourced from the areas closest to the facility Malmö. The mill is marked on the map using a green square
- Lantmännens overall share of Swedish wheat is applied on a field level, allocating 40% of the total produced amount from each field to the mill, spreading as far from the facility as necessary to attain the required amount of wheat
- The non-cultivation components of the production system are allocated to the drainage basins in which the process takes place i.e. energy, processing and

transportation water footprints are allocated to the drainage basin in which the mill is located

The map in Figure 24 is a representation of what the water footprint distribution *could* be, and should not be interpreted as the actual distribution.

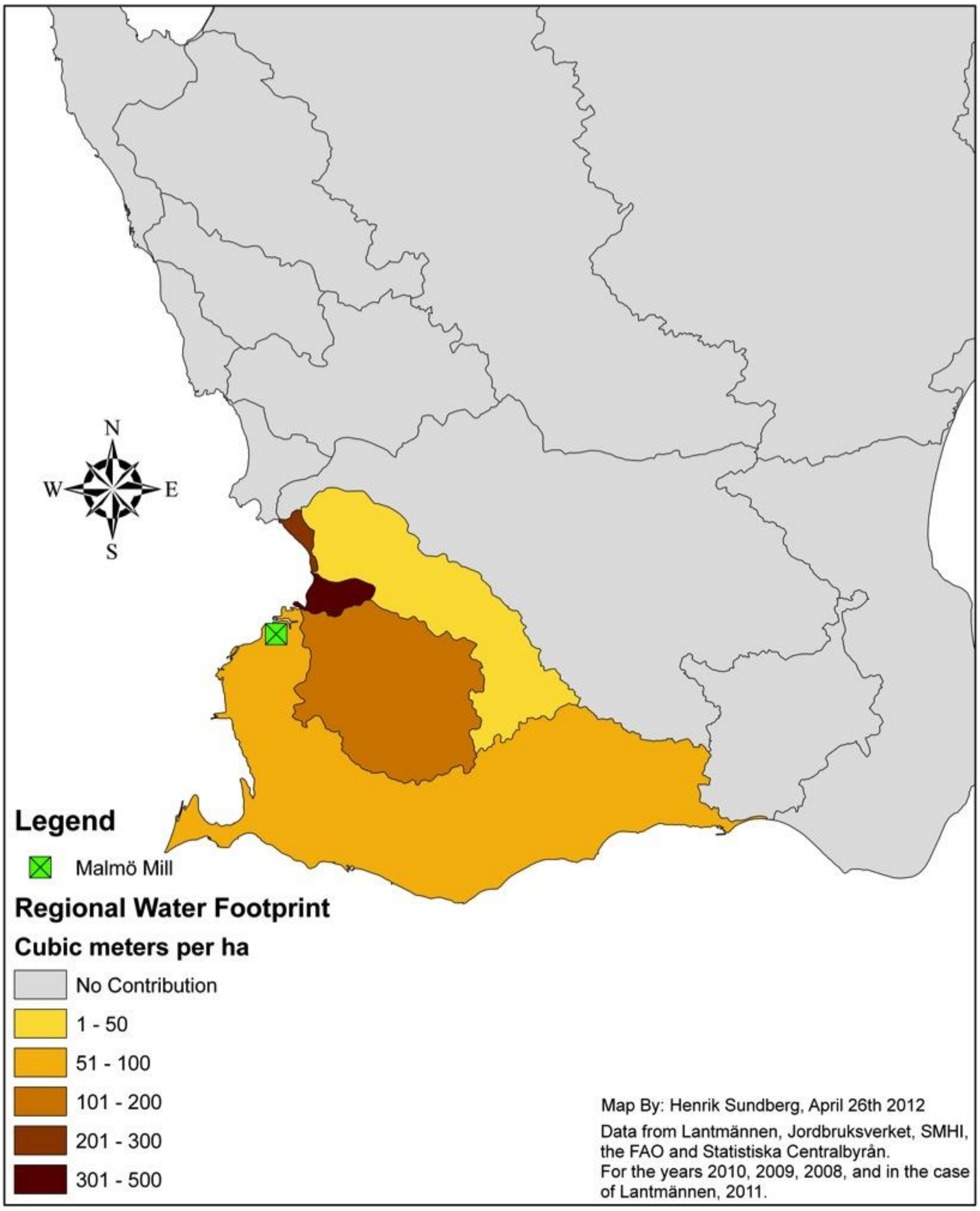

Figure 24: A graphic representation of what the geographic distribution of the water footprint associated with the production of wheat flour at the mill in Malmö could look like. The total water footprint is normalized by area and show average data from the years 2009 and 2010.

4.4 Discussion and Analysis

4.4.1 Consistency Check

A study by the Water Footprint Network titled: *The green, blue and grey water footprint of crops and derived crop products* (Mekkonen & Hoekstra, 2010b), presents the water footprints of a number of crop products, including wheat flour. The scope and methodology of that study differ somewhat from that of this one; Mekkonen and Hoekstra use a grid-based water balance model, and apply it globally for wheat cultivation, while this study uses the CROPWAT and only evaluate the results under Swedish sub-national conditions. The temporal scope of these studies vary as well, Mekkonen and Hoekstra use data from 1996-2005 while this study use data from 2008-2010 for cultivation, and 2009-2010 for case study A. These are likely to be the main reasons why the results differ, but no efforts are made here to further define the origin of this difference.

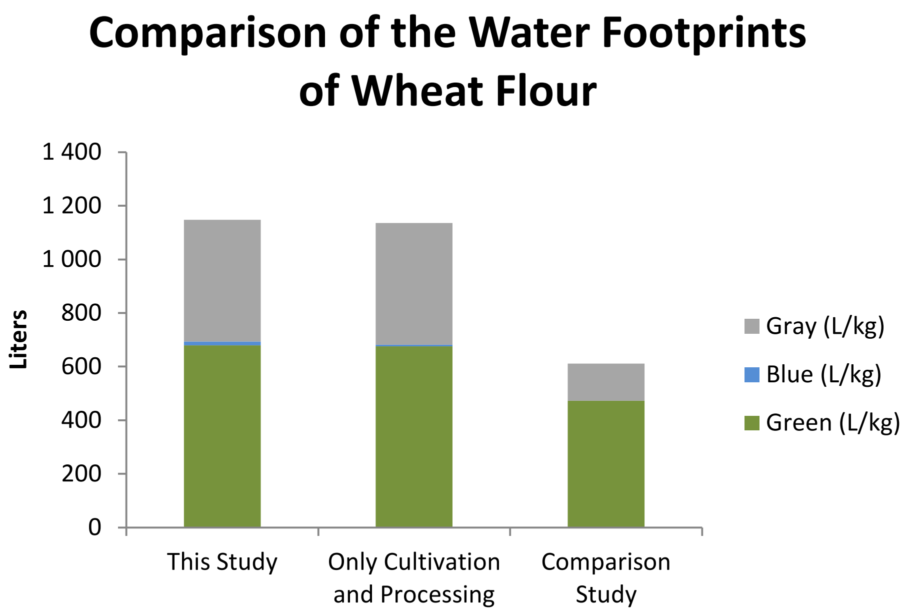

Figure 25: The water footprints of wheat flour from this study and from Mekkonen & Hoekstra (2010b). The later include only the cultivation and processing components and therefore both the total result and one altered to suit the scope of the Mekkonen and Hoekstra are presented. The values from the comparison study are from Swedish wheat flour.

The Mekkonen & Hoekstra study results in a water footprint, about 53% of the footprints of this study, which suggest that some further analysis should be done to evaluate the effects of the assumptions, method and scope of this study. It is worth noting however, that the results of the supply chain system, which makes up 98% of the total water footprint of this case study, agree well with Mekkonen and Hoekstras results. This indicates some disparity between the two compared studies, and the processing efficiencies in them. The compared study does not specify the type of wheat used and the data is likely to be an average of spring and winter wheat values, which would also lead to a difference between the case study and the compared system. The largest disparity between the current and the comparison studies lie within the gray water footprint, where the data for this study is derived on a county- and crop-specific level, while the comparison study use the FAO database, with a lower, Sweden-average, resolution in fertilizer application rates.

4.4.2 Sensitivity Analysis: Allocation Principles

The sensitivity analysis is conducted to evaluate the effects of an allocation applied to the case study. In an LCA of the wheat flour produced in Malmö, Tynelius (2008) used an economic allocation of the environmental impacts between the wheat flour and the byproducts. In that study a total allocation of 92.1% was placed on the wheat. This is applied to the result of this study as well, on a facility wide scale. The result is shown graphically in Figure 26 below.

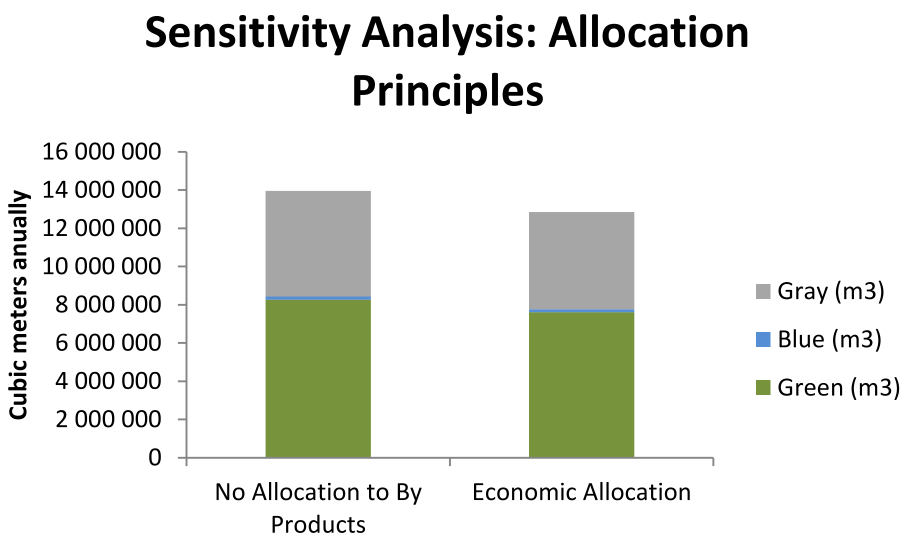

Figure 26: Result of the sensitivity analysis of an economic allocation. Some of the water footprint is allocated onto the byproducts. As the allocation percentage is applied to the entire case study, the result is a direct decrease of 7.9%.

