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Water Footprint Assessment of the Upper Litani Basin, Lebanon

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I. Summary

Water scarcity is a major global risk that is threatening food security of many countries in arid and semi-arid regions. To improve the performance on water use, the Food and Agriculture Organization (FAO) is working on a remote sensing tool (WaPOR) to monitor agricultural water productivity in three levels of continental, national and local scales. Part of the programme is to assess water productivity of selected irrigation schemes in Africa and Middle East. This study assessed the water productivity of major crops in the Upper Litani Basin (ULB) in Lebanon and will be modified and employed for the validation of Remote Sensing data in the WaPOR project.

The ULB is the main river basin in Lebanon and hosts half of the agricultural lands. Previous studies in the ULB reported significant increases in groundwater abstraction resulting in decreasing surface flows over the last 50 years. The water footprint (WF) concept was followed to execute a water footprint assessment (WFA) of all internal processes in the ULB. This WFA consists of four phases which are described below.

(1) Goal and scope: Goal: This study aims to assess the efficiency and sustainability of the green and blue water consumption in the ULB besides suggesting some adoptive scenarios and evaluating the improvements to formulate a water-sustainable scenario that achieve food security of the region.

Scope: The daily green and blue WF of human processes inside the ULB including households, industries, trees and major crops were accounted from 2011 to 2016. The blue water scarcity was assessed in a monthly basis by comparing total blue WF and sustainable water availability. Three scenarios were formulated to improve the situation, taking into consideration the Sustainable Development Goals of the UN.

(2) WF Accounting: The blue WF of crops was estimated using the AquaCrop-OS model which is able to simulate water use and yield of crops based on the environmental and management conditions. A list of 225 similar zones was derived from maps containing 10 major crop types, 4 soil types and 6 weather zones. Management settings in producing crops were based on literature and our own field surveys. The model was parameterized by adjusting sensitive parameters after comparing the simulated and observed yields. The blue WF of domestic, industries and trees were derived from previous studies.

(3) Sustainability assessment: The sustainability of crop production was assessed from three perspectives including process, product and geographic perspective. Main findings from all perspectives were as follow:

- Process: Drip irrigation and mulches were found water saving techniques compared to no mulching and sprinkler or surface irrigation practices. No optimal spatial zones were identified.
- Product: Wheat, barley and potato had a high nutritional blue water productivity. Tobacco and favabeans represented a high economic blue water productivity. It means that relatively low amount of blue water can be used to produce kcals or US$ for these crops.
- Geographic: Severe water scarcity happened to five months of the year, resulting in an overexploitation of 37 million m^3 per year.

(4) Response formulation: Three scenarios were formulated to improve water use performance

- Scenario 1: Mulching for all crops
- Scenario 2: Scenario 1 + drip irrigation for all summer crops
- Scenario 3: Scenario 2 + relocation of crops

Scenarios 1 and 2 had positive but limited effects on the water saving. These scenarios can reduce blue WF by respectively 16.9 and 22.4 percent per year. In scenario 3, a revised cropping pattern was suggested by focusing on high value crops and more efficient use of rainfall. Here, the blue WF savings was estimated 97 percent per year while nutritional and economic production had increased. Scenario 3 fulfilled the sustainable requirements and achieved the food security plan.

Several assumptions had to be made because of limitation in local data. However, this is the most comprehensive study so far compared to available studies and reports to focus on the high-resolution assessment of WF of the ULB region underlying the variations during 6 years of the study and it was calibrated and validated using in-situ data in the ULB. This study introduces many opportunities for future researchers to improve and expand this approach in the whole Lebanon and in other countries

II. Samenvatting

Waterschaarste bedreigt de voedselveiligheid van veel landen in droge en semi-droge gebieden. Om de prestaties in efficiënt watergebruik te verbeteren is het VN-bureau voor Voedsel en Landbouw (FAO) bezig een digitaal tele-detectie gereedschap (WaPOR) te ontwikkelen om de waterproductiviteit in landbouw te monitoren op continentaal, nationaal en lokaal niveau. Een onderdeel van dit programma is het schatten van de waterproductiviteit van geselecteerde irrigatie-schema's in Afrika en het Midden-Oosten. Deze studie schatte de waterproductiviteit van de belangrijkste gewassen in de Upper Litani Basin (ULB) in Libanon en zal worden gebruikt voor de validatie van het WaPOR project.

De ULB is het belangrijkste stroomgebied in Libanon en huisvest de helft van de landbouwgrond. Eerdere studies in de ULB beschreven drastische verhogingen van grondwateronttrekkingen waardoor de oppervlakteafvoer verminderde gedurende de afgelopen 50 jaar. In dit onderzoek is de watervoetafdruk (WF) aanpak gevolgd om een watervoetafdruk-schatting (WFA) uit te voeren van alle interne processen in de ULB. De WFA bestaat uit vier fasen, hieronder beschreven.

1) Doelstelling en afbakening: Doel: Het schatten van de efficiëntie en duurzaamheid van groen en blauw water verbruik in de ULB en het evalueren van potentiele verbeteringen voor het formuleren van een duurzaam scenario waarin voedselveiligheid binnen de ULB behaald wordt.
Afbakening: Het dagelijkse groene en blauwe waterverbruik van menselijke processen binnen de ULB, waaronder huiselijk, industrieel, bomen en gewassen zijn bijgehouden van 2011 tot 2016. De blauw waterschaarste is geschat in een maandelijkse tijdstap door de totale blauw waterconsumptie met duurzame blauw water beschikbaarheid te vergelijken. Drie scenario's zijn geformuleerd om de situatie te verbeteren, rekening houdend met de duurzaamheidsdoelstellingen van de Verenigde Naties.

2) WF-boekhouding: De blauwe WF van gewassen is geschat met het AquaCrop-OS model, waarmee het watergebruik en opbrengst van gewassen gesimuleerd kunnen worden op basis van omgevingscondities en beheerdersinstellingen. Een lijst met 225 soortgelijke gebieden is afgeleid van kaarten die 10 belangrijke gewassen, 4 grondsoorten en 6 weerzones bevatten. Beheerdersinstellingen zijn gebaseerd op literatuur en eigen veldonderzoeken. Het model is ingesteld door de gevoeligste parameters aan te passen na vergelijking van gesimuleerde en geobserveerde uitkomsten. De blauwe WF van huishoudens, industrieën en boomgewassen is gehaald uit eerdere studies.

3) Duurzaamheid schatting: De duurzaamheid van gewasproductie is geschat vanuit het proces-, product- en geografische aspect. De belangrijkste bevindingen vanuit deze perspectieven zijn als volgt:

- Proces: Druppel-irrigatie en mulchen zijn waterbesparende technieken vergeleken met niet mulchen en sprinkler of oppervlakte irrigatietechnieken. Geen optimale zones zijn gevonden.
- Product: Tarwe, gerst en aardappel hebben een hoge voeding- blauw water productiviteit. Tabak en tuinbonen vertegenwoordigen een hoge economische blauw water productiviteit. Dit betekent dat relatief weinig blauw water gebruikt wordt voor het produceren van kcals of US$.
- Geografisch: Tijdens vijf maanden per jaar is er ernstige waterschaarste, resulterend in een overexploitatie van 37 miljoen kuub water per jaar.

4) Formulering scenario's: Drie scenario's zijn geformuleerd om het water verbruik te verbeteren.

- Scenario 1: Gebruik van mulchen voor alle gewassen
- Scenario 2: Scenario 1 + druppel-irrigatie voor alle zomerse gewassen
- Scenario 3: Scenario 2 + herindeling van gewassen

Scenario 1 en 2 hebben positieve maar gelimiteerde effecten in waterbesparingen. Deze scenario's kunnen de WF verminderen met 16.9 en 22.4 procent. Scenario 3 focust op hoogwaardige gewassen en het efficiënter benutten van regenwater. Nu zijn de besparingen in blauw WF geschat op 97 procent per jaar, terwijl de voeding- en economische productie is gestegen. Scenario 3 voldoet aan de duurzaamheidseisen en aan het voedselveiligheidsplan.

Meerdere aannames zijn gemaakt door een gebrek aan lokale data. Echter is dit de meest gedetailleerde schatting van variaties in WF over zes jaar in de ULB tot zover. Het model is ingesteld en gevalideerd op basis van lokaal ingewonnen gegevens, waardoor de nauwkeurigheid hoger is dan in eerdere studies. Deze studie brengt kansen voor onderzoekers voor het verbeteren en uitbreiden van deze aanpak voor heel Libanon en in andere gebieden.

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List of Abbreviations

FAO	Food and Agriculture Organization of the United Nations
LLB	Lower Litani Basin
LRB	Litani River Basin
NENA	Near East and North Africa (Region)
ULB	Upper Litani Basin
UN	United Nations
UN OCHA	United Nations Organization for the Coordination of Humanitarian Affairs
USAID	United States Agency for International Development
WaPOR	Water Productivity Open access portal
WEF	World Economic Forum
WF	Water Footprint
WFA	Water Footprint Assessment

Chapter 1

Introduction

This study is a water footprint assessment that investigates the sustainability and efficiency of the water consumption within the Upper Litani River Basin, Lebanon. It also evaluates the effects of potential improvements.

1.1 Background

Water scarcity in the Near East and North Africa (NENA) region (see Figure 1) will increase significantly due to demographic growth, urbanization expansion, climate change and other factors according to the Food and Agriculture Organization of the United Nations (FAO, 2015a). The World Economic Forum ranks water crises among the main risks for the global economy in the coming decade. Water crises are defined as a significant decline in the available quality and quantity of fresh water, resulting in harmful effects on human health and economic activity (WEF, 2017). Most recent effects of water crises are in the Eastern Africa region, where drought, conflict and economic decline caused nearly 4 million refugees and 22.9 million people facing severe famine (United Nations, 2017). Water shortages played also an important role in the economic and political instability in Syria (Gleick, 2014). It is of major importance for countries in the NENA Region to improve the performance of water use.

In order to do this, FAO has launched the Regional Initiative on Water Security (FAO, 2015a). Their strategy is to identify information- and knowledge gaps and provide solutions. As part of it, FAO is working on a project (WaPOR) to develop publicly accessible database using remotely sensed- derived data to monitor agricultural water productivity, called Remote Sensing of Water Productivity (FAO, 2015b). Part of the programme is to monitor agricultural water productivity of selected irrigation schemes in Africa and Middle East. This study takes place simultaneously to the programme and assessed the water productivity, sustainability and efficiency of major crops in the Upper Litani Basin (ULB) in Lebanon following the water footprint approach. Obtained results in this research will be modified and employed for the validation of Remote Sensing data in the WaPOR project.

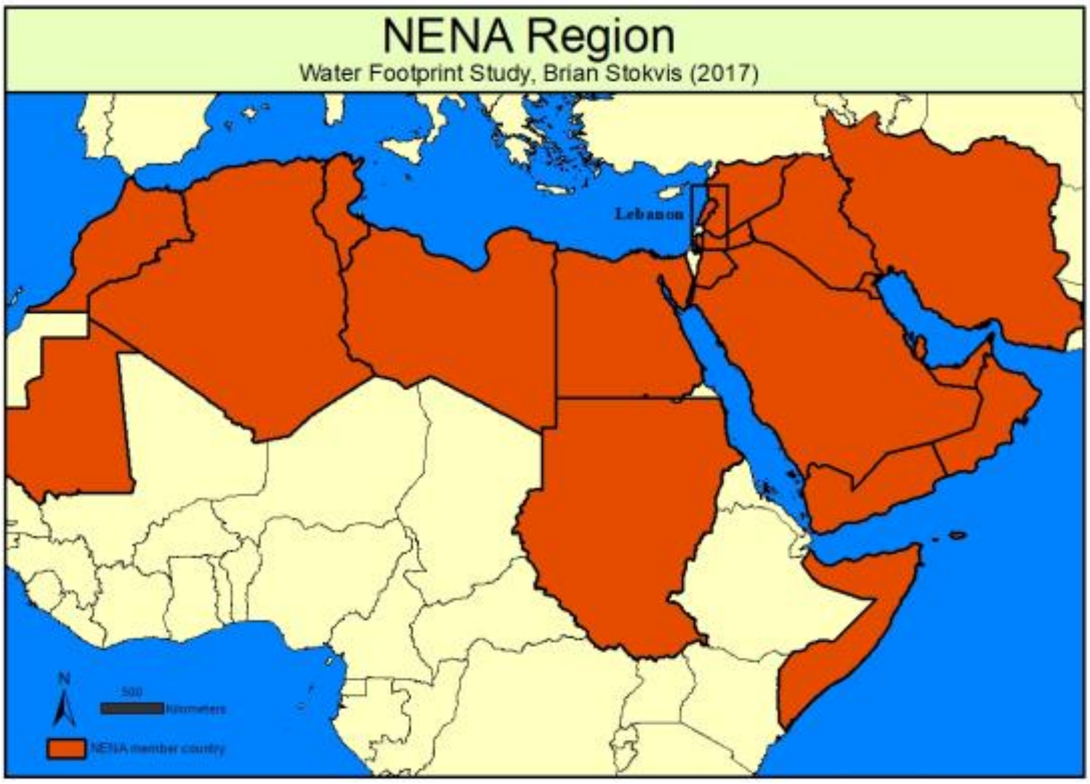

Figure 1 - NENA Region member countries with Lebanon highlighted - Brian Stokvis (2017).

1.2 Problem statement

Both the United Nations (2009) and the USAID (2014) (United States Agency for International Development) described Lebanon water resources as the most abundant in the NENA region. This statement was confirmed by FAO (2015a) in the analysis to the national water resources in this region. They estimated the renewable water availability per capita in Lebanon to be 1 144 m^3 per year, which is only exceeded by Iran and Iraq. The United Nations (2001) characterized countries as water-stressed if the availability per capita is below 1 700 m^3 per year. Considering the water scarcity threshold by the UN, Lebanon is one of the most water-abundant, but stressed countries in the NENA region.