The case study is not detailed enough to allow for an allocation in each individual process step, and therefore some of the water from processes which takes place only for the benefit of the wheat flour is still allocated onto the byproducts. The effects of this are negligible however, as the process component only makes up 0.01% of the total water footprint. The decrease of the water footprint due to the application of an economic allocation amount to 7.9%, decreasing the total water footprint, down to about 12 800 000 m^3.

The initial mass allocation means that 8.9% of the total hygiene water and energy used at the mill is connected to the production of wheat flour. This assumption is evaluated in a sensitivity analysis where the entire energy and hygiene water use of the facility is put onto the wheat flour. This increases the total water footprint by 8.14% and direct water use is increased to 0.03% while the energy component is 8.25% of the total. These results are presented graphically in Figure 27 below.

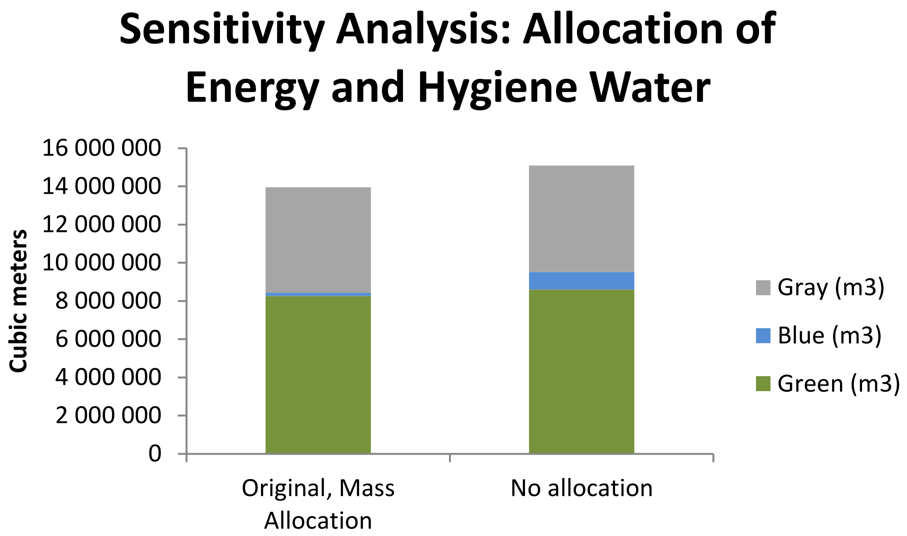

Figure 27: Result of a sensitivity analysis of the initial assumption that the direct water and energy use are directly related to the processed mass of wheat. Figure 24 refers to the allocation of supply chain water footprints to the byproducts, while this figure show the allocation of water use at the facility in Malmö.

The assumption that *all* energy and hygiene water use is related to the production of wheat flour is not likely to be very accurate nor does it significantly alter the result of the study.

4.4.3 Discussion

The results of the case study are similar to those of the supply chain study. The absolutely dominating component is the supply chain, the water footprint of which in turn is almost exclusively composed of the crop cultivation making up 98% of the total case study water footprint. This means that variations or uncertainties in other components than cultivation will have little or no effect on the overall result.

A consistency analysis shows that the result does not compare well to that of a report by the Water Footprint Network, but a number of differing method choices is likely to be behind this. Since the compared study is conducted worldwide, using data from international organizations it is deemed to have a lower accuracy than this study. The disparity between the two is surprising as the supply chain study, which makes up 99% of the result, compared better to another result using the same method. The largest difference lies within the gray water footprint, which might be due to a low level of detail in fertilizer application rates within the comparison study.

An economically based allocation of some of the water footprint onto the byproducts of the production process, leads to a slight decrease by about 8% of the total water footprint. The allocation is not done in depth on a process-specific scale, but on the entire system and should therefore be regarded as somewhat crude. It is deemed to be relatively accurate though, and indicated that the results are not significantly altered by an economic allocation.

The electricity and transportation components completely outweigh the direct process water use, which could shift the focus of a water footprint reduction from the facility itself to its support processes. The data on electricity and transportation is of poor quality however, and these implications need to be investigated further before any final conclusions can be drawn.

4.4.4 Improvement Analysis

The case study of wheat flour at the mill in Malmö could be improved significantly if it was made for the facility as a whole, including all raw materials, products and byproducts. An evaluation of the hotspots and water use inefficiencies at the mill could then be possible. It is however the cultivation component which is the absolutely most dominant one and instead of making more detailed footprints of the mill, more resources could be put into better defining the cultivation component, and the supply chain system to better understand the key component.

4.5 Conclusions

The level of detail in case study A is, as previously mentioned, quite low. This means that conclusions drawn from the study should be considered preliminary at best and any process-specific analysis should not be conducted based on the outcome of this case study. The geographic extent is even more synoptic, and should only be used as an idea of what the water footprint could look like, until further details are available, and a better map can be produced.

It is interesting however, to be able to show the water footprint of the entire value chain of a finished consumer product such as wheat flour. Even if the results of this study are not detailed enough to allow any statements from Lantmännen, the case study clearly shows that the cultivation component, similar to the supply chain system, is by far the most dominating. The results are also reasonably resilient as sensitivity analysis have shown, and are not altered more than about 10% unless concepts such as net green water are applied.

From this it is concluded that for any future studies, even more emphasis should be placed on the cultivation of crops, and to create a detailed sustainability assessment to be able to compare the water footprint of Lantmännens flour to that of other similar products.

5 Case B: Lantmännen Agroetanol Norrköping – Bioethanol

Lantmännen Agroetanol is the only large-scale manufacturer and supplier of grain based fuel ethanol in Sweden. The customers are the large oil companies who mix ethanol into the 95-octane gasoline. In addition to the approximately 210 million liters of ethanol, Agroetanol also produce about 175 000 tons of protein rich animal fodder (Westerberg, 2012). This case study focuses on the production of fuel ethanol from winter wheat grain because winter wheat constitutes between 60-80% of the raw material for the process.

5.1 Goal, Scope and Purpose Definitions

The goal of this case study is to calculate the water footprint associated with the production of bioethanol at Lantmännens facility in Norrköping. The water footprint will be presented together with the results from the supply chain study to allow a comparison between the water footprints of the different steps within the value chain of winter wheat and ethanol, to give Lantmännen an overview of the total water footprint of the ethanol from their plant.

5.1.1 Scope Definition

This case study is limited to the production of bioethanol from winter wheat, at Lantmännens facility in Norrköping. The byproduct DDGS from this process will also be included as some of the water use will be allocated to it in line with the EU Renewable Energy Directive, the EU Fuel Quality Directive and the Swedish Hållbarhetsdirektivet (roughly: Sustainability Directive) .

The temporal scope is limited to the year 2011, as the data on water use at the facility is readily available for this year, from a detailed water use calculation at the facility.

5.1.2 Functional Unit

The functional unit in the case study is *1 m^3 of liquid fuel ethanol at the factory gate in Norrköping*.

5.1.3 System Boundaries

The case study is conducted on a gate-gate basis, but includes the supply chain water footprint as a parameter, and therefore the result is a cradle-to gate analysis.

5.1.4 System Description

The production system consists of two components, transportation and processing. The production of fuel and electricity are support components to the case system in the same way as in the supply chain system, and are therefore not treated in detail here. A simplified overview of how the system is defined is presented in Figure 28 below.

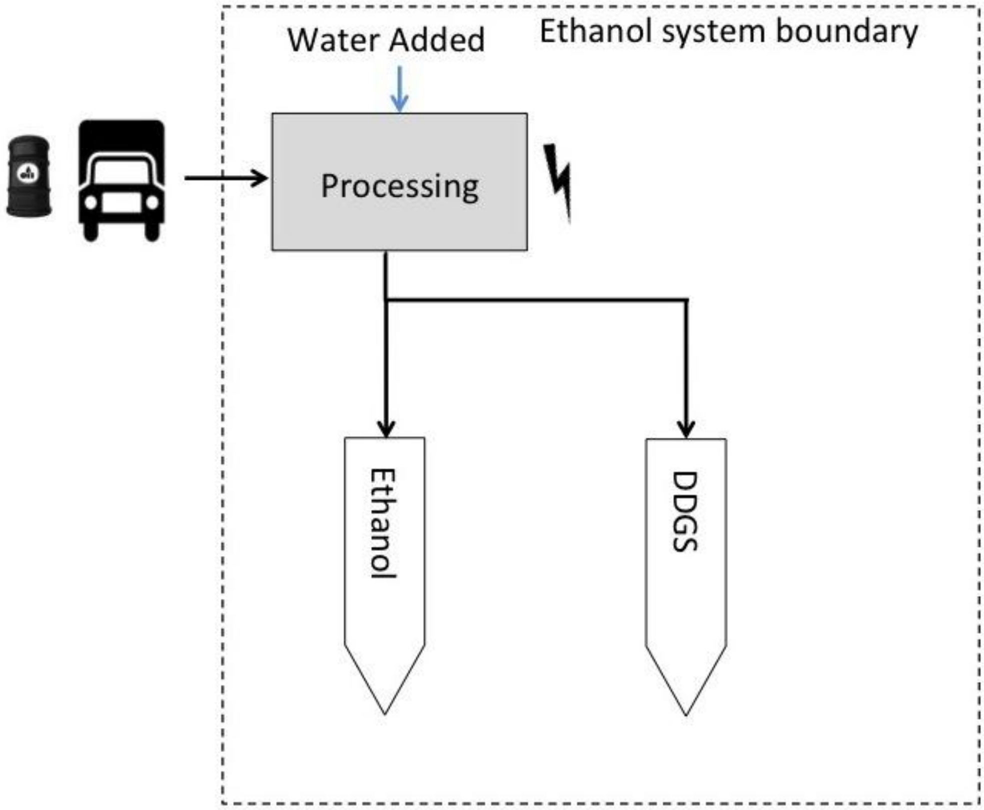

Figure 28: A simplified description of the ethanol production system. The two products DDGS and Ethanol share the water footprint based on an energy allocation.

5.1.4.1 Transportation

The transportation component consists of a single transport stretch, from each storage facility to the ethanol plant in Norrköping. In the same way as in the supply chain system the water footprint associated with transportation originates from the production as well as the composition of the fuel used.

5.1.4.2 Processing

The processing component includes a number of processes, from when the wheat raw material reaches the factory, to the finished ethanol. The details of the production are not described in depth, instead the facility is seen as a black box, where the total inputs and outputs are considered, but the sub-processes are not.

5.1.5 Cut off criteria

Like the supply chain system, no explicit definition of cut off criteria is applied to the case study systems, but processes that contribute with less than 0.1% to the total water footprint, are deemed to be insignificant. They are however still presented for the sake of interest.