USAID (2014) estimated the evolution of water flows in Lebanon's largest river basin, the Upper Litani Basin (ULB) by comparing historical and future water balances (see Figure 2). It reported a significant increase in groundwater abstraction resulting in decreasing surface flows. Assuming climatic stability (no change in precipitation and evaporation), these changes were entirely the result of human withdrawals for irrigation and domestic water uses. Nowadays, this assumption is questionable regarding the debate about climate change.

Ramadan et al. (2013a) studied the sensitivity of climate change impact on the hydrology of the Litani Basin (both upper and lower segments) and assessed the effect of several climatic change scenarios on the basin's runoff. They conclude that the forecasted climate change in Lebanon affect the discharge regime in the ULB both in quantity and timing. The combined changes in temperature and precipitation will decrease the runoff by 25% in summer times and the wet season will start sooner. Ramadan et al. (2013a) based their conclusions partly on Ramadan et al. (2013b) who found the same decreasing trend of the Litani runoff as USAID (2014) (Figure 2). They adjust this trend to the temperature and precipitation changes instead of an increase in irrigation. The effect of climate change on river runoff is thus questionable. However, even without climate change, the drying trend of the ULB is clear and should be addressed.

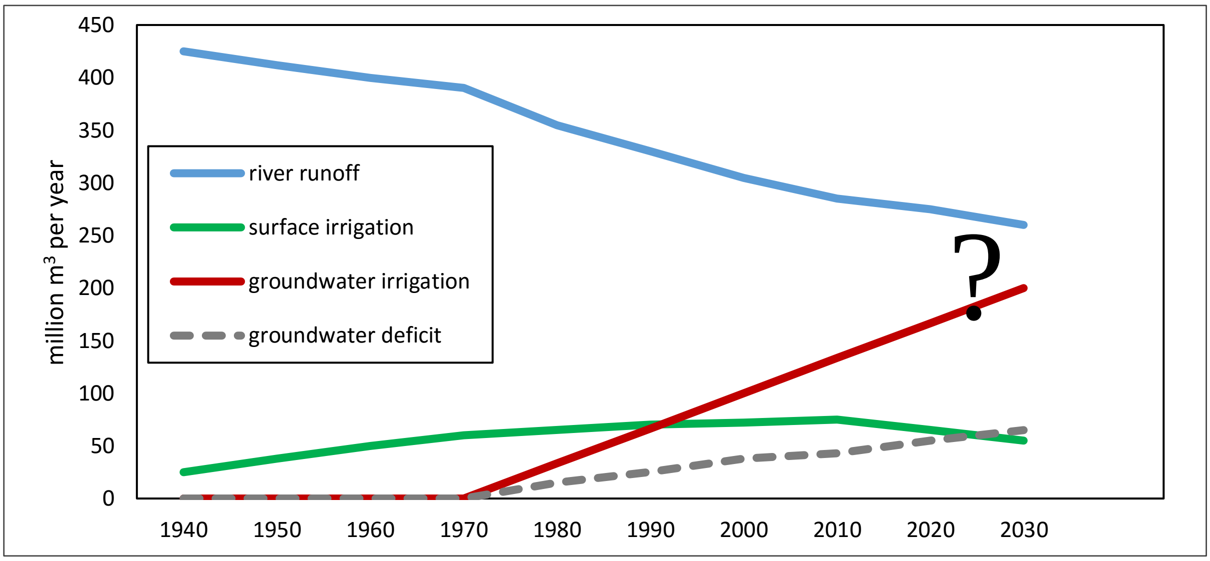

Figure 2 - Evolution of water flows in Upper Litani Basin (ULB).
Source: USAID (2014).

1.3 Water footprint approach

The Water footprint (WF) concept was introduced by Arjen Hoekstra in 2002 and provides a metric to measure the amount of water consumed to produce goods and services along the full supply chain. Nine years later, the manual was written by Hoekstra et al. (2011) to provide a set of definitions and methods for WF accounting and assessment.

The WF has three components: green (rainwater), blue (surface and groundwater) and grey (pollution). A Water Footprint Assessment (WFA) can be done to analyze the relation between human activities and issues as water scarcity and pollution. A WFA could be obtained for different entities, like a process, product, consumer, group of consumers, geographic area, business (sector) or the whole humanity. This study is a WFA to the green and blue WF of all internal water using human-processes in the Upper Litani Basin. A complete WFA consists of four phases as shown in Figure 3. The activities in each phase is described in the linked section in the figure.

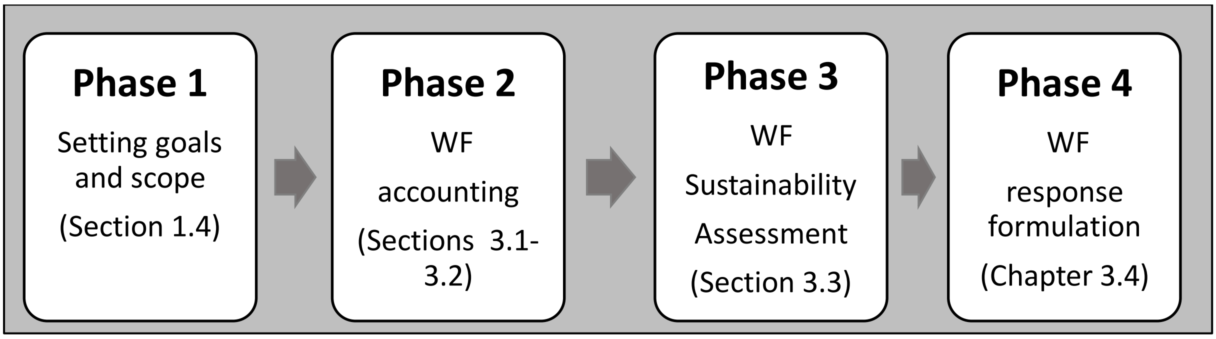

Figure 3 - Phases of a complete Water Footprint Assessment.

1.4 Setting the goals and scope

In this research, the green and blue WF of all human processes inside the ULB are studied. The processes are divided into four groups including households, industries, perennial crops (trees), and major herbaceous crops. WF-data for the former three groups are obtained from USAID (2014). The WF of major herbaceous crops are estimated using a crop simulation model. A daily time step is used for accounting the WF of major crops for a six-year period [2011 – 2016]. An overview of settings in this study is shown in Table 1. The scope and goals are further formulated in the next paragraphs of this section.

1.4.1 Scope

The sustainability is assessed by taking three different perspectives: geographic, product and process. In the case of a geographic perspective, the monthly blue water consumption is compared to the monthly sustainable blue water availability. The outcome is a blue water scarcity rate per month. In the case of a product perspective, the economic and nutritional blue water productivity of different products are compared. This will help to distinguish between valuable and less valuable crops. In the case of a process perspective, the variation of environmental and management factors in in the production processes are analyzed. This helps to obtain information about well- and underperforming regions or management strategies.

Table 1 - Water Footprint Assessment settings.

Setting	This study
WFA type	Catchment level
Name of basin	Upper Litani Basin (Lebanon)
Period	2011-2016 (72 months)
Origin of WF	Only internal processes
WF Type	Green and Blue
Accounting groups	Households, Industries, Trees and Crops
Accounting time interval	Daily
Sustainability perspectives	Geographical, Product and Process
Sustainability interval	Monthly
Response formulation	Three scenarios

The formulated scenarios are mainly based on improvements to the current crop patterns and farming techniques, taking into consideration the Sustainable Development Goals of the United Nations. These goals imply food security and economic growth in a sustainable way. Schyns et al. (2015) followed the four steps of the WFA at country level for Jordan. Lebanon is near Jordan and has similar environmental characteristics, like climate. They found severe internal water scarcity and an overexploitation of groundwater. Problems that were also addressed to the ULB in recent studies (AquaStat, 2008; Jaafar & King-Okumu, 2016; USAID, 2011).

Among the advices of Schyns et al. (2015) to Jordan were to: (1) use fossil groundwater resources only in urgent times; (2) focus on smart and efficient irrigation scheduling and improved soil and crop management (3) cap the water footprint in a river basin and aquifer to maximum sustainable level and (4) increase allocation efficiency by making sure domestic water demand is met and using the remaining available water below maximum sustainable level for the production of high value crops. Their recommendations to improve the water situation in Jordan are taken as guideline when formulating scenarios for this study in step four. The ultimate response scenario should therefore consecutively satisfy the following conditions:

i. Total blue water footprint ≤ Sustainable water availability
ii. Use of fossil groundwater only in urgent times, in low amounts and at low frequencies
iii. Food production ≥ Domestic food demand
iv. Maximum economic value of produced crops

The three scenarios are formulated based on the three sustainability assessment perspectives. The first two scenarios are focused on condition i; decreasing the water consumption. These scenarios are widely recommended in previous advice reports (AquaStat, 2008; Jaafar & King-Okumu, 2016; USAID, 2011). A third scenario is made that should satisfy all conditions. The three scenarios are:

- Scenario 1: Mulching for all crops
- Scenario 2: S1 + Drip irrigation for all summer crops
- Scenario 3: S2 + Relocation of crops

1.4.2 Goals

The main goal of this study is to

> assess the efficiency and sustainability of the green and blue water consumption in the Upper Litani Basin besides suggesting some adoptive scenarios and evaluating the potential improvements to formulate a water-sustainable scenario that achieve food security of the catchment.

The following research questions are asked with the main goal:

1	What is the WF-efficiency of major crops in the ULB?
2	What are the economic and nutritional values of major crops in terms of blue WF in the ULB?
3	What is the environmental sustainability of the blue WF in the ULB?
4	What adoptive scenario could achieve both food security and water sustainability in the ULB?

1.5 Study area

The Litani River (shown in Figure 4) origins in the Bekaa valley; it is the longest river in the country, and flows entirely within Lebanon. The basin is divided into two sub-basins since the construction of the Qaraoun dam in 1956. The Litani river is a major source for drinking and irrigation water and the dam is used to provide electricity The Lower Litani Basin (LLB, 500 km^2) mainly consists of natural lands and hosts the river delta into the Mediterranean Sea. Since most human activities are in the Upper Litani Basin (ULB, 1 500 km^2) the ULB was selected as the study area.

The ULB lies in the Bekaa valley between two parallel mountains. There is a semi-arid climate with wet winters (November – May) and dry summers (April – October). The annual precipitation volume is estimated to be about 1 100 million m^3 from which 1 030 million m^3 falls in the winter and 70 million m^3 in the summer. The natural runoff is estimated to be 440 million m^3 divided into 230 million m^3 of rain runoff and 210 million m^3 of base flow. Three main cropping schemes are perennial crops, high value summer crops and a rotation of winter and summer crops. Inappropriate water management in the ULB caused a widespread water pollution and serious water shortages inside the basin. Better water management and new farming techniques are necessary to increase water productivity and decrease water consumption chains (USAID, 2014).

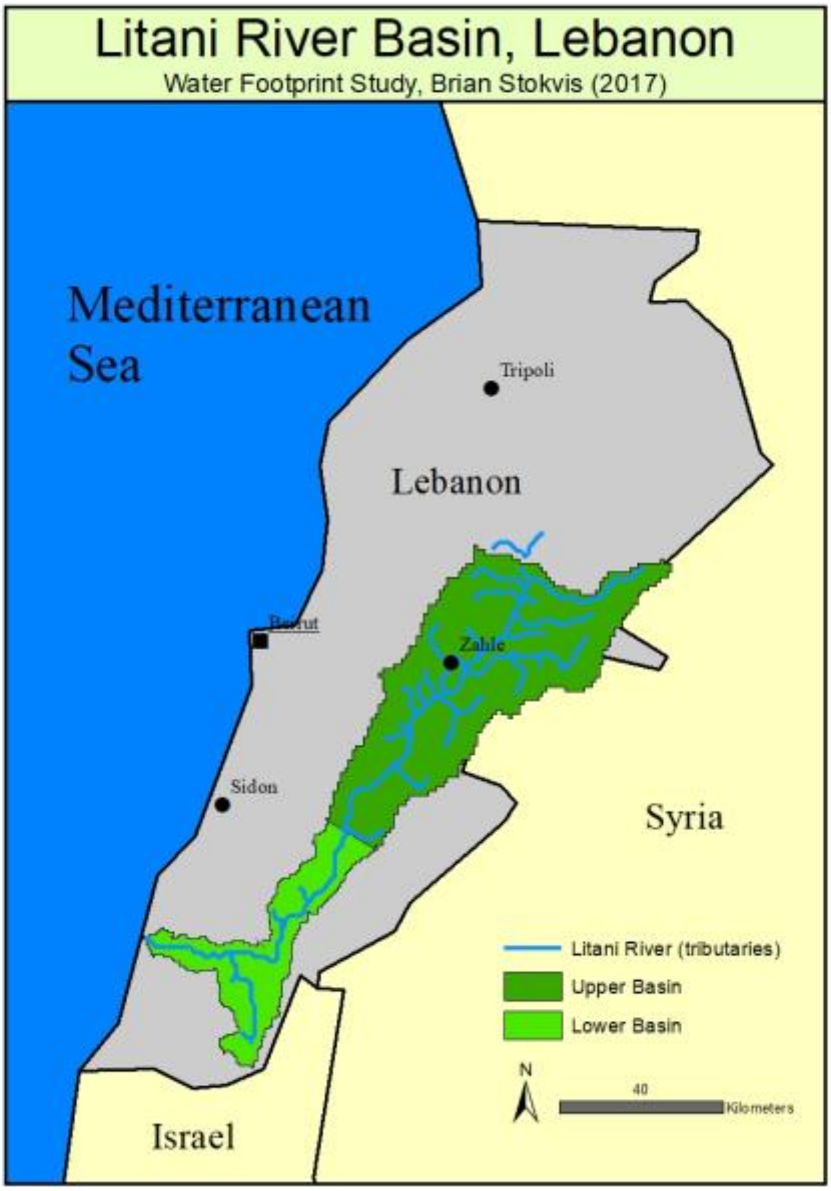

Figure 4 - Lebanon within Upper and Lower Litani Basin (ULB & LLB) – Brian Stokvis (2017).