5.1.6 Allocation

The Agroetanol plant processes about 550 000 tons of grains annually, out of which winter wheat make up about 70% by mass. The water and energy use are available as annual totals for the entire facility and therefore an allocation of the water footprints are necessary. The basis of this allocation is mass, and 70% of the facility water and energy is allocated to the winter wheat used in the production (Westerberg, 2012). It is assumed that the energy and process water use are relatively homogenous for all the products, so that the mass based allocation is valid for the wheat flour.

There is also an allocation of the ethanol water footprint to the byproduct DDGS (Dried Distillers Grains with Solubles) on an energy basis, where the distribution is 60.2% on the ethanol and 39.8% on the DDGS per GJ. Due to the lack of detail in the case study, this allocation is on a facility-wide scale, and processes that are not the same for both products may not be properly represented. The allocation should be regarded as somewhat crude, and the impact of it is evaluated and discussed in a sensitivity analysis in the discussion and analysis section.

5.1.7 Data Quality

The data quality requirements are the same as in the supply chain system, and follow the classification described in section 3.1.6 and Table 2. The data required for the calculations in this case study is described and classified in Table 22 below. Data for the supply chain system is not described here, but can be found in Table 3.

Table 22: Data sources and quality ratings for data in the ethanol case study. Data for the energy use, allocation data and production data originate from the environmental report from the facility in Norrköping, from production software and from correspondence with Noak Westerberg, environmental administrator at Agroetanol, quoted as Westerberg, 2012.

% of Result	Category	Component	Source	Data Quality
0.25%	Transport	Distances	GIS and Google Maps	D4-
		Fuel composition	(Energimyndigheten, 2011b)	B3
		Water footprint, Biodiesel (L/ton-km)	(Hoekstra & Gerbens-Leenes, 2010)	C4
		Water footprint, Fossil diesel (L/ton-km)	(Gleick, 1994)	C4-
		Filling degree	Estimation	D4-
4.85%	Electricity and energy	Swedish average electricity composition (Svensk medelel)	(Energimyndigheten, 2011b)	B3
		Water footprint of primary energy carriers	(Gerbens-Leenes et al., 2009)	C4-
		Energy Use	(Westerberg, 2012)	A1
		Steam production from electricity generation	(Westerberg, 2012)	C1
0.09%	Processing	Total mass of winter wheat used annually	(Westerberg, 2012)	A1
		Wheat-to-Ethanol conversion	(Westerberg, 2012)	A1
		Annual DDGS and Ethanol Output	(Westerberg, 2012)	A1
N/A	Allocation methods	Economic allocation, ethanol and DDGS	(Westerberg, 2012)	A1
		Energy allocation	(Westerberg, 2012)	A1

5.2 Inventory

The calculation methods and assumptions necessary for each component of the water footprint are described in detail in this section. Any processes shared with the supply chain system are referred back to the relevant section there.

5.2.1 Transportation

The transportation distance from the storage facility to the factory in Norrköping is assumed to be 100 km as stated in Table 10 in the supply chain section. The effects of this assumption are assessed in the sensitivity analysis of this case study. The mass of winter wheat transported to the processing plant is about 351 100 tons annually. This gives a total annual transportation water footprint of 323 600 m^3 green, 378 000 m^3 blue and 114 000 m^3 gray water when the filling degree is 80% using the same calculation method as in the supply chain study.

5.2.1.1 Relating data to functional unit

The production of 1 m^3 of liquid fuel ethanol requires about 2.67 tons of wheat, calculated using a conversion rate of 37.4%. This gives a transport water footprint of 1.48 m^3 green, 1.73 m^3 blue and 0.52 m^3 of gray water per m^3 of ethanol.

5.2.2 Processing

The annual water use was reported to be 397 615m^3 in 2011. This water is taken from the municipal drinking water system, and is assumed to be purely blue water. Out of this about 167 550 m^3 is allocated to the processing of winter wheat. The wastewater from the ethanol plant is released to the treatment plant at Slottshagen and does not contribute to polluting any fresh water source. Therefore, the plant has no gray water footprint.

5.2.2.1 Relating data to functional unit

The process water footprint is related to the functional unit by dividing the annual water use related to winter wheat with the annual production. Out of the total production of 187 854 m^3 of ethanol in 2011, 131 498 m^3 is attributed to the winter wheat as a raw material, again assuming 70% of the input is winter wheat. This gives a processing water footprint of 1.27 m^3 of blue water per m^3 of ethanol.

5.2.3 Supply Chain

The total annual use of grains for input to the production was 505 905 tons, out of which 70% or 354 134 tons were assumed to be pure Swedish winter wheat. Using the average water footprint of the supply chain system for winter wheat as described in the main body of this report, the total annual supply chain water footprint is about 109 000 000 m^3 green 1 020 000 m^3 blue and 73 500 000 m^3 of gray water.

5.2.3.1 Relating data to functional unit

The total production of 131 498 m^3 ethanol gives a water footprint of 834 m^3 green 7.8 m^3 blue and 559 m^3 of gray water per m^3 of ethanol.

5.2.4 Energy use

The ethanol plant in Norrköping use energy in three forms, steam produced from bioenergy at the E.on facility next door at 423 445 MWh annually, electricity assumed to be of average Swedish composition at 59 792 MWh annually and Gasol, assumed to be similar to natural gas as far as water footprints are concerned, at 6 993 MWh annually. The steam is a byproduct of electricity generation at the E.on facility and it is assumed that for each MWh of electricity 10 MWh of steam is produced, meaning that the water footprint of steam production is one tenth that of electricity from the same energy carrier. The water footprints resulting from the combination of these values with the water footprint of primary energy carriers from Table 5, are presented below in Table 23.

Table 23: The total and per m³ water footprint of the energy use at the ethanol plant.

	Green (m^3)	Blue (m^3)	Gray (m^3)
Electricity	1 097 780	2 464 630	144 220
Steam	2 195 140	8 643 360	1 082 330
Gasol/Natural gas	0	2 520	0
Facility total	3 292 920	11 110 500	1 226 540
Per m^3 EtOH	25.0	84.5	9.3

5.2.4.1 Relating data to functional unit

The water footprint per functional unit is presented in Table 23 and is the result of distributing the total water footprint over the produced volumes of ethanol.

5.3 Results

The results of the ethanol case study are presented below in Table 24 and Figure 29-Figure 31. The production of steam makes up about 76% of the total energy water footprint, rendering it the second largest after the supply chain component.

Table 24: Results of the ethanol case study. An energy allocation is used in the base case presented here.

	Green (m^3)	Blue (m^3)	Gray (m^3)	Total m^3	Percent of Total Water Footprint
Process Water	0	167 550	0	167 550	0.09%
Energy Use	1 982 340	6 688 520	738 380	9 409 240	4.85%
Supply chain	109 602 690	1 020 420	73 455 710	184 078 820	94.81%
Transport	194 190	227 740	68 430	490 360	0.25%
Total	**111 779 210**	**8 104 240**	**74 262 520**	**194 145 970**	**-**
Per m^3 ethanol	**850**	**62**	**565**	**1477**	**-**

The results in Table 24 are shown graphically in Figure 29-Figure 31 below.

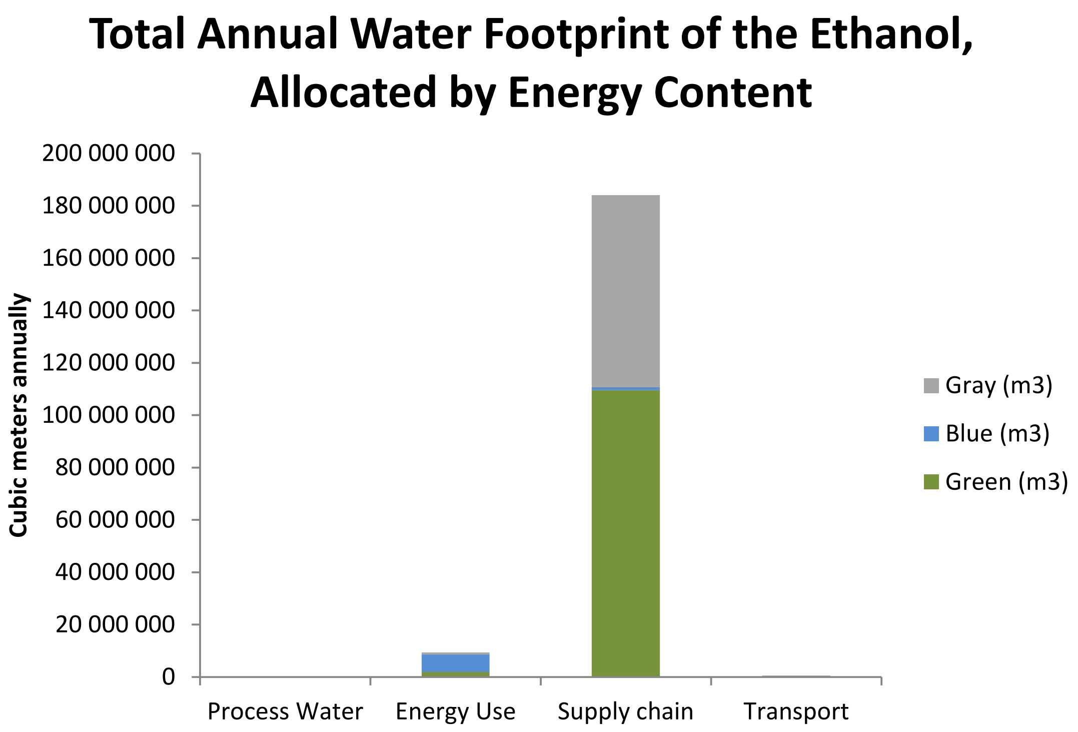

Figure 29: The total annual water footprint for winter wheat based ethanol from the facility in Norrköping. The allocation of 60.2% to the ethanol is applied to the facility as a whole.

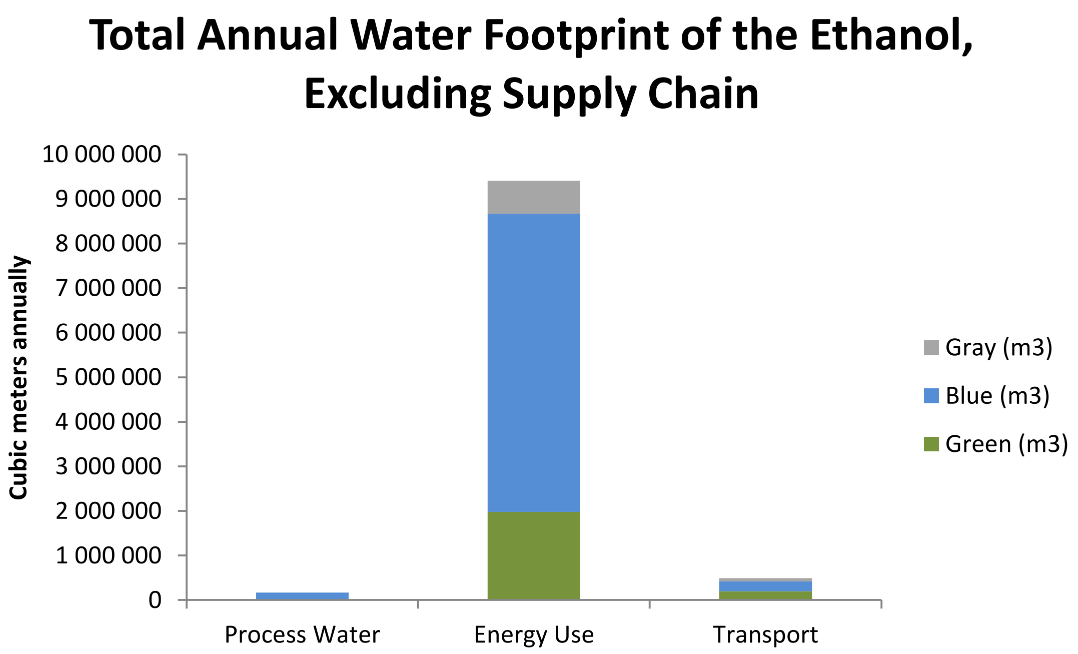

Figure 30: The total annual water footprint of the winter wheat based ethanol produced at the Agroetanol facility. The supply chain component is suppressed to show the composition of the remaining components.

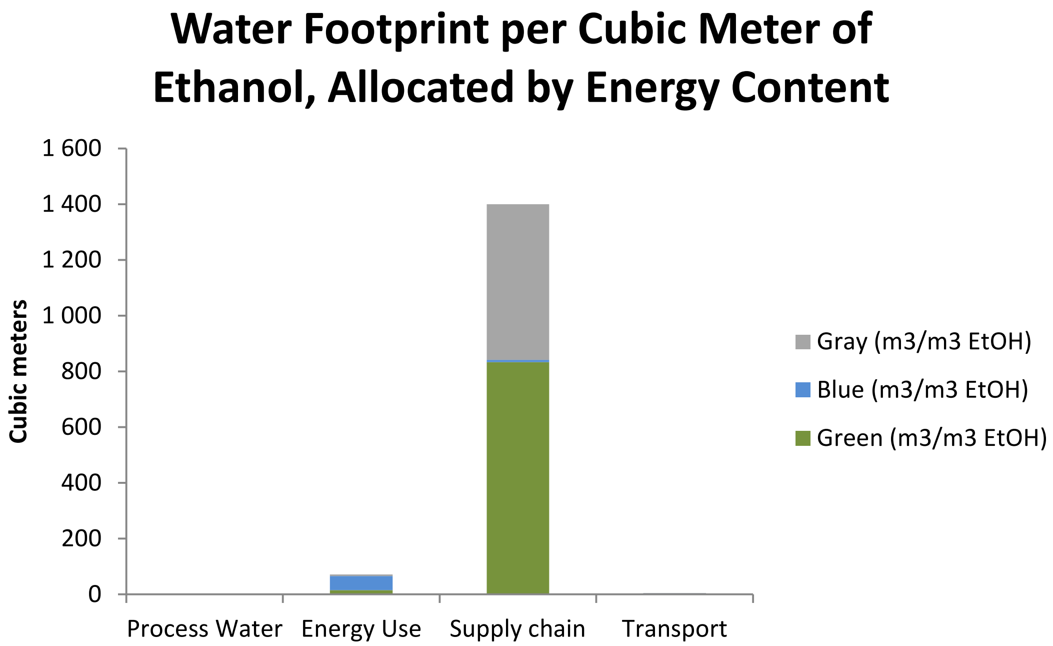

Figure 31: The per-unit water footprint of ethanol from the Agroetanol facility in Norrköping. The energy allocation is applied to the facility as a whole.

5.3.1 Geographic distributions

A representation of what the geographic distribution of the water footprint of the ethanol could look like is shown in Figure 32. The image is created using a number of assumptions, similar to those made in case A and C:

- The wheat is sourced from the areas closest to the facility in Norrköping, marked on the map
- Lantmännen´s overall share of the Swedish wheat is applied on a field level, allocating 40% of the total produced amount on each field to the facility, spreading as far from the facility as necessary to attain the required amount wheat
- The non-cultivation components of the production system are allocated the drainage basins in which the process takes place i.e. energy and transportation water footprints are allocated to the drainage basin in which the Agroetanol plant is located

The map in Figure 32 is a representation of what the water footprint distribution *could* be, and should not be interpreted as the actual water footprint distribution.

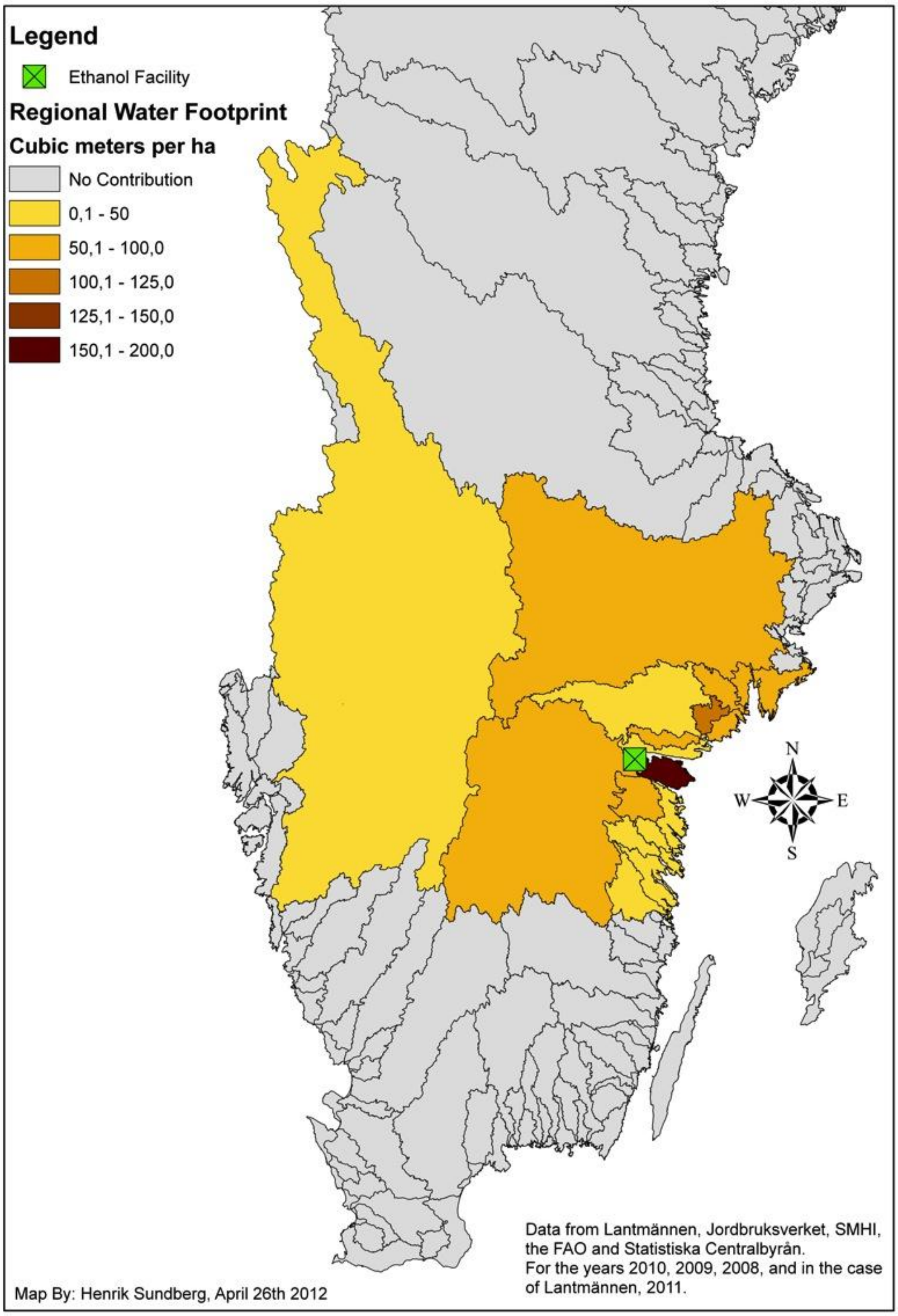

Figure 32: A graphic representation of what the geographic distribution of the water footprint associated with the production of ethanol at the Agroetanol facility in Norrköping could look like. The total water footprints are normalized by area and show data from 2011 for the facility and average data from 2008-2010 for the cultivation and supply chain.

The wheat cultivation is assumed to take place close to Norrköping and therefore the majority of the water footprint is located in the river basins around the facility. The water footprints from transport, energy use and direct process and hygiene water use at Agroetanol are assumed to be located in the drainage basin in which that facility stands, giving it the largest total water footprint per ha.

5.4 Discussion and Analysis

5.4.1 Consistency Check

To verify the results of this case study, it is compared to a study by the water footprint network titled: *The green, blue and grey water footprint of crops and derived crop products* (Mekkonen & Hoekstra, 2010b). The same report is used to compare the water footprints of case study A and C as well as the supply chain study. The differences in the results are shown graphically in Figure 33 below.