1.6 Outline

This report is a Water Footprint Assessment of the Upper Litani Basin. Chapter 2 is a literature review that consists of previous studies in the Litani Basin, available crop simulation models, earlier river basins studies and a description of the used model. In chapter 3, the method to estimate crop water consumption is comprehensively described. The results for the current situation and for the three scenarios are given in chapter 4. In chapter 5, the outcomes are discussed. Chapter 6 presents the major conclusions drawn from this research as well as recommendations for future studies.

Chapter 2

Literature review

This chapter reviews the available literature to obtain more knowledge about the basin, crop simulation models and methods. Section 2.1 is a summary of previous studies in the ULB. This section clarifies a research gap that has to be filled by this study. Section 2.2 evaluates different approaches to meet the goal and objectives of this research. Section 2.3 compares available crop simulation models and suggest the most suitable one for this study. Section 2.4 outlines a further description of the underlying formulas of this model.

2.1 Earlier studies in the Litani River Basin and in Lebanon

A goal of this research is to determine the water consumption inside the basin. In the case of the ULB, some relevant studies where made in the recent past. These studies will be summarized in this section, to provide knowledge that can be helpful for this research.

AquaStat (2008), the statistical water-database of the FAO, studied the national profile of Lebanon. The country was surveyed in 2000 to get insight in farming techniques. They stated that 60% of the national water withdrawal was for agricultural purposes. It repressed that national water consumption had increased historically due to intensification of irrigated area from 23 000 ha in 1956 to 90 000 ha in 2000. Governmental implementations of pumping wells and irrigation schemes in the 1990s results in a higher pressure on groundwater resources. Since the 2000s, an increasing attention has been paid to the water management and water use efficiency in Lebanon.

AquaStat (2008) stated that there was a general agreement that the situation was not sustainable because water resources where being depleted. They determined that the scarce water resources are increasingly being used for high-value crops such as vegetables. The value of a crop is seen from an economic perspective ($ per hectare) instead as from a water perspective ($ per volume of water). The latter is never investigated and thus not clear at all. The water saving intentions are recognized but hampered by lack of information.

In another study by FAO (2012b), the agricultural state policy was analyzed regarding sustainable land management. It described the region of the ULB, the Bekaa Valley, as the major agricultural area, consisting 42% of Lebanon's farm lands and 50% of the irrigated land. It was further noticed that over-fertilization in Lebanon caused significant environmental contamination, leading to groundwater pollution and eutrophication of rivers and lakes. This report recommended farmers to implement water saving techniques like drip irrigation, integrated pest management and organic mulching. The potential effects of these recommended strategies on water scarcity where not yet clear however, since they made no calculations. There is no underlying quantification of these improvements.

Due to chronic water shortages driven by unsustainable water management in Lebanon, the USAID (2014) set up the Litani River Basin Management Support (LRBMS) program in 2009 to support the Litani River Authority (LRA) towards Integrated River Basin Management (IRBM). This project was completed in 2014 and one subject was to improve irrigation management. Within this subject, they analyzed the groundwater network, land use classification, irrigation practices and as result, the evolution of the water balance. It was claimed that annual water demands exceeds physical water availability, resulting in a yearly groundwater decline of 0.5-2 meter. In summer periods, the almost dried Litani River leads to a groundwater shortage of 70 million m^3. The yearly irrigation water consumption was estimated to be 190 million m^3. The net annual domestic and industrial water demands combined where estimated at 20 million m^3, based on a rate of 150 liter per capita and a population of 375 000 people. According to USAID (2014), the total water demand of the ULB was estimated 210 million m^3 per annum.

Since the Syrian crisis, the arrival of approximately 275 000 refugees has increased the domestic water demand in areas of the Bekaa Valley. Jaafar and King-Okumu (2016) studied the updated water balances for the ULB and the nearing Upper Orontes Basin. They applied the increasing demand due to refugees based on USAID (2014). They reported an annual domestic water demand of 60 million m^3 in the ULB. Also, this study estimated the crop water demand based on new irrigation maps and information about irrigation practices obtained from respectively remote sensing and field surveys. They used the crop simulation model of AquaCrop to calculate the irrigation demand of all summer crops in the ULB. Jaafar and King-Okumu (2016) estimated the irrigation water demand to be 249 million m^3 for the summer season. However, the actual irrigation water consumption could reach 332 million m^3, considering an irrigation efficiency of 60% and a return flow of 20%. According to Jaafar and King-Okumu (2016), the total water consumption, including the Syrian refugees, in the ULB is 332 million m^3 plus 60 million m^3 equals 392 million m^3 per annum.

While previous studies provided high level of data for the ULB, both in quantity as in quality, the lack of a detailed quantification of agricultural water demand is still there. Based on hydrological cycles, it is proved that the current situation is not sustainable, but a scenario that provides a sustainable solution is not yet formulated. Estimations in annual consumptive water usages ranges from 210 million m^3 to 392 million m^3. Previous studies including USAID (2014) and Jaafar and King-Okumu (2016) recognized this gap and recommend further researches on the temporal variability and intra-annual changes in water demands. This study aims to fill this gap by using more detailed information.

2.2 River basin studies

There are different scopes in river basin studies such as high water (flood defense), poor water (improve water quality), low water (demand vs supply study) or a more integrated water management study that combines two or more scoops. This study in particular studied the quantity of water in the catchment. Two approaches can be followed in the quantification of water consumption in a geographical area like a catchment: top down and bottom up (Hoekstra et al., 2011).

A top-down approach analyzes virtual trades between regions and links them with water consumption in each region. According to Hoekstra et al. (2011), it does not necessarily holds over a single year, because the production and trade of a product could be in different years. It also depends largely on trade data, which is not often available in high quality. Previous river basin studies following the top-down approach are Chen et al. (2005); Dumont et al. (2013); Feng et al. (2011); Mayer et al. (2016); Zhao et al. (2010).

With the bottom-up approach, the water consumption all groups of consumers (crops, trees, livestock, households, industries etc.) within a basin are studied individually. The total consumption can be obtained by summing up the WF of each group. This approach is suggested for accounting the water consumption inside a basin.

Aldaya and Llamas (2008) studied the WF of different economic sectors inside the Spanish part of the Guadiana basin. The study assessed the green and blue WF of these sectors to facilitate the allocation of water users efficiently. They were innovative by relating economic (cash/drop) and ecological (nature/drop) blue water productivity. The analysis provided remarkable results about the spread of low value crops that has large WF. Zeng et al. (2012) assessed the green and blue WF of the Heihe River Basin in China followed by a sustainability assessment in a monthly basis. Both studies provided interesting knowledge about the state of the water house holding. However, there are undeniable sources of errors, biases and uncertainty originating from rough assumptions, simplifications and inadequate data in the studies of Zeng et al. (2012) and Aldaya and Llamas (2008).

Dumont et al. (2013) analyzed the green and blue WF of the Guadalquivir basin in Spain with an emphasis on the WF of groundwater. The Environment Agency (2014) studied the green, blue and grey WF of domestic water use, five major crops and it pollution for the Hertfordshire and North London Area (UK) under two climate change scenarios to estimate future water scarcity. The aim of the study was to elaborate the current status of water resources and provide potential improvements. Miguel et al. (2015) evaluated the WF of crops within the Duero river basin in Spain. They used a new developed crop simulation model.

Zhuo et al. (2016) assessed the WF of crops in the Yellow River Basin (China) using high temporal resolution of daily WF and monthly blue water scarcity and a spatial resolution of 5x5 arc min. Zhuo et al. (2016) claimed that the blue water estimations agreed better to global WF database of crops derived by Mekonnen and Hoekstra (2011) than green water estimations. This is important, because the fraction of green water in crops is highest in general.

Van Gaelen et al. (2016) developed an agro-hydrological model, AquaCrop-Hydro, to simulate crop productivity and water availability in agricultural catchments. In the pilot study, the model was tested for the Plankbeek catchment in Belgium. This model combines the results of the general AquaCrop model with a hydrological model to evaluate the effects of croplands on the river discharge. They divided the basin into homogeneous land units (LU), and ran the AquaCrop model for each individual LU.

This study followed a combination of the approaches reviewed in the literature. It assessed the WF of different sectors, which are domestic and industries, trees and crops. The WF of crops is estimated with a crop simulation model considering homogeneous land units (LU). The sustainability is assessed on a monthly scale by comparing the total blue water consumption of all sectors combined with the total sustainable blue water availability. The economic blue water productivity is used to find high and low value crops. In addition, the nutritional blue water productivity (kcal /drop) is assessed to evaluate the food security of the region. Different scenarios were formulated based on the sustainability assessment and the productivity of crops. Next step is to find a suitable model to simulate the water use of crops.

2.3 Crop Simulation models

Crop simulation models are used to estimate water use and yield of crops based on environmental conditions. A description with advantages and limitations of some available models is given below. Based on the characteristics, and some comparative studies, a most suitable model is regarded.

- CropWat uses crop and climate data to calculate crop water and irrigation requirements. It is capable to estimate crop performance under rainfed and irrigation conditions. This model requires minimal input data and works under different ecological zones and climates. The accuracy of CropWat is limited for dry zones however and it is unable to simulate effects of rising CO_2 concentrations on crop water use (ACIAR, 2015; FAO, 1992).
- AquaCrop is an evolution of CropWat and is a dynamic model to simulate yield response of crops to water under varying management and environmental conditions. AquaCrop requires a limited inputs but performs as good as more complex models like the SWAP and DAISY model (ACIAR, 2015; Steduto et al., 2009).
- NAFRI is a soil water balance model that can also be used to estimate yield reductions caused by soil nutrient and water stress. It requires minimal input data, but is only calibrated for one specific area (ACIAR, 2015; Inthavong et al., 2012).
- The SWAP model is an agro hydrological model that simulates water flow and salt transport. Setting up of necessary data for this model is very time consuming and costly (Lassche, 2013; Van Dam et al., 1997).
- The H08 model is a water resources model that can estimate the virtual water used for agricultural and livestock products. The H08 model does not model deep groundwater and therefore underestimates the blue water (APEC, 2012; Hanasaki et al., 2010).
- The GEPIC-EPIC is a GIS based model, that can simulate consumptive water use of crops based on climate, soil, crop, terrain and crop management data (Liu et al., 2007; Liu & Yang, 2010).
- The GCW Model determines daily evapotranspiration for crops based on soil water balances. The model cannot represent variabilities between different crops or even between varieties of the same crop (Siebert & Doll, 2008; Siebert & Doll, 2010).
- The LPJmL model is a dynamic global vegetation and water balance model that computes green and blue water fluxes for natural and agricultural vegetation. For individual river basins, the uncertainty in estimating green and blue water use is relatively high due to the low variability of input data for precipitation (Prentice et al., 1997; Rost et al., 2008).
- DAISY is a soil-plant-atmosphere system model. This model has a complex input and output file structure and its interface is not user-friendly (Abrahamsen & Hansen, 2000; Liang et al., 2016)

- AquaGIS is an extended version of the AquaCrop model that can be used for use of areas that requires a large number of simulation runs. Lorite et al. (2013) tested the use for five different locations and four climate stations in Spain. They reported that using AquaGIS instead of AquaCrop reduced the amount of time by more than 99%. AquaGIS runs with the same crop and management files as the usual AquaCrop version. It seems however that AquaGIS is only compatible with AquaCrop (4.0) which is currently no longer available. (FAO, 2015; Lorite et al., 2013)
- AquaCrop-OS (Foster et al., 2017) is an open source model of the AquaCrop model that can be run in multiple operation systems, for example Matlab. As like AquaGIS this version is favorable when applying in large geospatial frameworks or long-run policy analysis and can be linked with other disciplinary models (Foster et al., 2017).

2.3.1 Most suitable model

Kersebaum et al. (2016) studied the uncertainty of seven different models. The comparison was done for water consumption, crop yield and water footprint. They reported that no model performed the best on all tested sites, mainly for two reasons of limitation in input data and calibration challenges. Further they stated that the response of crops to external factors like CO_2 concentration and heat stress is still uncertain.

AquaCrop is the most used crop simulation model in WF studies because of its simplicity in combination with a high accuracy on estimating crop yields in response to water. The literature gives us no reason to change to a different model for this study. It even provides an opportunity to test AquaCrop-OS for a whole river basin for the first time. AquaCrop-OS is used to estimate the water footprint of major crop for the LRB and will be described more in depth in the next section.

2.4 AquaCrop-OS model

In the previous section, several crop simulation models were described and their pros and cons were discussed. This research found AquaCrop-OS the most suitable one to meet the research goal and objectives. This section gives explanation of the underlying algorithms and assumptions of AquaCrop to get a better understanding of the model. Most of the information is from the detailed description of Van Gaelen (2016), who used AquaCrop to evaluate agricultural management on catchment scale. They get their information from the AquaCrop manuals. Information about AquaCrop-OS is from Foster et al. (2017)

AquaCrop is a plant simulation model with a water-driven plant growth engine. AquaCrop can only simulate one plant and soil type per simulation run. The AquaCrop-OS version makes it possible to simulate multiple point simulation runs (like a basin) in a batch. Each simulation requires 16 input textfiles (or 18 for two crops in rotation with corresponding irrigation management) and follows four calculation steps to estimate the crop water use and crop yield. The input files are divided into five groups: Crops, Soil, Environment, Management and General.

2.4.1 Crop canopy development and production

The growth engine of a crop is driven by the temperature and is limited by the availability of water. These engine and limitations are expressed in the formulas in four calculation steps. First, the fraction of the green canopy of the total surface area, the crops canopy cover (CC) is simulated using Equation 2.1. This simulation follows a logistic function from the initial value (CC_0) to the maximum (CC_x) considering a growth coefficient (cgc) in the early season and a decline coefficient (cdc) in the late season. Second, the crop transpiration (Tr) is simulated based on a reference evapotranspiration (ET_0) and a crop transpiration coefficient ($Kc._{TR}$), proportional to the CC (Equation 2.2). Third, the biomass (B) is calculated based on the crop transpiration and a normalized crop water productivity (wp^*) (Equation 2.3). Fourth, the biomass is converted into crop yield (Y) considering a harvest index (hi) (Equation 2.4).

$$CC_i = \frac{soil\ covered\ by\ green\ canopy}{unit\ ground\ surface\ area} \tag{2.1}$$

$$Tr_i = K_{s_i}\, K_{C.TR_i}\, ET_{0_i} \tag{2.2}$$

$$B = WP^* \sum_{i=1}^{n} K_{s.b_i} \frac{Tr_i}{ET_{0_i}} \tag{2.3}$$

$$Y = hi * B = fHI * hio * B \tag{2.4}$$

Where CC is the canopy cover (m^2/m^2) on day i, Tr is the crop transpiration (mm/day), ET_{0i} is the reference evapotranspiration (mm/day), $K_{C.TR.i}$ is the crop transpiration coefficient (-) proportional to CC, K_{si} is the soil water and salinity stress coefficient (-), K_{sbi} is the cold stress coefficient (-), B is the total biomass production (g/m^2), wp^* is the normalized crop water productivity (g/m^2), Y is the dry yield (g/m^2), hi is the harvest index (g/g) which is a product ofto the reference harvest index (hio,g/g) adjusted for water and temperature stress with f_{HI} (-) and n is the number of simulation days per growing period.

2.4.2 Soil water balance

AquaCrop simulates a daily soil water content (S) based on a soil water balance between incoming (rain, irrigation, capillary rise) and outgoing (surface runoff, deep percolation, soil evaporation, crop transpiration) water fluxes (Equation 2.5).

$$S_i = P_i + I_i + C_i - SO_i - D_i - E_i - T_i \tag{2.5}$$

where S is the soil water content (mm) on day i, P is the precipitation (mm), I is the irrigation (mm), C is the Capillary rise (mm) depending on the soil type and availability of a shallow groundwater table, SO is the surface runoff (mm) following Curve Number (CN) method (Equation 2.6) (Rallison, 1980), D is the deep percolation (mm) estimated with the drainage ability (m^3/m^3/day) depending on the soil type, E is the soil evaporation (mm) and T is the crop transpiration (mm). Evaporation (Equation 2.7) and transpiration (Equation 2.2) are simulated separately from the soil balance.

$$RO_i = \frac{(P_i - 0{,}2 * Si)^2}{P_i + S - 0{,}2Si} \tag{2.6}$$

$$E = K_{ri} * K_{ei} * ET_{0i} \tag{2.7}$$

where Si is the maximum potential storage (mm) depending of the soil type, K_r is the evaporation reduction coefficient (-) and K_e is the evaporation coefficient (-) proportional to the soil fraction that is non-covered by the crop (1-CC).

2.4.3 Response to stresses and management types

The growth engine in AquaCrop can be hampered by abiotic stresses like water stress, temperature stress, soil salinity stress and soil fertility stress. The response of a crop to these stresses is parametrized in the crop parameters. The degree of stress coefficients (K) ranges from 0 (full stress) to 1 (no stress). Descriptions of all stresses are given in the crop parameter description table in appendix C.1.

AquaCrop can simulate various agricultural management types that affects the soil water balance and crop productivity. These management options could consider crop cultivars such as season length, density, planting date, sowing type besides different irrigation types such as rainfed, specified interval, triggered on actual soil content or measuring net water requirement and field management practices including mulching, soil bunds.

2.5 Conclusion

Several studies mentioned that Lebanon, and in particular the ULB facing severe water scarcity (AquaStat, 2008; Jaafar & King-Okumu, 2016; USAID, 2011) . An assessment of the temporal and intra-annual variability of this problem and evaluation of the potential improvements is still missing. This study aims to quantify the WF of the ULB using a bottom-up approach and assess the monthly water scarcity. Different scenarios are developed based on crop performance, economic and nutritional aspects. The AquaCrop-OS model is used to simulate the water consumption and yield of major crops in the region. By considering spatial distribution of soil types, crop types and climatic zones, similar zones were identified. These zones are simulated in batches with the AquaCrop-OS model.

Chapter 3

Method

In this chapter, the method of the Water Footprint Assessment of the Upper Litani Basin is described. It consists of the data collection for the AquaCrop-OS model (Section 3.1), setting-up of the model and conversion from AquaCrop-OS output to WF (Section 3.2), the water footprint assessment (3.3) and the scenario response formulation (3.4). An overview of this chapter is shown in Figure 5.

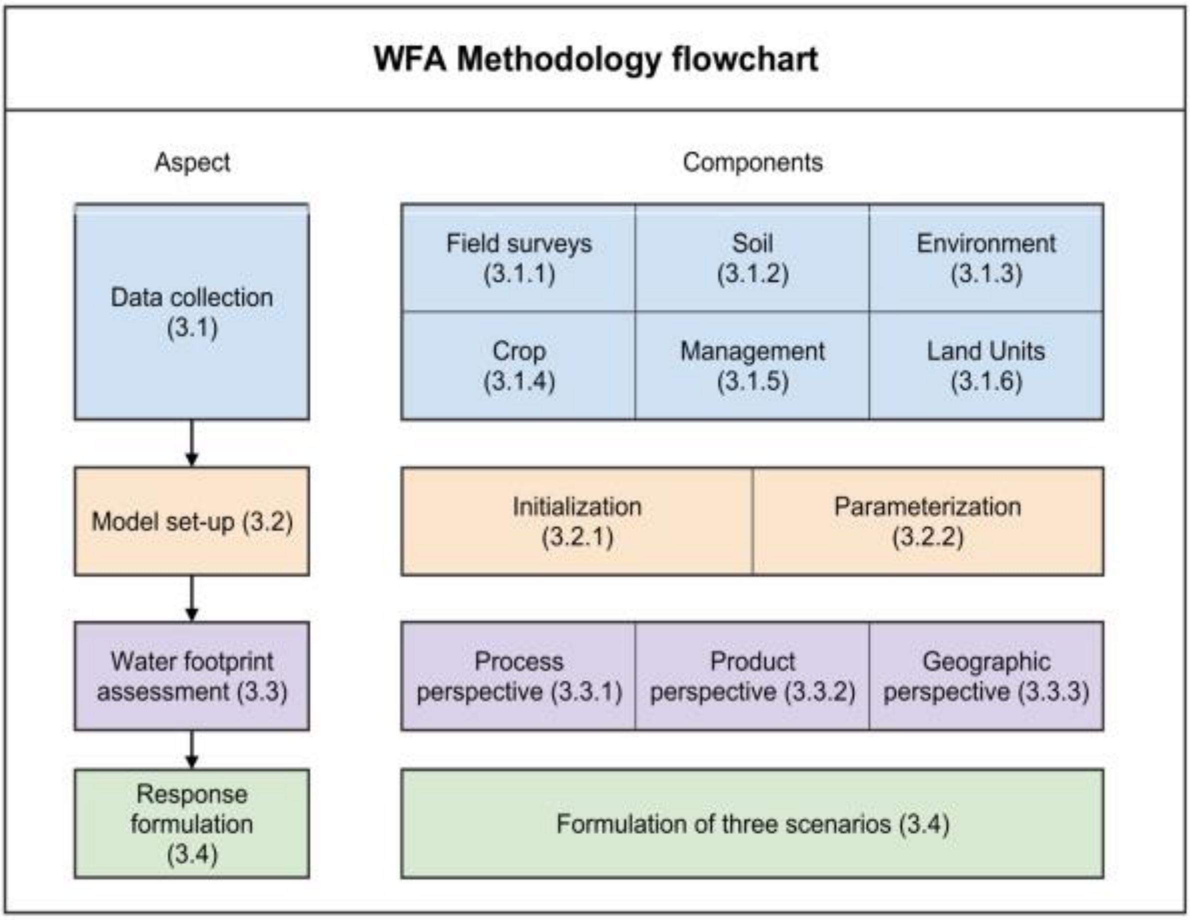

Figure 5 - Overview of the method chapter.

3.1 Data Collection for AquaCrop-OS

Data was collected from available reports and studies on the Litani Basin beside our field surveys in Bekaa Valley. Being a point-based model, AquaCrop-OS was run for each individual land unit (LU) separately. The catchment was divided into LUs with similar soil, weather and land use types. The different LUs per crop type were collected into one batch folder. Next, the different management types per crop type were derived from the literature and our new derived surveys. This crop specific information was added to the batch folder with the corresponding crop input files. A single simulation of the AquaCrop-OS model requires 16 to 18 input files, depending on the number of crops growing a field. The data inside the batch folders was simulated with AquaCrop-OS using the software Matlab.

3.1.1 Field surveys

As mentioned in the introduction, the water productivity of the Litani River Basins wass also assessed by the FAO programme “Remote sensing for Water Productivity”. In order to improve amount of data, field surveys were done in the basin. Two crops of potato and wheat were surveyed at the time that most farmers harvested their potato and wheat fields.

The surveys confirmed that farmers are tended to over fertilize their soils. All farmers use high amount of fertilizers. Other interesting results from the surveys for this study were that all farmers follows a full irrigation scheme for early potato (summer crop) and a supplementary scheme for wheat (winter crop). A summary of the results of the surveys is shown in Table 2. All data from the survey is given in Appendix B. The collected data is used as follows:

- Weather files are collected from LARI (2017) to use as environmental data (Section 3.1.2)
- Crop development data for early potato and wheat to set up crop settings (Section 3.1.3)
- Irrigation and fertilization data for management characteristics (Section 3.1.5)
- Yield data for early potato and wheat to parameterize AquaCrop-OS (Section 3.2.2)

Table 2 - Summary of results Potato and Wheat surveys in the ULB.

Crop	**Early Potato**			**Wheat**		
Surveys	25			25		
Start period	Late February – Mid March			Late October – Early December		
End period	Early July – End July			Late June – Mid July		
Average season [days]	133			129		
Average yield [t/ha]	39			2.2		
	No [%]	**Yes [%]**		**No [%]**	**Yes [%]**	
Initial mulching	100	0		100	0	
Initial fertilization	0	100		36	64	
Initial irrigation	100	0		100	0	
Seasonal mulching	100	0		100	0	
Seasonal fertilization	0	100		0	100	
Seasonal irrigation	0	100		0	100	
Irrigation technique	Sprinkler 100 %			Sprinkler 100 %		
Irrigation strategy	Full 100 %			Supplementary 100 %		
Irrigation events	10			2		
Irrigation interval	7			-		
Irrigation amount	41 mm			63 mm		
Irrigation Source [%]	66 ground	5surface	29 both	67 ground	25surface	8 both

3.1.2 Soil data

The soil component was simulated with the soil hydraulic properties derived from soil textures. The hydraulic properties consist of sand content, clay content, organic matter and density factor. The soil data was obtained from the ISRIC SoilGrids 250 meter global database (Hengl et al., 2017). The TAXOUSDA classification system was used to derive the different soil types in the ULB. There are five layers of varying depth over the whole soil column of 2.3 meter. For the upper layer, the runoff characteristics are needed for simulation of surface runoff (Equation 2.6). Figure 7 (Appendix A.1) shows the spatial distribution of four soil types: Orthents, Xeralfs, Xerepts and Xerolls. There is a small spatial variation in hydraulic properties over a single soil type. The average value of 3 locations of a soil type was used in this study. The soil properties are shown in Table 3.

Table 3 - Hydraulic soil properties of soil types inside the basin.

Type		Orthents				Xeralfs			
		Shallow or "skeletal soils". Found on recent erosional surfaces or very old landforms				Alfisols in areas with very dry summers and moist winters			
Layer		Sand	Clay	OrgMat	Density	Sand	Clay	OrgMat	Density
#	[m]	[%]	[%]	[%]	factor	[%]	[%]	[%]	factor
1	0.05	26	37	6.31	1	41	25	6.48	1
2	0.10	26	37	3.55	1	42	25	3.84	1
3	0.15	28	35	2.64	1	43	22	2.29	1
4	0.30	32	33	1.78	1	45	21	1.49	1
5	1.70	32	33	1.38	1	45	21	0,92	1
Type top layer		Clay loam		CN top	79	Type top layer	Loam	CN	67
Type		Xerepts				Xerolls			
		Inceptisols: dry summers and moist winters				Mollisols in mediteranaean climate			
Layer		Sand	Clay	OrgMat	Density	Sand	Clay	OrgMat	Density
#	[m]	[%]	[%]	[%]	factor	[%]	[%]	[%]	factor
1	0.05	28	38	4.19	1	37	33	4.70	1
2	0.10	30	35	3.33	1	38	31	3.10	1
3	0.15	32	33	2.64	1	40	29	2.01	1
4	0.30	35	31	2.06	1	42	27	1.26	1
5	1.70	35	32	1,89	1	43	27	1.15	1
Type top layer		Clay loam		CN top	79	Type top layer	Clay loam	CN	79

Source: Hengl et al. (2017).

3.1.3 Environment

The environmental data exists of a CO2 file and weather file. The CO2 values were obtained from the Mauna Loa observatory in Hawaii that is available in the AquaCrop database. The weather data was derived from six stations over the area. The basin was divided into six zones (Thiessen Polygons) by dividing the available space and allocate it to the nearest station. This method is justified by the assumption that spatial climatic variability is low enough, due to the absence of large natural barriers such as mountains or lakes. In addition, the largest distance from a station to a relating point is only 25 km. The weather zones are shown in Figure 8 (Appendix A.2) (note: weather station 5 is too far away from the basin to be relevant).

The raw weather data were obtained from the Lebanese Agricultural Research Institute (LARI). This data was analyzed by identifying and removing the outliers and calculating missing data. The reference evapotranspiration ET_0 was only measured at the Icarda and Tal Amara stations. For the stations were ET_0 was not measured, values of Icarda or Tal Amara were used, depending on which one was the nearest. The average monthly minimal and maximum temperatures plus daily precipitation rate for each station are shown in Figure 6. The total climate data per station is given in Appendix A.4.