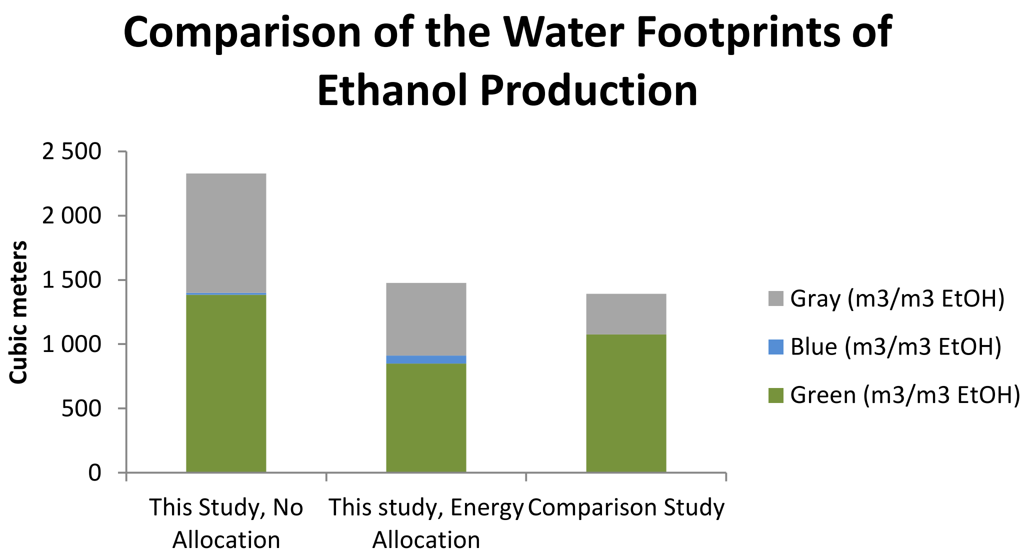

Figure 33: The water footprints of ethanol derived from wheat from this study and from Mekkonen & Hoekstra (2010b). The energy allocated result is shown as a reference, the comparison study is not energy allocated.

The comparison study results in a water footprint about 60% of the footprints in this study. Just like in Case study A, the water footprints of both Mekkonen & Hoekstra and this study consist almost exclusively of the cultivation component. The largest difference is within the gray water footprint, where the comparison study uses international data, while this study use county- and crop-specific fertilizer application rates. The details in the disparities between the studies are discussed at length in case A and in the supply chain study.

5.4.2 Sensitivity Analysis

5.4.2.1 Allocation Principles

The effects of the energy allocation applied in the main part of the ethanol case study are evaluated in this sensitivity analysis. The energy allocation principle suggest that 60.2% of the total water footprint is allocated to the ethanol production, while an economic allocation would place 77% on the ethanol, and no allocation would of course place 100% of the water footprint on the ethanol. The differences are shown in Figure 34 below.

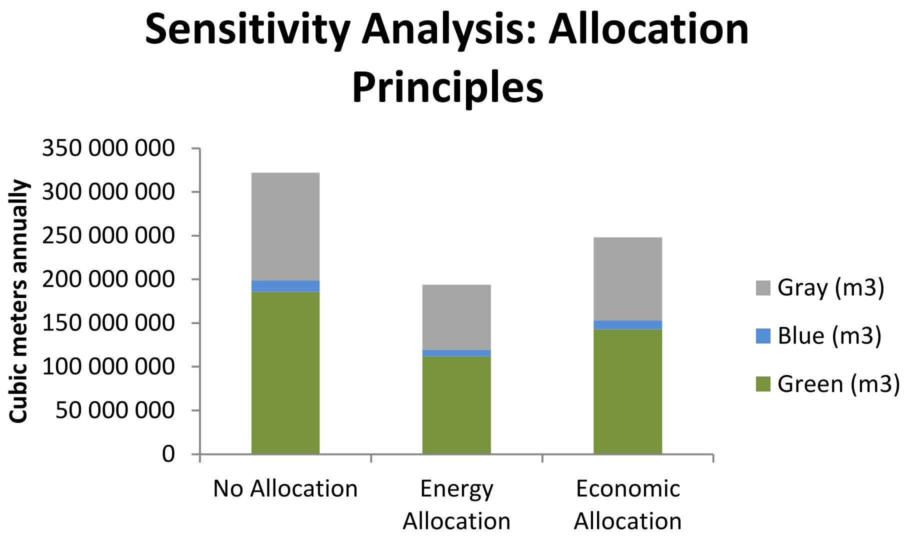

Figure 34: Result of sensitivity analysis of different allocation principles.

As previously mentioned, the allocation is applied to the facility as a whole, meaning that the entire water footprint is divided between DDGS and ethanol. This suggests that the difference in the three cases will be proportional to the allocation percentage. No allocation gives a 66% increase and economic allocation gives a 30% increase as compared to the initial energy allocation. The decision to use an energy-based allocation in this case study originates from the established practice to do so in life cycle analyses of ethanol, and from directives by the EU and Sweden as previously mentioned.

5.4.3 Discussion

The result of this case study is similar to that of case study A and the supply chain study: the cultivation is the absolutely most dominating component, making up about 94% of the entire ethanol water footprint. The result differs from the other studies however, in that the energy component takes a more significant role, due to the steam used in the ethanol factory. It is produced as a byproduct of bioelectricity generation and the water footprint of the bioenergy is significantly higher than that of fossil or hydro-based energy carriers, because of the cultivation of the fuel crop used in the bioenergy plant. This study does not further investigate the energy carriers used at the E.on facility providing the steam, and the fuel is assumed to be of the same composition as the biofuel in the electricity generation of the supply chain study, see section 3.2.2 and Table 5 for further details. This means that the water footprint of the bio-generated steam is quite uncertain and should be regarded as an indication of what the water footprint could look like, and not the absolute value of it.

It is interesting to observe that the process water, although apparently large in volume, is far outweighed by energy and transportation water footprints, and the direct water use at the facility might be a marginal contribution to the total. This implication need to be verified however, as data quality is low in regards to both transport and energy water footprints.

In much the same way as in case A, the result does not compare well to the water footprint network study. The probable reasons for this are discussed at length in case A and the supply chain study, and are not further elaborated on here.

The choice of applying the energy allocation in the main study, has a significant impact on the final result decreasing the water footprint from more than 2 360 m^3 to almost 1

480 m^3 of water per m^3 of ethanol. The decision was based on established LCA practices according to Swedish and EU directives, and 1 480 m^3 should be regarded as the final result.

5.4.4 Improvement Analysis

The 94% of the water footprint attributed to the cultivation of the winter wheat used in the ethanol plant, clearly signals that this is the area within which the analysis should be improved. Much like in the supply chain system and case A, efforts should be concentrated on improving the understanding of the cultivation system. By including the entire facility on a detailed scale, the water use both for individual processes but also for other crops could be separated, improving the quality of the case study water footprint.

The energy component contributes almost 5% of the total water footprint due to the cultivation of crops for the biofuel used in the production of the steam used. The data quality within this component is low, and by specifying the energy carriers a more detailed and accurate water footprint of the steam production could be calculated. It is also worth mentioning that some of the steam is used in the drying of the DDGS, which means that it would not be allocated to the ethanol production at all. This indicates that further refinement of the energy use on a process specific level could directly decrease the total water footprint of the ethanol.

5.5 Conclusions

Just as in case A the level of detail is quite low. This means that conclusions drawn from the study should be considered preliminary at best and any process-specific analysis should not be conducted based on the outcome of this case study. The geographic extent is based entirely on assumptions and should not be viewed as more than an overview of what the water footprint distribution could look like.

The water footprint of biofuels is a hot topic, and calculation methods as well as allocation principles are debated. It is therefore interesting to be able to calculate the water footprint of the whole value chain of liquid fuel ethanol. Even if the results of this study are not detailed enough to allow any statements from Lantmännen, it clearly shows that the cultivation component, similar to the supply chain system, is by far the most dominating. It also shows that the choice of allocation method makes a significant difference for the result.

From the results and discussions of this study it can be concluded that the details of the supply chain, especially the cultivation component, should be further refined in order to increase the robustness of the result. Creating a basis for a sustainability assessment should also be a priority, so that the ethanol produced in Norrköping can be compared to ethanol produced elsewhere and from other crops.

6 Case C: Lantmännen Ceralia, Järna - Gammaldags Idealmakaroner

The Kungsörnen facility in Järna is a part of Lantmännen Ceralia, which develop, produce and market primarily grain based products under well known brands such as AXA, Kungsörnen, Start, Gyllenhammars, Gooh, GoGreen, Sopps, Amo, Kornkammeret and Regal. The Ceralia factory in Järna produces a variety of products, one of which is pasta of the Kungsörnen brand. (Lantmännen, 2012) This case study focuses on a specific variety of Kungsörnen pasta called *Gammaldags Idealmakaroner*, roughly translated old-fashioned ideal macaroni.

6.1 Goal, Scope and Purpose Definitions

The goal of this case study is to assess the water footprint associated with the production of *Gammaldags Idealmakaroner* at Lantmännens facility in Järna. The water footprint of the processing and transportation involved will be presented together with the results from the supply chain study to produce a water footprint of the entire value chain. The purpose is to allow a comparison between the water footprints of the different steps within the value chain of winter wheat and macaroni and to give Lantmännen an overview of the total water footprint of the macaroni from their plant.

6.1.1 Scope Definition

The case study is limited to the production of the specific type of macaroni described above. The decision was based on the fact that the composition of the flour used in the production is purely winter wheat. A number of other products are made from the same raw material blended with other flours at the facility in Järna, but these are not included in the study. The temporal scope is limited to the year 2010 due to limited data availability for the other years.

6.1.2 Functional Unit

The functional unit in the case study is *1 kg of Kungsörnen Gammaldags Idealmakaroner at the factory gate in Järna.*

6.1.3 System Boundaries

The case study is conducted on a gate-to-gate basis, but includes the supply chain water footprint as a parameter, and therefore the result is a cradle-to-gate analysis.

6.1.4 System Description

The production of macaroni at Järna can be divided into four components: transportation from storage to the Malmö mill, processing at the mill in Malmö, transportation from Malmö to Järna, and finally processing at Järna. Figure 35 is a simplified overview of these components, which are described in detail in the sections below. The production of fuel and electricity are support components and described in the supply chain system and will not be further defined here. The direct conversion rate from wheat to macaroni is 70.8% derived from a facility-total at Järna of 92.2%, and the conversion of wheat into D0 flour in Malmö at 76.7%. The wheat to D0 conversion rate is assumed to be the same as for wheat to wheat flour in case A and the facility wide estimate for Järna is necessary, as the per-product conversion is not readily available.