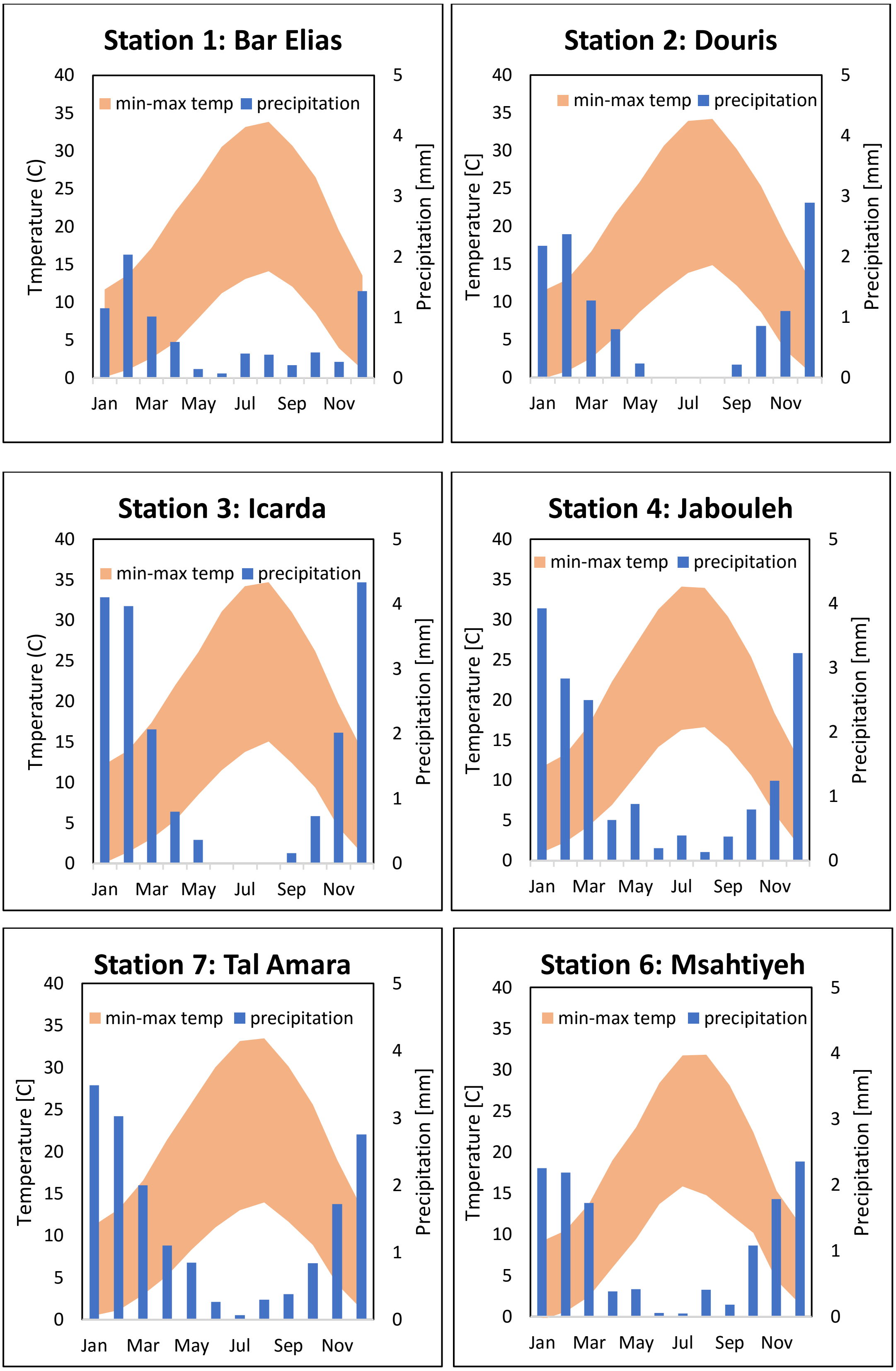

Figure 6 - Monthly averages of minimum and maximum temperature and daily precipitation in 6 weather stations in the ULB.

Source: LARI (2017).

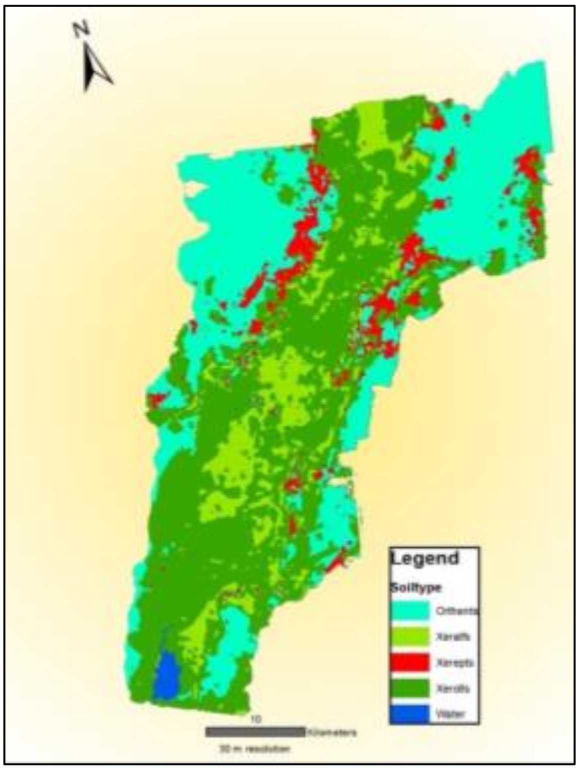

Figure 7 – Soil types in the ULB.
Source: Hengl et al. (2017).

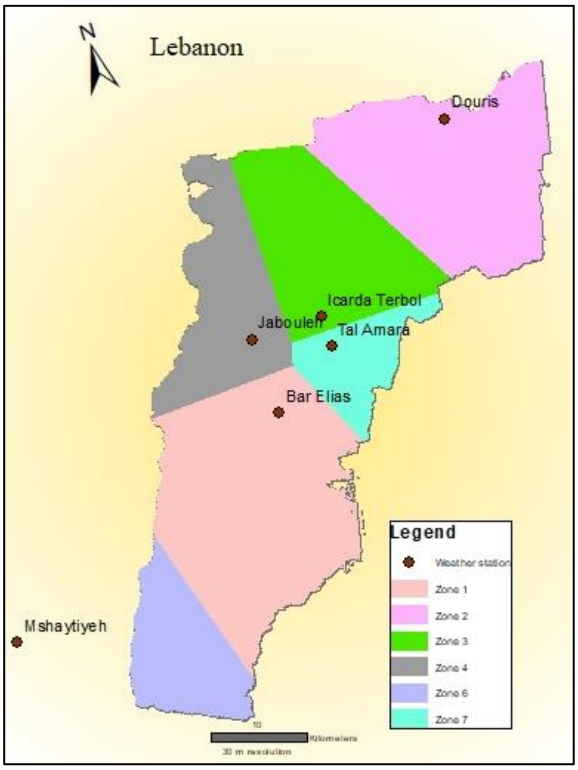

Figure 8 – Weather zones in the ULB.
Source LARI (2017).

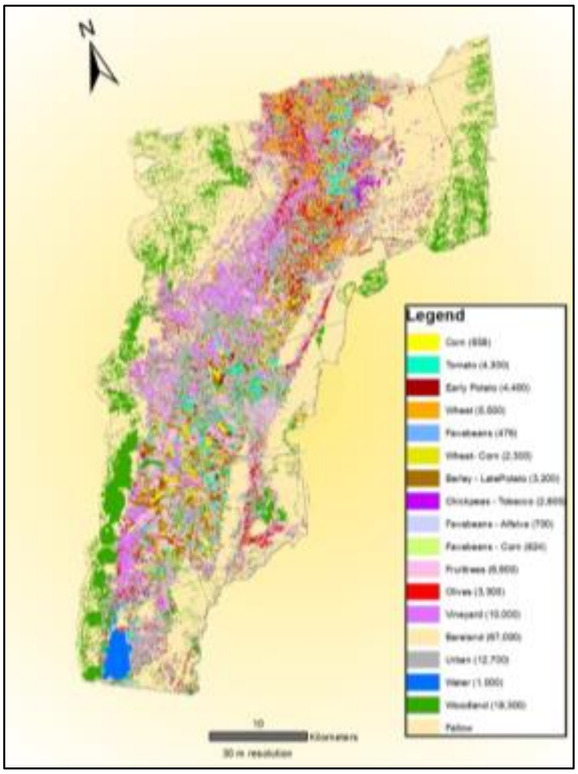

Figure 9 - Land use types in the ULB for the year 2011.
Source: USAID (2014).

3.1.4 Crop data

USAID (2014) created land use maps with a 5-meter spatial resolution using satellite images for three periods in 2011. A crop calendar was established based on these maps in combination with field surveys. Because of the high resolution of the maps, the quantification of the areas and the relating calendar, this crop data set was used in this study. Alternative available land use data sets had lower spatial resolution and were not able to distinguish between individual crops (Defourny P., 2009; FAO, 2014c).

Attempts to request the original maps from USAID (2014) in GIS extension failed. As an alternative, the maps were loaded in ArcGIS as a picture and replaced using the geo-referencing tool. In the first step, the city labels were washed out from the original picture, using Photoshop. The procedure in ArcGIS started with geo-referencing the picture to the right place, based on topographical landmarks like the city of Zahle and the Qaraoun Lake. Next, the land use types were translated to a shapefile in ArcGIS by using the classification tool; this tool creates polygons from similar color bands of the original picture on maximum likelihood. Nine crop types were categorized by USAID (2014), from which potato was divided into an early and late version. With exception of lettuce, all herbaceous crops were selected, representing 94% of the total harvested area (28 300 ha) in the ULB.

Based on the crop calendar, crop cultivation could be in a form of a single crop (monoculture) or in a summer/winter rotation with other crops. This difference influences the soil balances and requires separated simulation runs. All combinations of monoculture and crop rotation patterns are given in Table 4. A new land use map was created that considers the crop rotations (shown in Figure 9 and Appendix A.3). From the weather files, we know that the wet period exists from November till April, and the dry period is from May till October. Therefore, the plant dates for winter crops (barley, chickpeas, favabeans and wheat) and early potato were generated from rainfall events. The planting criteria was a successive period of 4 days with 10 mm of rainfall. The summer crops are planted on fixed dates, because these crops rely highly on irrigation. A description of the used crop data is given in Appendix C.1.

Table 4 - Land use types with corresponding area sizes for the year 2011 in the ULB.

<table>
<tr><th>#</th><th>Area[ha]</th><th>Nov</th><th>Dec</th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th></tr>
<tr><td>1</td><td>700</td><td colspan="8">Fallow</td><td colspan="3">Corn</td><td>F.</td></tr>
<tr><td>2</td><td>4 300</td><td colspan="7">Fallow</td><td colspan="4">Tomato</td><td>F.</td></tr>
<tr><td>3</td><td>4 400</td><td colspan="3">Fallow</td><td colspan="6">Early Potato</td><td colspan="3">Fallow</td></tr>
<tr><td>4</td><td>5 500</td><td colspan="8">Wheat</td><td colspan="4">Fallow</td></tr>
<tr><td>5</td><td>500</td><td colspan="7">Favabeans</td><td colspan="5">Fallow</td></tr>
<tr><td>6</td><td>2 300</td><td colspan="8">Wheat</td><td colspan="3">Corn</td><td>F.</td></tr>
<tr><td>7</td><td>3 200</td><td colspan="8">Barley</td><td colspan="4">Late Potato</td></tr>
<tr><td>8</td><td>2 800</td><td colspan="7">Chickpeas</td><td colspan="3">Tobacco</td><td colspan="2">Fallow</td></tr>
<tr><td>9</td><td>700</td><td colspan="7">Favabeans</td><td colspan="4">Alfalfa</td><td>F.</td></tr>
<tr><td>10</td><td>800</td><td colspan="7">Favabeans</td><td>F.</td><td colspan="3">Corn</td><td>F.</td></tr>
<tr><td>11</td><td>6 500</td><td colspan="12">Fallow</td></tr>
<tr><td colspan="3">Total harvested land</td><td colspan="11">28 300 ha</td></tr>
</table>

Source: USAID (2014). F. stands for Fallow

3.1.5 Management

Management input files consists of two main sets of data on field management and irrigation management. Available literature on agricultural management strategies in the ULB were employed to learn about farming practices in the region (AquaStat, 2008; Jaafar & King-Okumu, 2016; USAID, 2014). AquaStat (2008) and USAID (2014) quantified the share of all irrigation techniques in general.

They only distinguished between individual crops in small sentences (e.g. “sprinklers are often used for potatoes” and “drip irrigation is used in coastal areas”). Jaafar and King-Okumu (2016) did also quantify percentages about how often an irrigation technique is used for all individual crops in the ULB.

This study used the deviation of farming techniques per crop of Jaafar and King-Okumu (2016) (see Table 5). They did not allocate the techniques spatially. The data was used by run the batch folder for an individual crop for each irrigation technique separately. The results of each simulation run were multiplied to the corresponding percentage (% > 0). From all studies, it pointed out that field management techniques such as mulches are not used in the ULB. For at least wheat and potato, the soil was well fertilized. It is assumed that fertilizers were used for other crops as well, so no fertility stresses.

All farmers in the surveys used sprinkler irrigation techniques, both for producing wheat and potato. On average, the irrigation depth for wheat was 75 mm, and for potato 63 mm. The interval between irrigation events were 60 days for wheat (supplementary) and 7 days for potato (full). These intervals were used for all winter and summer crops respectively. The irrigation depths for the remaining crops and used percentages for irrigation efficiency and surface wetted per irrigation technique were derived from FAO (2017). The input in AquaCrop-OS exists of total irrigation amount. The net irrigation used by crops is obtained by multiplying to the irrigation efficiency. The surface wetted by each irrigation technique affects the soil evaporation. The whole surface is wetted for surface and sprinkler irrigation, and therefore the soil evaporation is higher as for drip irrigation (30 % of the surface wetted).

Table 5 – Management techniques (irrigation and mulching) per crop type in the ULB.

Setting		Drip irrigation			Surface			Sprinkler			Field technique
Surface wetted [%] [a]		30			100			100			
Efficiency [%] [a]		90			60			75			
Crop	Area[ha] [b]	% [c]	Int [d]	mm [e]	%	Int	mm	%	Int	mm	Mulching
Alfalva	700	22	7	78	21	7	116	57	7	93	No
Barley	3 200	0	60	63	0	60	95	100	60	76	No
Chickpeas	2 800	10	60	56	0	60	84	90	60	67	No
Corn	3 800	0	4	63	4	4	94	96	4	75	No
Favabeans	2 000	8	60	63	39	60	95	53	60	76	No
E Potato	4 400	0	7	53	0	7	79	100	7	63	No
L Potato	3 200	0	7	59	0	7	89	100	7	71	No
Tobacco	2 800	22	7	56	21	7	84	57	7	67	No
Tomato	4 300	4	7	41	17	7	61	79	7	49	No
Wheat	7 800	0	60	63	0	60	95	100	60	76	No
Total	28 300										

Sources: [a] FAO (2017); [b] USAID (2014); [c] % irrigation type used (Jaafar & King-Okumu, 2016); [d] interval between irrigation events (Own field surveys); [e] irrigation depth (wheat and potato from own field surveys, other crops the characteristics from FAO (2017)).

3.1.6 Land Units

All spatial data of soil type, weather zone and land use type were combined to create homogenous Land Units (LUs). Data of each LU with similar crop type were put together in a crop batch folder, which also contains the irrigation technique(s) of the corresponding crop type. A list of al 225 LUs is given in Appendix A.5.

3.2 Initialization and parameterization

For a simulation model to perform well, it is required to have high and adequate input data and a good initialization of the model. This section describes the initialization and parameterization steps to run the model. A general setting is the consideration of a shallow groundwater table. USAID (2014) studied the geohydrology and stated that the average groundwater depth exceeds 2 m by far. A groundwater level was therefore not included in the model.

3.2.1 Initialization

The length of the simulation period depends on the climatic data, which was from January 2009 to December 2016. LUs could be in a form of a single summer crop or winter crop or with both type of crops. Depending on the crop types, the model was initialized in the first one or two seasons. Summer crops are fully grown in one year and could thus be run for 7 years. Winter crops are grown in two calendar years and could be run for 6 simulation years since winter crops starting in 2016 could not run the entire crop cycle. The model needs one year of initialization, which is not considered in the water accounting of the ULB. To harmonize the water accounting periods of summer and winter, the initialization of summer crops is 2 years. For LUs with both summer and winter crops, the accounting period starts at the begin of the second winter crop season. In all situations, the water consumption was accounted for six years. The simulation scheme is shown in Table 6. Out some trial and error, it pointed out that after few years of simulation, the soil balance was near field capacity at the start of the crop season. So, the initial soil value was at field capacity for all simulations.

Table 6 – Simulation scheme.

Season	2009	2010	2011	2012	2013	2014	2015	2016
Summer	1	2	3	4	5	6	7	8
Winter		1	2	3	4	5	6	7
Both	1	2-3	4-5	6-7	8-9	10-11	12-13	14-15
Period	Initialization period				Water accounting period			

3.2.2 Parameterization

A parametrization and calibration guide was provided by the drainage paper 66 of FAO (FAO, 2014a). They advise to start the simulations with estimated parameters (from literature) and compare the output with observed values, then adjust the parameters and run the simulation again. This procedure should be repeated until the simulated results closely agree with the observed data. The Root Mean Square Error (RMSE) was used as indicator to evaluate the model performance (Equation 3.1). The RMSE values give an indication of the deviation between the simulation results and observations:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{n}} \tag{3.1}$$

where O_i is the observed yield for simulation I, S is the simulated yield and n is the number of simulations. The observed data was derived from FAOStat, the statistical database of FAO. Observed yields were available until 2014, so the model performance was done for the years 2011 till 2014. The output for early potato and wheat was also compared to the obtained yields from our own survey.

The parameters for the first simulation run were obtained from the user manual of AquaCrop (FAO, 2017). Vanuytrecht et al. (2014) studied the sensitivity study of AquaCrop and showed that in water stressed conditions, the model is most sensitive to the parameters regarding the soil water characteristics, root development and emergence. During the calibration, most attention was paid to these parameters. The parametrization results are given in Appendix C.2 and C.3. A summary of the model performance for each crop is shown in Table 7.

Table 7 – Calibration performance per crop type.

Crop	RMSE [%]	Crop	RMSE [%]
Alfalva	No data	Potato[1]	6.25
Barley	2.93	Tobacco	7.12
Chickpeas	5.53	Tomato	4.35
Corn	3.46	Wheat	17.25
Favabeans	5.81		

1: Sum of early (58%) and late potato (42%) corrected for their areas.

3.3 Water Footprint Assessment

The output of the AquaCrop-OS model exists of crop growth characteristics and water fluxes. These output data was converted to the green and blue WF of a crop by following the post processed soil balances of Chukalla et al. (2015) and the WF procedure of Hoekstra et al. (2011). First, the soil water balance (Equation 2.5) was divided into a green and blue part (Equation 3.2 and 3.3). The environmental water fluxes (Rain, Irrigation and Runoff) are proportional to the green (rain) or blue (irrigation) origin. The fluxes from the soil water balance (percolation and evapotranspiration) are proportional to the soil water balance on the previous day. Next, the green and blue share of the crop water use (CWU) over the season were calculated (Equation 3.4 and 3.5). Last, the green and blue WF were obtained by dividing the CWU with the yield (Y) over the season (3.6 and 3.7).

$$Sg_t = Sg_{t-1} + (P_t + I_t - RO_t)\left(\frac{P_t}{P_t + I_t}\right) - (D_t + ET_t)(\frac{Sg_{t-1}}{S_{t-1}}) \tag{3.2}$$

$$Sb_t = Sb_{t-1} + (P_t + I_t - RO_t)\left(\frac{I_t}{P_t + I_t}\right) - (D_t + ET_t)(\frac{Sb_{t-1}}{S_{t-1}}) \tag{3.3}$$

$$CWU_{green} = \sum_{t=1}^{T} \frac{sg_t}{s_t} ET_t * 10 \tag{3.4}$$

$$CWU_{blue} = \sum_{t=1}^{T} \frac{sb_t}{s_t} ET_t * 10 \tag{3.5}$$

$$WF_{green} = \frac{CWU_{green}}{y} \tag{3.6}$$

$$WF_{blue} = \frac{CWU_{blue}}{y} \tag{3.7}$$

where S is the soil water content (mm) on day t, S_g is the green soil water content (mm), S_b is the blue soil water content (mm) CWU_{green} is the green water consumption (m^3), CWU_{blue} is the blue water consumption (m^3), the factor 10 is to convert from mm to m^3, WF_{green} is the green water footprint (m^3 per tons) and WF_{blue} is the blue water footprint (m^3 per tons).

3.3.1 Efficiency regarding WF of crops [Process perspective]

The annual green and blue water consumption (mm per year) per LU were derived from the WF accounting with Equation 3.9 and 3.10.

$$LUcon_{green} = WF_{green} * \frac{1}{10} * yield \tag{3.9}$$

$$LUcon_{blue} = WF_{blue} * \frac{1}{10} * yield \tag{3.10}$$

where $LUcon_{green}$ is the seasonal green water consumption (mm), LU_{blue} is the seasonal blue water consumption (mm) and the factor 10 is to convert from m^3 to mm. The LU_{cons} are summed for the LUs that contains two crops in rotation. The spatial distribution of LU_{cons} are displayed on the ULB map.

The WF for each crop were analyzed by comparing the performance per soil type, weather zone and management types. This analysis helps to identify over and underperforming regions and techniques. The WF of a crop was obtained by summing the WF for all relating LUs for that crop, corrected for its relative contribution (see Equation 3.11).

$$WF_{crop} = \sum WF_{LU} * \frac{Area_{LU}}{Area_{crop}} \tag{3.11}$$

3.3.2 Economic and nutritional value WF of crops [Product perspective]

From the introduction (Section 1.4.1), we know that it is important for catchments in sub-arid regions to be efficient with water consumption. It was further described that a growing number of people in countries in the NENA region faces severe famines due to water scarcity. Food production is thus of major importance in the ULB. The main focus should therefore be on producing crops that represent a high nutritional value in order to meet the basins food demand. The remaining share of available water should be used to produce crops with a high economic value.

The basins food demand is estimated by multiplying the basin-population with a needed number of calories per capita. USAID (2014) stated the population in 2010 to be around 375 000, but it will increase to 450 000 by 2030. Goal of this study is to provide a sustainable scenario for the future, so the estimated population of 2030 is taken as baseline of the assessment. According to the United Nations, the daily energy requirements for a moderate active person with a mean bodyweight are 2 355 kcal. Crops are mainly eaten for its carbohydrates, not for their fats and proteins. Therefore, it is assumed that foods that are rich in proteins and fats should be imported. The recommend part of carbohydrates is between 40% and 70% of the total energy intake. A value of 50% was considered as the fraction of energy that should come from crops. It makes the total annual food demand for the ULB at 2 355 * 365.25 * 450 000 * 0.5 = 193 537 *10^6 kcal.

The produced food and cash per crop were obtained by considering the nutritional and economic blue water productivity. The nutritional blue water productivity (NBP) is the amount of kcal per m^3 of blue water. The economic blue water productivity (EBP) is the amount of US$ per m^3 of blue water. The NBP and EBP were obtained by multiplying the blue water productivity (t/m^3) to the nutritional (kcal/t, Equation 3.12) and economic value ($/t, Equation 3.13). The blue water productivity per crop is the inverse of the blue WF, which is already obtained in Equation 3.7. The nutritional and economic value per crop were obtained from literature. The economic and nutritional production per crop were derived by multiplying the NBP and EBP with the total blue water volume per crop (Equation 3.14 and 3.15). The total annual economic and food production in the basin was obtained by summing over all crops.

$$EBP = \frac{1}{WF_{blue}} * economic\ value\ (\$/t) \tag{3.12}$$

$$NBP = \frac{1}{WF_{blue}} * nuritional\ value\ (kcal/t) \tag{3.13}$$

$$economic\ production = EBP * blue\ volume \tag{3.14}$$

$$food\ production = NBP * blue\ volume \tag{3.15}$$

The economic value per crop varies over the study period (2011 – 2016), depending on external economic factors. FAOStat provides free access to food and agriculture data over 245 countries and territories. This database has the price of agricultural products, what farmers received over their crops. The producer prices for Lebanon were taken from the database to value the crops in the ULB. No data was available for the year 2016, and for some crops neither in some other years. Therefore, the values for 2015 were repeated for 2016. For other gaps, the data was taken from countries for which prices are most similar to Lebanon; for barley, from Turkey; for Corn, from Jordan and for Chickpeas, Favabeans, Tobacco and Wheat from Iran. The nutritional values for crops were derived from the Dutch Food Centre (Dutch Food Centre, 2017). The amount of kcal per 100g is multiplied to 10 000 to convert to kcal per tons. The economic and nutritional values per crop are shown in Table 8.

Table 8 - Nutritional and economic values of major crops in the ULB.

Economic value [$/t][a)]	Alfalfa	Barley	Chick peas	Corn	Fava beans	Potato	Tobacco	Tomato	Wheat
2011	65.8	263.3	1082.1	253.1	2475	268.7	3372.4	417.2	321.4
2012	65.8	291.2	1672.1	218.2	1704.8	363.5	7106.3	445.1	391.4
2013	65.8	267.3	1376.1	230.1	1936.5	460.3	8358.2	468.5	391.4
2014	65.8	284	738.3	304.9	1331.1	439.9	4368.2	506.8	391.4
2015	65.8	215.6	865.5	199	1462	416.6	7827.5	505.5	232.2
2016	65.8	215.6	865.5	199	1462	416.6	7827.5	505.5	232.2
[million kcal/t] [b]	2.9	33.3	15.5	35.4	3.9	8.5	0	1.9	32.9

Sources: [a)] FAOStat (2017); [b)] Dutch Food Centre (2017).

3.3.3 Blue water scarcity [Geographic perspective]

The water scarcity of the ULB was assessed in a monthly basis by comparing the total blue WF to the sustainable water availability. The monthly blue WF per crop was assessed using the AquaCrop-OS model. In addition, blue WF of households, industries and trees were taken into account, using available resources. The blue WF of these groups were taken from USAID (2014). They estimated the future water consumption (2030) for domestic and industrial demands to be 25 million m^3 per year.

This value was already corrected for return flows, and is uniformly divided over the year. For trees, they estimated an annual irrigation demand of 25 million m^3, divided over 5 months in the summer period (April – August) that resulted in 5 million m^3 per month.

The sustainable water availability is the natural discharge minus the environmental flow requirements (EFR) according to Hoekstra et al. (2011). They suggest to consider the EFR to be 80% of the natural discharge. The natural discharge is the resulting flow from environmental processes, without any human intervention. It is hard to determine this natural flow at this time, because of widespread (illegal) irrigation events. So, the natural flow was based on historical measurements. The most reliable historical measurements were for the period 1938-1962 (USAID, 2014). The annual flow was then estimated to be about 411 million m^3. The irrigation volume was then about 30 million m^3, so the annual natural flow is 441 million m^3. The monthly natural flow was calculated by multiplying the observed monthly flow (1938-1962) with $\frac{441}{411}$ to correct for the irrigation in that period.

The monthly sustainable water availability and demands for domestic, industries and trees are shown in Table 9. The demands from households, industries and trees already exceeded the sustainable water availability during May – August, without even considering crops. Therefore, three additional options were added to increase the water availability in a responsible way.

- Lower EFR demand: Zhuo et al. (2016) mentions that an EFR of 80 % is probably too strict. For this study, the EFR was set at 60 % of the natural flow.
- Approve little fossil water extraction: in Section 4.1.1 was mentioned that the abstraction of fossil water should be as low as possible. Currently, the annual abstraction is estimated at 80 million m^3. USAID (2014) in collaboration with the Litani River Authority formulated a future scenario where they approve an abstraction of 30 Mm^3. For this study, an abstraction of 10 million m^3 from fossil groundwater was considered an acceptable rate.
- A new irrigation scheme: It was also mentioned by USAID (2014) that an irrigation canal, C900, is planned. In this canal, water can be transported from Lake Qaraoun to upstream areas in the ULB. The canal is able to increase water availability up to 30 million m^3. Water should be abstracted from the Litani river during the wet winter.