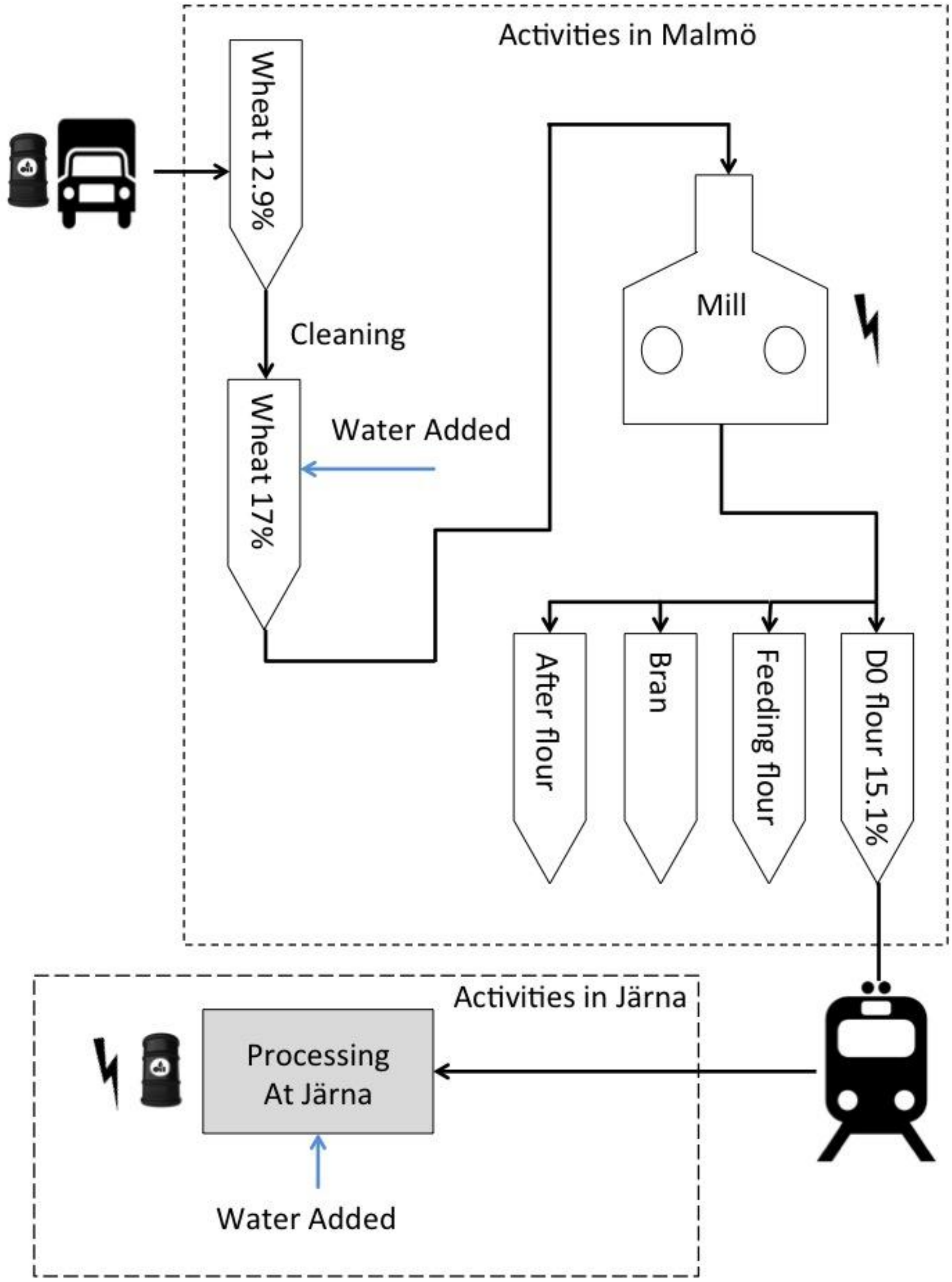

Figure 35: A simplified overview of the components of the system. The wheat is transported from storage to the production at the mill in Malmö; the milled D0 flour is then transported by train to Järna, where it is processed into macaroni.

6.1.4.1 Transportation: Storage to Malmö Mill

The transportation component consists of a single transport stretch, from each storage facility to the mill in Malmö. Just like in the supply chain system, the water footprint associated with transportation originates from the production of the fuel used, as well as the composition of it.

6.1.4.2 Processing: Malmö

The Malmö processing component includes a number of processes, from when the wheat raw material reaches the mill, to the finished D0 flour product. The water footprint related to processing is mainly found in the use of electricity and natural gas, but also in the water added during the process, in the same way as for the wheat flour in case A. Any wastewater from the facility in Malmö is, again just as in case A, returned to a water treatment facility which means that the mill has no gray water footprint associated with process or hygiene water.

6.1.4.3 Transport: Malmö to Järna

The D0 flour is transported by train from Malmö to Järna, and the water footprint associated with this comes from the production of the electricity required to propel the train.

6.1.4.4 Processing: Järna

When the D0 flour arrives at Järna it is processed into macaroni. The water footprint associated with this component is from the use of process water, electricity, oil and the hygiene water at the plant. The wastewater from Järna is treated in a wastewater treatment plant before it is returned to a natural system, which means that there is no gray water footprint from the plant.

6.1.5 Cut off criteria

Like the supply chain system, no explicit definition of cut off criteria is applied to the case study systems, but that contributes to less than 0.1% to the total water footprint, are deemed to be insignificant. They are however still presented for the sake of interest.

6.1.6 Allocation

The data on water use for the Järna facility is not divided into process and hygiene water and an allocation of the volumes used in processing all the products at the Kungsörnen plant is necessary to get a realistic water footprint. The same reasoning is valid for the use of electricity and oil, and the same allocation principles is used. The allocation is based on the mass of finished products, out of which the specified type of macaroni make up 18.4%. There is a similar mass allocation of the hygiene water use at the Malmö facility: The wheat processed to make the required D0 flour for the production of macaroni is 3.4% of the total in Malmö.

6.1.7 Data Quality

The data quality requirements are the same as in the supply chain system, and follow the classification described in section 3.1.6 and Table 2. The data required for the calculations in this case study is described and classified in Table 25 below. Data for the supply chain system is not described here, but can be found in Table 3.

Table 25: Data sources and quality ratings, the data used in case C is classified below.

% of Result	Category	Component	Source	Data Quality
0.57%	**Transport**	Distances	GIS and Google Maps	D4-
		Fuel composition	(Energimyndigheten, 2011b)	B3
		Water footprint, Biodiesel (L/ton-km)	(Hoekstra & Gerbens-Leenes, 2010)	C4
		Water footprint, Fossil diesel (L/ton-km)	(Gleick, 1994)	C4-
		Filling degree	Estimation	D4-
		Energy Requirement for train transport (GJ/ton-km)	(Hoekstra & Gerbens-Leenes, 2010)	C4
4.57%	**Electricity and energy**	Swedish average electricity composition (Svensk medelel)	(Energimyndigheten, 2011b)	B3
		Water footprint of primary energy carriers	(Gerbens-Leenes et al., 2009)	C4-
		Energy Use	(Björkman, 2012)	A1
0.01%	**Processing in Malmö**	Total mass of winter wheat used in D0 production	(Johansson, 2012)	A1
		Wheat-to-D0 flour conversion	(Koch, 2012)	A1
		Water use and water content	(Koch, 2012), (Lantmännen Ceralia, 2011)	A1
0.08%	**Processing at Järna - Kungsörnen**	Total mass of winter wheat used annually	(Johansson, 2012)	A1
		D0 Wheat-to-pasta conversion	(Johansson, 2012)	A1
		Annual product output	(Johansson, 2012)	A1
		Total Water Use	(Björkman, 2012)	A1
		Conversion rate D0 flour to macaroni	(Johansson, 2012) (Björkman, 2012)	A1

6.2 Inventory

The calculation methods and assumptions necessary for each component of the water footprints are described in detail in this section. Any processes shared with the supply chain system are referred back to the relevant section there.

6.2.1 Transportation: Storage to Malmö

The transportation distance from the storage facility to the Malmö mill is assumed to be 100 km as stated in Table 10 in the supply chain section. The mass of 14% wheat that is transported to the Malmö mill is 5 946 tons annually, which gives a total annual transportation water footprint of 5 460 m^3 green, 6 410 m^3 blue and 1 930 m^3 gray water when the filling degree is 80%.

6.2.1.1 Relating data to functional unit

The production of 1 kg of macaroni requires 1.41 kg of wheat, calculated using a total conversion rate of 70.8% derived from the combination of the conversion at the mill in Malmö and the D0 flour to macaroni conversion in Järna. This gives a total transport water footprint of 2.54 L green, 4.32 L blue and 0.62 L of gray water per kg of macaroni.

6.2.2 Processing: Malmö

The water used for processing is calculated the same way as for the wheat flour in case A. The water content of the outgoing D0 flour is higher however, giving a slightly altered calculation procedure. In Table 26 below, the calculations can be followed in detail and the water footprint is calculated from this.

Table 26: The masses and water contents in the different process steps at the mill in Malmö. In step three 22% of the mass is removed as byproducts of the process, but no water footprint is allocated to these. The total water use of the process can be found by subtracting the input water (161.7 kg) from the total after adding water (222.9 kg).

	Water content	Dry mass (kg)	Total mass (kg)	Total water (kg)
Winter Wheat	12.9%	1088.5	1250.1	161.7
Added water	17.0%	1088.5	1311.4	222.9
Biproducts, 22% of mass	17.0%	849.0	1022.9	173.9
D0 flour	15.1%	849.0	1000.0	151.0

The values in Table 26 give a total processing water footprint of 455 m^3 blue water annually. In addition to this 3.4% of the total hygiene water is allocated to the macaroni, at an annual total of 106.8 m^3 blue hygiene water.

6.2.2.1 Relating data to functional unit

The process water footprint is related to the functional unit by dividing the annual total with the annual production, which gives a total processing water footprint of 0.000108 m^3 or about 0.11 L of blue water per kg of macaroni.

6.2.2.2 Data Validation

The annual processing water footprint of 455 m^3 represents about 5.2% of the Malmö mill total. Compared to the mass share of 3.4% of the annual grain used for the production of D0 flour. The wheat flour in case A had an almost exact match between the share of mass and the share of process water, and with a 0.2% higher water content of the D0 flour a deviation between mass share and process water share is expected.

6.2.3 Processing: Järna

After allocating 18.4% of the total water use at the Kungsörnen facility to the macaroni, the blue water footprint is 4527 m³. Any wastewater from either processing or hygiene use is sent to a wastewater treatment plant and therefore there is no gray water footprint from the facility. The water is assumed to return to the system at a point in time far enough from the time of extraction that it is considered not available, and therefore not credited back to the system.

6.2.3.1 Relating data to functional unit

Dividing the annual water use by the annual total production gives a water footprint of 0.0011 m³ or 1.1 L of blue water per kg of macaroni.