The adjusted water availability+ is then as follow:

$$Availability^{+} = Natural\ flow - EFR\ 60 + C900 + Approved\ fossil \tag{3.16}$$

where EFR 60 is the Environmental Flow Requirement of 60 % of the natural flow, C900 is the added irrigation water supply ($\leq 30\ million\ m^3\ per\ year$) and the approved fossil water extraction ($\leq 10\ million\ m^3\ per\ year$).

The availability+ and the described adjustments are shown in Table 9. All fluxes with exception of the crops are shown in Figure 10. It also shows the current runoff measured in 2011. The annual current runoff was used to calculate the abstraction from fossil groundwater storages. The difference between natural and current runoff is caused by the blue WF which had renewable water as irrigation source. The current annual runoff according to USAID (2014) is 300 million m^3. The natural runoff is 440 million m^3. The part of the blue WF that was higher than this difference must be extracted from fossil groundwater. The calculation of annual fossil extraction is given in Equation 3.17. The remaining blue WF was extracted from renewable water. The renewable water is all water that contribute to the annual natural runoff (surface flow and base flow).

$$Fossil_{year} = WF_{Blue_{year}} - \left(Natural_{year} - Current_{year}\right) = WF_{Blue_{year}} - 140 \tag{3.17}$$

Monthly rate of water scarcity was assessed following Hoekstra et al. (2011). Here, the water scarcity is the ratio of blue WF over by the renewable water resources (availability+). The water scarcity levels exist of low (< 100%), moderate (100-120%), significant (120 – 140%) and severe water scarcity (> 140%).

Table 9 - Flow types (in million m^3) in the ULB.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot
O.Flow [a)]	63	79	78	55	33	17	11	9	10	13	16	28	411
N.Flow [b)]	67.4	84.6	83.5	58.9	35.3	18.2	11.8	9.6	10.7	13.9	17.1	30	441
EFR 80 [c)]	54.0	67.7	66.8	47.1	28.3	14.6	9.4	7.7	8.6	11.1	13.7	24.0	353
Ava [d)]	13.5	16.9	16.7	11.8	7.1	3.6	2.4	1.9	2.1	2.8	3.4	6.0	88
D+I [e)]	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	25
Trees [f)]	0	0	0	5	5	5	5	5	0	0	0	0	25
EFR 60 [g)]	40.4	50.8	50.1	35.3	21.2	10.9	7.1	5.8	6.4	8.3	10.3	18.0	265
Fossil [h)]					2	2	2	2	2				10
C900 [i)]	-10	-10	-10		1	8	9	9	3				30
Ava+ [j)]	17.0	23.8	23.4	23.6	17.1	17.3	15.7	14.8	9.3	5.6	6.8	12.0	186

Sources: [a)] Old flow (1938-1962) from USAID (2014); [b)] Natural flow = old flow + irrigation (1938-1962); [c)] Environmental flow requirements of 80% based on Hoekstra et al. (2011); [d)] Sustainable availability = N Flow – EFR 80; [e)] Domestic and industrial blue WF from USAID (2014); [f)] Perennial (tree) crop blue WF from USAID (2014); [g)] Adjusted less stringent EFR; [h)] allowed fossil extraction based on but (more stringent) USAID (2014); [i)] Additional irrigation supply from canal c900 based on USAID (2014); [j)] Adopted sustainable availability = N Flow – EFR 60 + Fossil + C900.

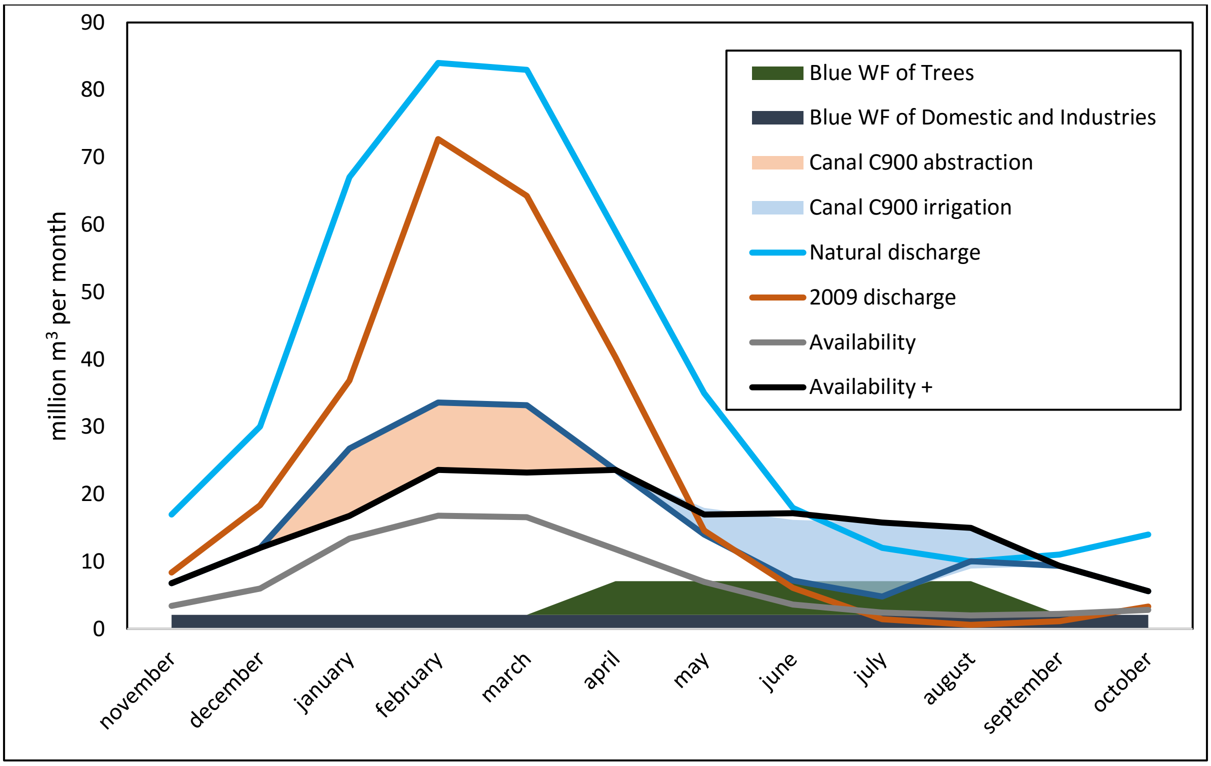

Figure 10 - Reference situation of natural [a)] and measured [b)] water flows in the ULB; regular [c)] and adjusted [d)] sustainable water availability; and blue WF of domestic and trees [e)].

Period: 2011-2016. Source: [a & b)] USAID (2014); [c)] based on EFR of 80%; [d)] based on EFR of 60 % and including 30 million m^3 of irrigation water supply from Canal 900 and allowed fossil water abstraction of 10 million m^3 per year; [e)] USAID (2014).

3.4 Response scenarios

In the fourth phase of the WFA, scenarios are formulated. From the literature review (Section 2.1), we learned that the ULB is facing severe water stresses. USAID (2014) had formulated some potential improvements such as mulching as a farming technique and increasing the area of drip irrigation installations. Chukalla et al. (2015) stated that both are water saving techniques compared to farmlands where no mulches were applied and surface or sprinkler irrigation techniques were used. Especially in a semi-arid environment, a combination of these two techniques were expected to have large positive effects.

The first scenario exists of the introduction of mulches for all crops. The second scenario exists of mulches for all crops and drip irrigation for all summer crops. A third scenario was formulated based on the WF analysis from the process, product and geographic perspective. From the geographic perspective, the months in which water scarcity occurs were identified. From the product perspective, we know which crops are most contributing to this water scarcity. It is also derived which crops are important for food and cash production. In this scenario, the low value crops were removed or replaced by high value crops until water consumption exceeds water availability Further consists this scenario of the best performing techniques, derived from the process perspective.

The three formulated scenarios are:

- Scenario 1: Mulching to all crops
- Scenario 2: Scenario 1 + drip irrigation for all summer crops
- Scenario 3: Scenario 2 + relocation of crops

Chapter 4

Results

The results for the AquaCrop-OS model are presented in this chapter. Section 4.1 is about the results for the reference scenario from a process perspective. Section 4.2 is from a product perspective and Section 4.3 from a geographic perspective. In section 4.4 are the effects of three response scenarios described.

4.1 Efficiency regarding WF of crops [Process perspective]

The green and blue WF for the major crops in the ULB were analyzed in this section. The variation of WF for each crop type were investigated to identify poor and well performing conditions. The average green, blue and total water consumption are shown in Figure 11. It shows that the share of blue WF is the highest in the total WF. LUs with crop rotation used more water compared to single crops, and are demonstrated dark red in the right map. The amount of blue water was up to 1 000 mm per year for crops in rotation.

The WF of each crop was calculated with Equation 3.11. The settings in Table 5 are used as irrigation properties in the reference case. The WF per irrigation technique was multiplied to the percentage how much that technique was used. The total WF of a crop type is the sum over all techniques.

The influence of the four soil types orthents, xeralfs, xerepts and xerolls and six climatic zones on the performance in WF is shown in Figure 12. The bars show the relative deviation of the total WF to average total WF. The relative difference for each soil type and climate zone were obtained. A deviation of 10 % for example means that the total WF is 10 % higher. Bars that has negative values represents thus more efficient water consumption. When bars were missing (e.g. tobacco and tomato in zone 3), it means that that type of crop was not growing in that area.

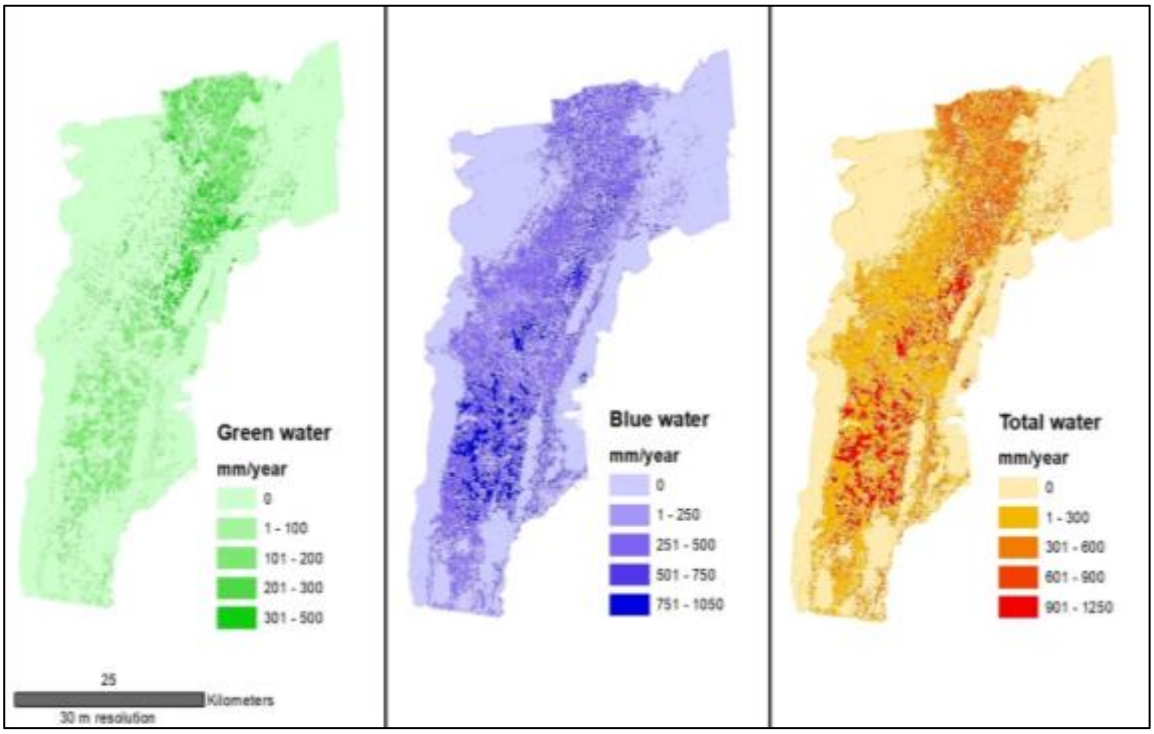

Figure 11 – Spatial distribution of average annual green, blue and total water footprints of crops, industries, households and trees in the ULB.

Period: 2011-2016.

It can be noticed that the variation of total WF between different soil types was limited. For the soil type orthents, the WF was little higher as average for all crops. Orthents is thus not preferred for crop production which is expressed in the spatial distribution of crops over the ULB. Not many crops are planted on locations with orthents as soil. They are mostly located on xeralfs and xerolls soils. The performance on these soils was little higher but the effects were also limited (< 5%). Larger differences were noticed over different climate zones. Mainly for wheat were high outliers, ranging from -18 to 30%. The difficulty in modelling of winter wheat with AquaCrop was earlier discussed by Van Gaelen et al. (2016) and should be investigated further. The sensitivity was lower for other crops. For each zone were both crops that uses more water as crops that used less water as average. The obtained influence of soil and climate on WF are in line with the analysis of Zhuo et al. (2014). They concluded that the WF is mainly sensitive for climatic factors and less to soil type.