6.2.4 Energy use

After the 18.4% mass allocation, the facility in Järna uses about 11 977 GJ, of electricity and 811 GJ of oil for the production of the specified macaroni annually. Using the same method and values as in the supply chain system under heading 3.2.2, the water footprints related to electricity and oil use are calculated for Järna. In addition to this 2 484 GJ of electricity and 324 GJ of natural gas is used in Malmö for the processing of wheat into D0 flour. Table 27 shows the total water footprint of the energy use at both facilities.

Table 27: Total and per kg water footprint for the energy use in the Järna production system. The table includes the energy used both in Malmö and in Järna.

	Green (m³)	Blue (m³)	Gray (m³)
Electricity	73 800	166 000	9 690
Oil	0	892	730
Natural gas	0	32	0
Facility total	73 800	167 000	10 400
Per kg macaroni	0.0175	0.0396	0.00248

6.2.5 Supply Chain

The total input of 14% wheat for the 2010 production was 5 946 tons. Using the average water footprint of winter wheat in Sweden, the result from the supply chain study, the following annual total supply chain footprints are calculated to: 3 090 000 m³ of blue water, 41 000 m³ of blue water and 2 070 000 m³ of gray water.

6.2.5.1 Relating data to functional unit

The total 2010 production of macaroni was 4 208 280 kg, resulting in a water footprint of 735 L green 9.75 L blue and 492 L of gray water, at a total of 1 237 L per kg of macaroni.

6.3 Results

The total water footprints for the Järna facility and per kg of macaroni are presented in Table 28 below. The per-kg footprints are calculated using the total production of 4 208 280 kg in 2010. The results are shown graphically in Figure 36 - Figure 39.

Table 28: Results of the Järna case study, dominated by the supply chain component just as in the other case studies.

	Green (m^3)	Blue (m^3)	Gray (m^3)	Total (m^3)	Percentage of Water footprint
Process Water at Malmö	0	455	0	455	0.01%
Process Water at Järna	0	4 530	0	4 530	0.08%
Energy Use	73 750	166 510	10 420	250 680	4.57%
Supply Chain	3 091 960	41 040	2 069 050	5 202 050	94.77%
Transport	10 700	18 160	2 610	31 470	0.57%
Total	**3 176 410**	**230 690**	**2 082 080**	**5 489 180**	**-**
Per kg of Macaroni	**0.75**	**0.05**	**0.49**	**1.30**	**-**

The macaroni production in Järna is dominated by the supply chain component, like the other case studies. The wheat cultivation, which constitutes 99.14% of the supply chain study, thus makes up about 94% of the total water footprint of the macaroni. This domination and the composition of the other components are presented in the graphs below:

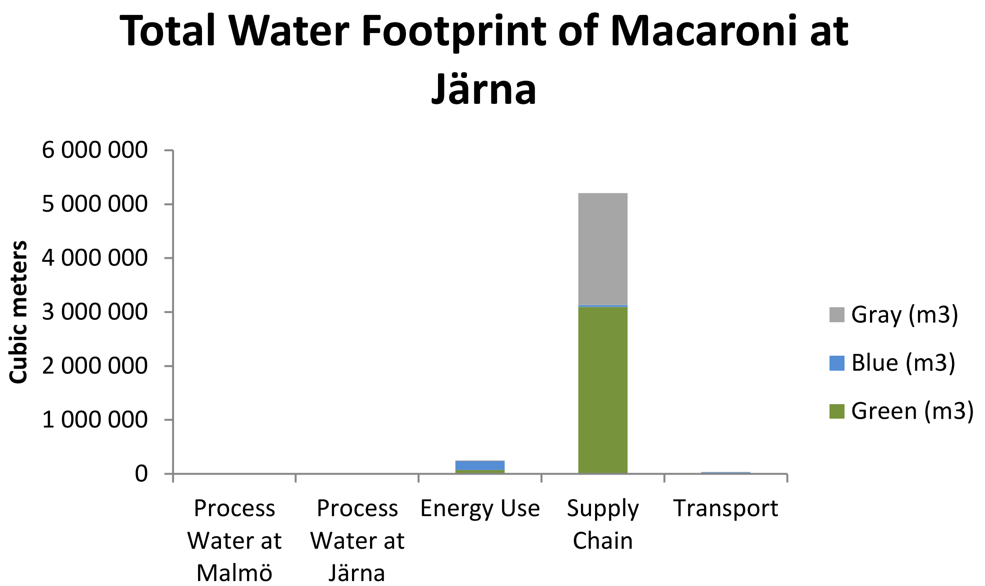

Figure 36: The water footprint of the annual production of macaroni at the facility in Järna, for the year 2010. The total produced volume was 4 208 280 kg of macaroni. The water footprint per kg of macaroni is shown in Figure 38 and Figure 39.

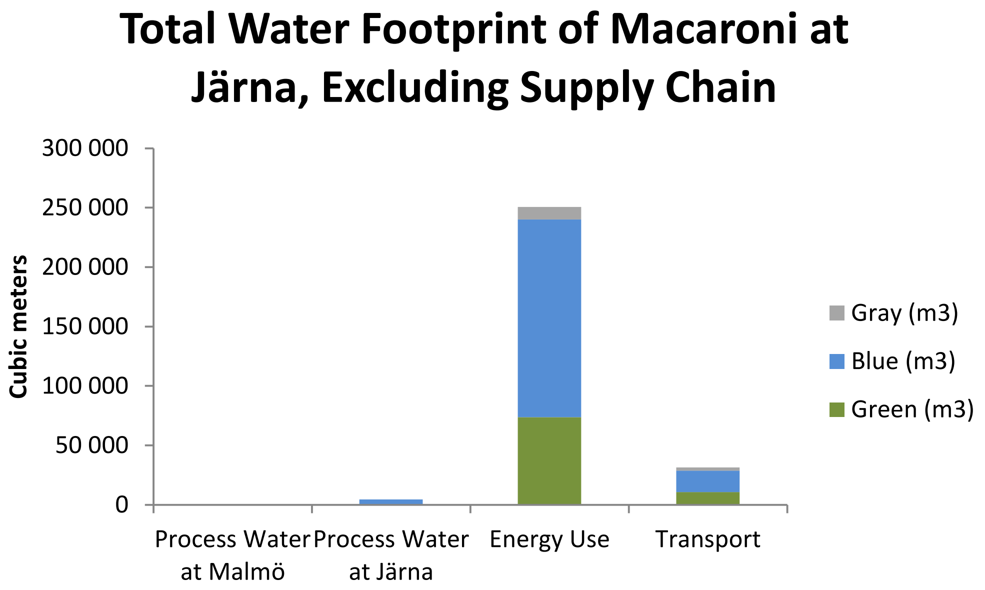

Figure 37: The water footprint of the annual production of macaroni at the plant in Järna, excluding the supply chain component, to allow the other components contributions to be viewed in detail.

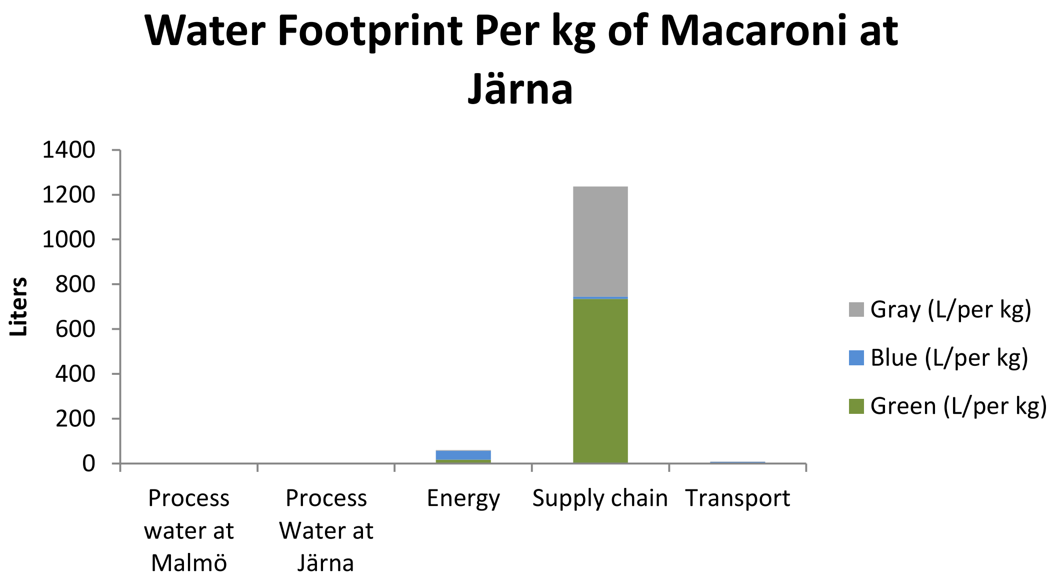

Figure 38: The average water footprint per kg of macaroni at Järna in 2010. The results from Table 28 are divided by the total production in 2010 to produce a detailed composition of the per-unit water footprint.

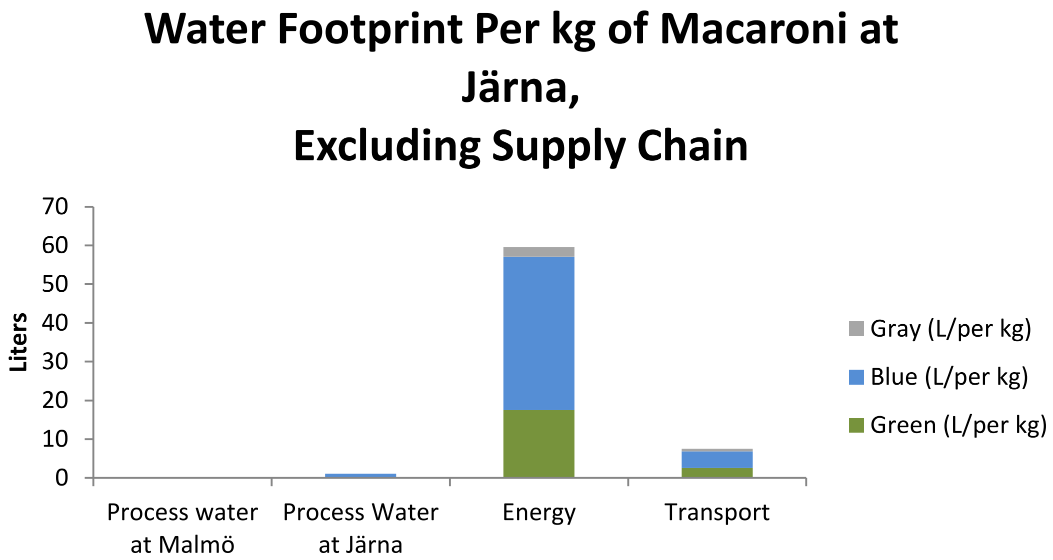

Figure 39: The average water footprint per kg of macaroni at Järna in 2010. The supply chain component has been omitted to allow the other components to be shown in detail.

6.3.1 Geographic distributions

A representation of what the geographic distribution of the water footprint of the macaroni could look like is presented in Figure 32. The image is created using a number of assumptions. These are:

- The wheat is sourced from the areas closest to the Malmö mill
- Lantmännens overall share of the Swedish winter wheat is applied on a field level, allocating 40% of the total produced amount on each field to the facility, spreading as far from the facility as necessary to attain the required amount of wheat
- The non-cultivation components of the production system are allocated the drainage basins in which the process takes place i.e. energy and transportation water footprints are allocated to the drainage basin in which the Järna or Malmö factories are located

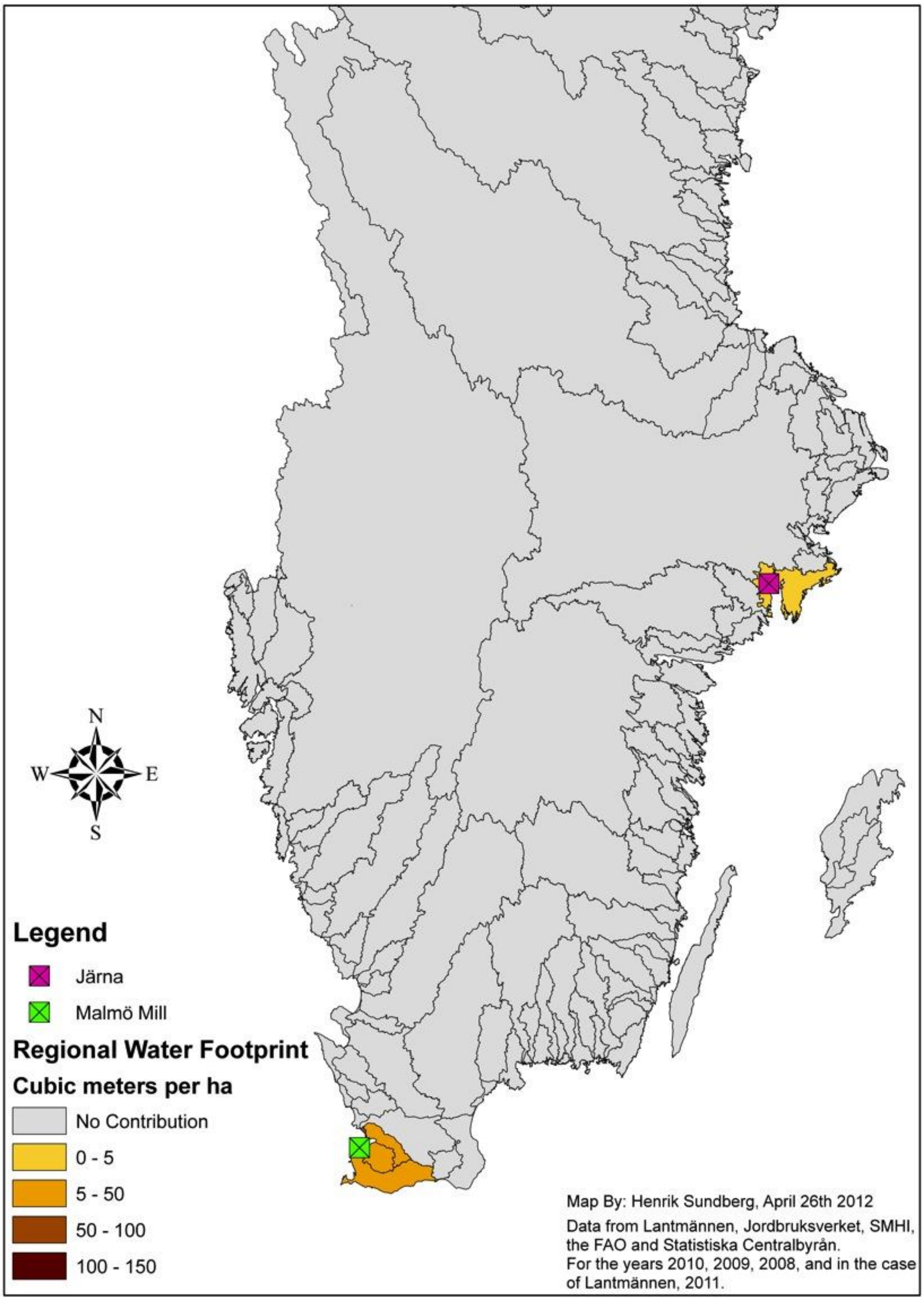

Figure 40: The geographic extent of the water footprint of macaroni from the factory in Järna. The map should be considered a representation of what the footprint could look like and not its actual distribution. The total water footprint within each basin is normalized by the area. Production data is for the year 2011.

The wheat cultivation is assumed to take place close to the Malmö mill and therefore the majority of the water footprint is located here. The water footprints of transport, energy and direct process plus hygiene water use at Järna are all located to the same drainage basin as Järna, giving that basin a relatively large water footprint even though none of the wheat used is cultivated there.

6.4 Discussion and Analysis

6.4.1 Consistency Check

The results of the Järna case study are compared to those of the study by the Water Footprint Network on crops and derived crop products used for comparison in the other case studies (Mekkonen & Hoekstra, 2010b). The results of both are presented in Figure 41. Similar to the outcome of the comparison in the other studies the compared water footprint is about half, (48%) that of the result of this study.

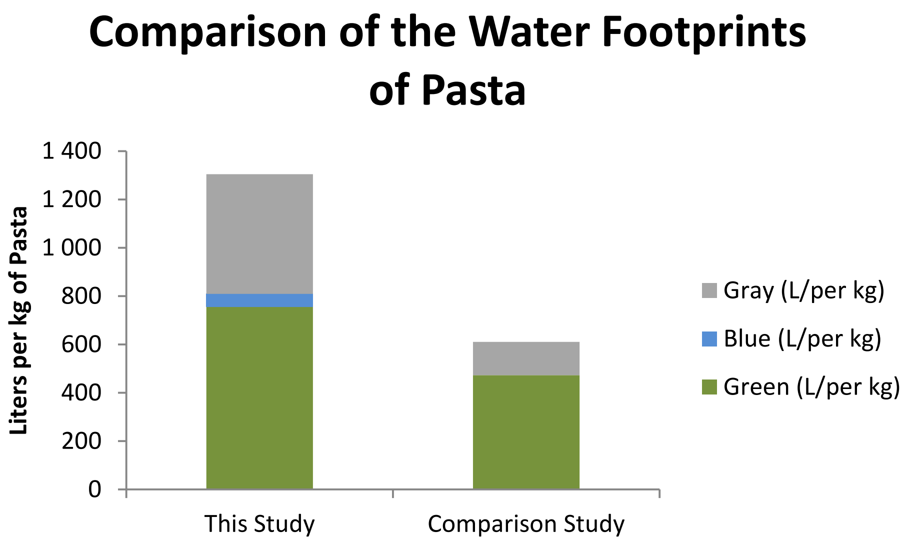

Figure 41: The water footprint of two production systems for pasta. In addition to this study, the results from the study used for comparison in the other case studies are included.

6.4.2 Discussion

The results of this study points in the same direction as the other case studies and the supply chain study. All are dominated by the cultivation component of the supply chain system. In this case it makes up about 94%, while the energy used both in Järna and Malmö constitute almost 5%, with transport and process and hygiene water combined comprising about 0.5%. Just as in the other cases this means that variation or uncertainties within other components than cultivation have little or no effect on the outcome.

As this case study resemble the others to a great degree, no sensitivity analyses have been made, instead it is assumed that the robustness of the Malmö case study and the supply chain study is valid in this case as well. No allocations were made, as the required economic data could not be easily obtained.

6.4.3 Improvement Analysis

Some key improvements to the Järna case study would be to make an analysis of the entire facility on a process-specific level, finding comparison studies with a more similar structure to validate the results and completing sensitivity analyses to evaluate the effects of assumptions, weak data and allocation principles. The result does however, just like in the other case studies and the supply chain system, point back to the cultivation component and the greatest improvement of the analysis would be achieved by focusing on this.

Completing a sustainability assessment would allow the result to be evaluated based on available water resources and to compare the sustainability of the water use to that of other similar products.

6.5 Conclusions

Just as in all of the case studies the level of detail is poor and the results of the study should be considered preliminary at best. The Järna case study is even less detailed than case A or B and the results should not be considered as anything but an overview of what the water footprint of macaroni from Järna potentially is. Again, just like in the other cases the geographic extent is even less detailed and based purely on assumptions. It should only be used as an image of what the geographic extent of the water footprint could be.

From the result of the Järna case study it can be concluded that the processes that take place at the factories in Järna and Malmö have a small impact on the water footprint compared to the cultivation of the winter wheat that is consumed. In future studies the emphasis should be on the cultivation of the winter wheat and further refinements of the water footprints involved in it.

7 Conclusions

The conclusions of the individual case studies and the supply chain are similar if not identical. This is mainly due to the fact that the cultivation component of the supply chain system dominates them all by contributing by between 99-94% of the total water footprint. It is therefore concluded that future projects should focus on refining the calculation methods and data for the cultivation component.

Another important finding is that the lack of a widely recognized method of weighing the water footprints renders the results difficult to interpret. The results of this study are valid only for the specified areas in which the cultivation occurs and the impact of the different water uses are not calculated. An example of how this affects the conclusions is that the roughly 200 000 m^3 of drinking water used at the ethanol factory in Norrköping annually is completely negligible when compared to the 112 000 000 m^3 green water used in the cultivation of the wheat raw material. These have vastly differing impacts however, and it would not be surprising if the green water had a lower total impact, even though it is almost 600 times the volume. Hopefully the impending ISO standard for water footprint analysis will include a impact assessment methodology which will be universally acceptable and allow the comparison of one water footprint to another, but until that is the case, the results of water footprint studies should be interpreted with great caution.

Generally speaking, the availability of water in Sweden is relatively good and the yield of wheat as well as the water footprint of it is comparatively low. Considering this it could be suspected that the overall sustainability of winter wheat cultivation in Sweden would compare well globally, from a water use perspective.

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