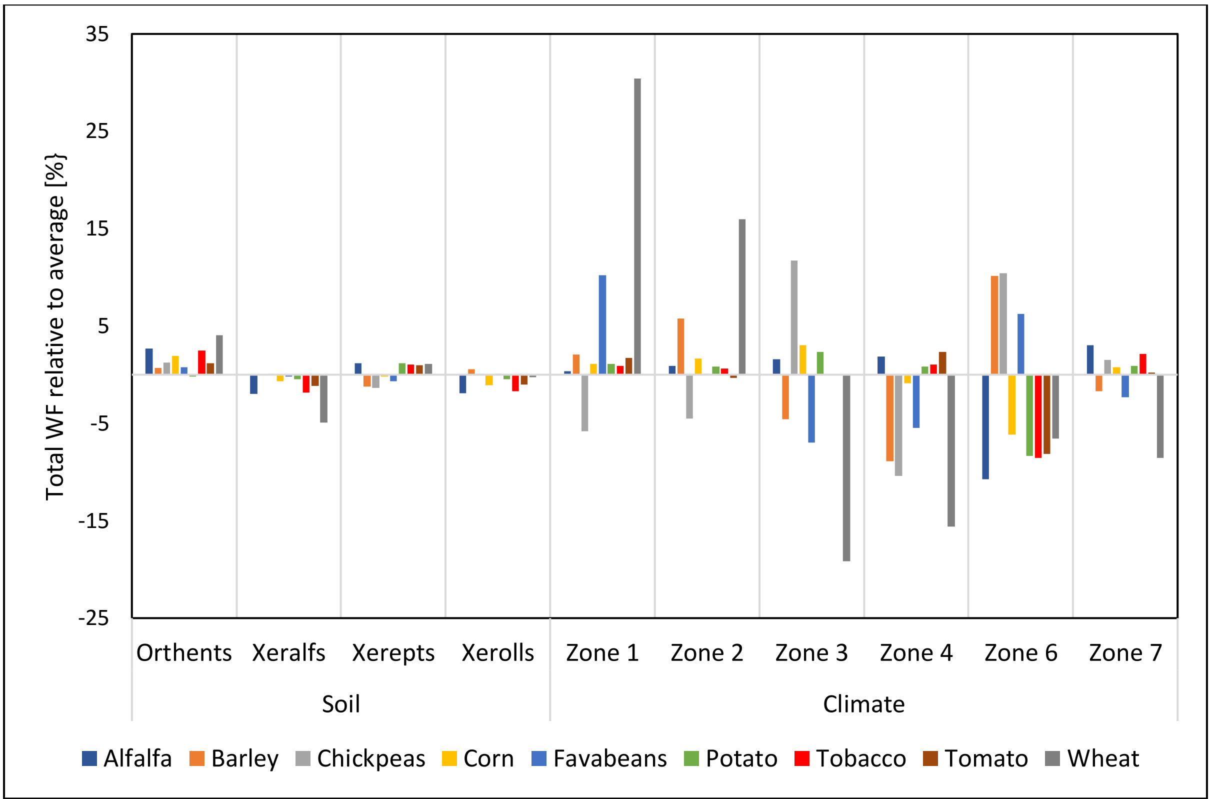

Figure 12 – Variation in total WF per crop type across different soil types (left) and climate zones (right) in the ULB.

Period 2011-2016.

Figure 13 shows the obtained green and blue WF for all relevant management types and results from Mekonnen and Hoekstra (2011) for the Beqaa valley (except for alfalfa). Missing bars were because that type of management is not considered in this study. The reference situation was with the mentioned settings for irrigation technique observed (Table 5) and without use of mulches. Scenario 1 was with the same irrigation settings but with use of mulches. The WF for the three irrigation techniques exists of the situation for that technique with mulching and without mulching, both counting 50%.

While the total WF for winter crops were quite similar, Mekonnen and Hoekstra (2011) estimated a higher green over blue WF fraction. These differences can be explained by the fact that Mekonnen and Hoekstra (2011) did not consider crop rotation. This can be noticed for favabeans and wheat, which are growing both in rotation with other crops and in a monoculture scheme. The share of blue WF is higher for both wheat and favabeans, when they are grown in rotation. This makes sense because the blue part of the soil water balance had increased during irrigation events in the summer season. The obtained WF for all summer crops were higher compared to Mekonnen and Hoekstra (2011). While the data for this study was limited, especially about crop development, the spatial resolution for weather data was significant higher, and field surveys was included. The same was true for the crop calendar in this study. The high green WF for summer crops by Mekonnen and Hoekstra (2011) is thus unrealistic, since rainfall is very limited in the summer. It was further shown that mulches and drip irrigation are water saving techniques. The WF of all crops decreased by using mulches. The same trend of higher water efficiency was observed for the use of drip irrigation instead of surface or sprinkler.

The conclusion of the process analysis is that the use of mulches and drip irrigation had water saving effects on crop production. Without exception, the WF will decrease due to these measures. Further was found that there are no environmental characteristics that had significant water saving effects. This knowledge is important for the formulation of Scenario 3 which was about the relocation of crops in the ULB.

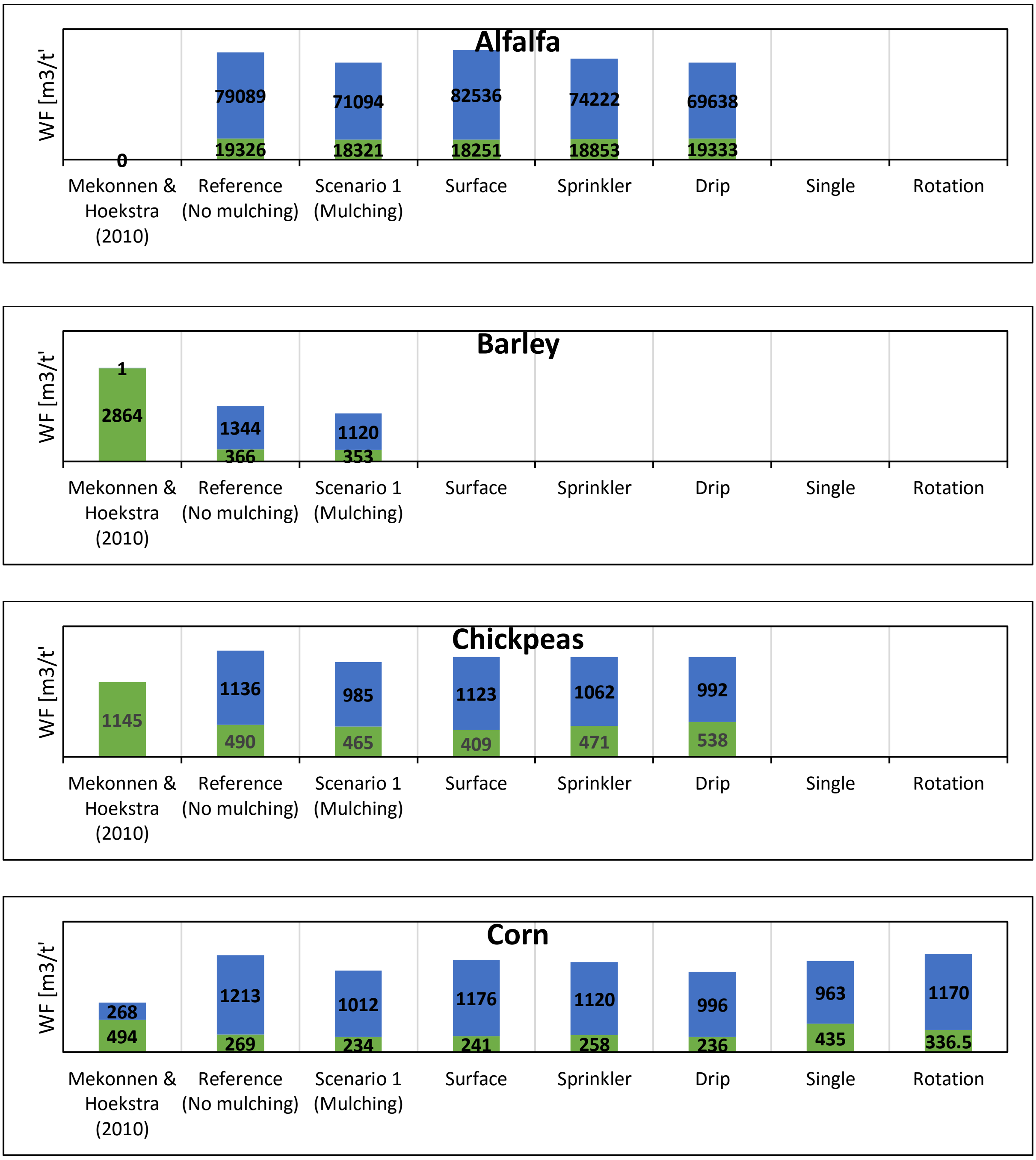

Figure 13 - WF of crops for different techniques and management types in the ULB.

Period: 2011-2016.

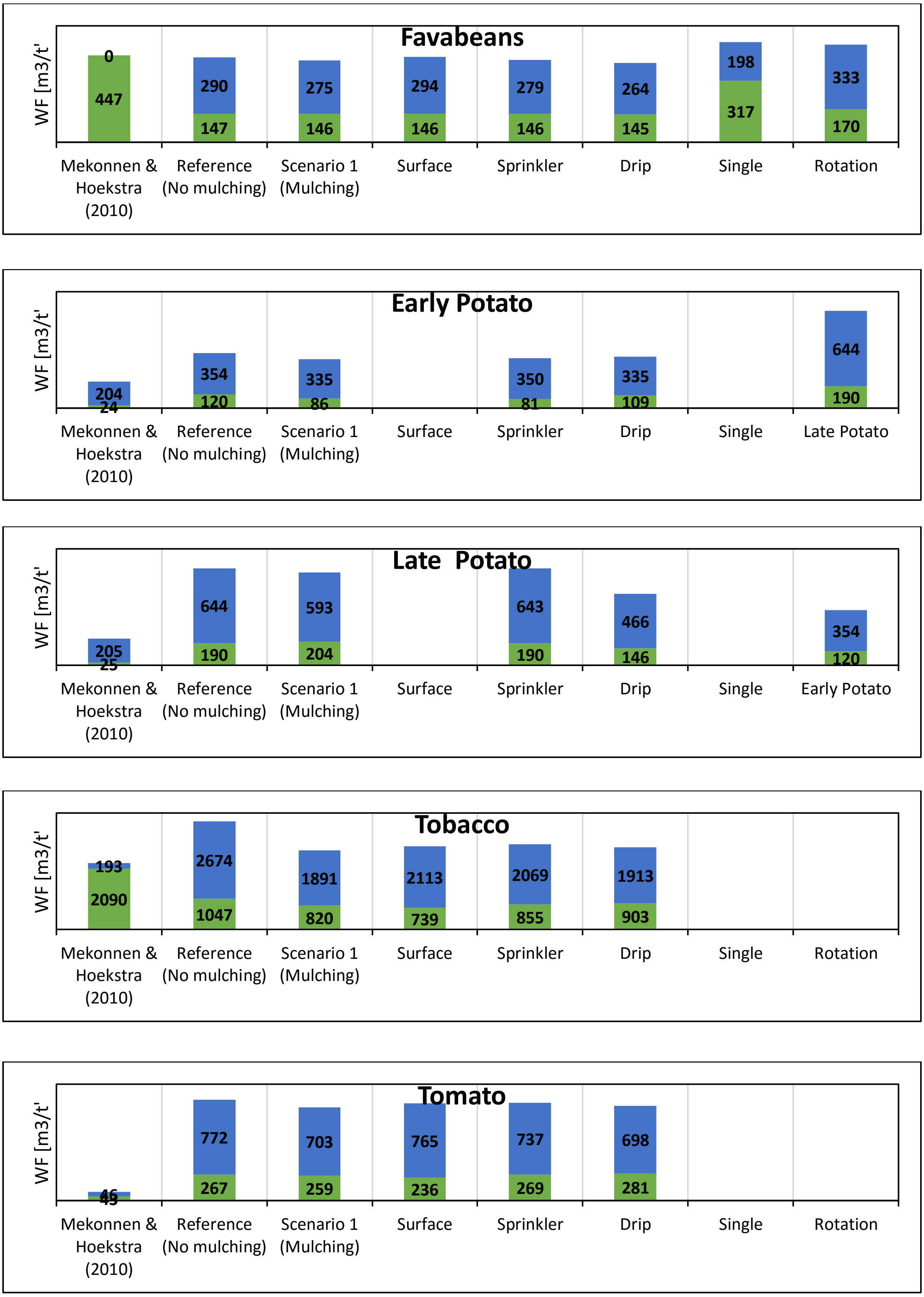

Figure 13 - WF of crops for different techniques and management types in the ULB.
Period: 2011-2016.

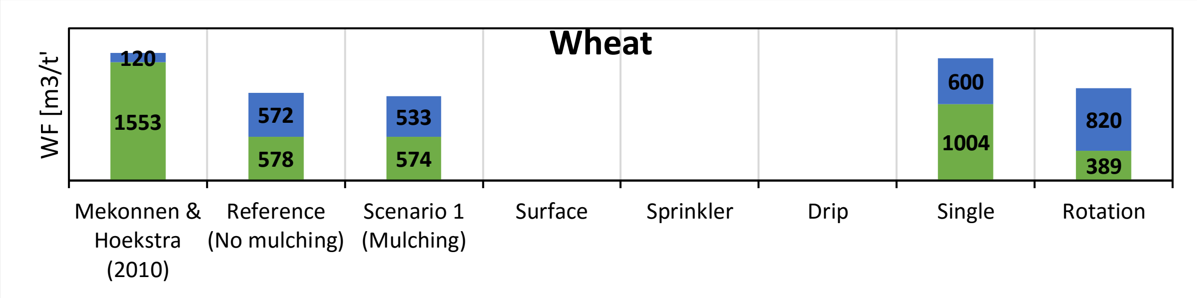

Figure 13 - WF of crops for different techniques and management types in the ULB.

Period: 2011-2016.

4.2 Economic and nutritional WF of crops [Product perspective]

The economic and nutritional blue water productivity (EBP and NBP) of crops is important for identifying high and low value crops. These are shown in combination with their total annual water consumption in the period [2011-2016] in Figure 14. It shows that wheat and favabeans were the best performing crops regarding NBP and EBP respectively. This is because both grows in the winter and thus the share of green is larger compared to summer crops. The amount of kcal per tons for corn and wheat were 35 and 33, respectively. However, the blue WF of corn was 1 213 which is extremely higher than WF of wheat, 120. The same phenomenon was in EBP of favabeans and tobacco. The US$ value of tobacco is 4 to 6 times larger than that of favabeans. Again, the higher blue WF of tobacco leads to less US$ per m^3 compared to favabeans.

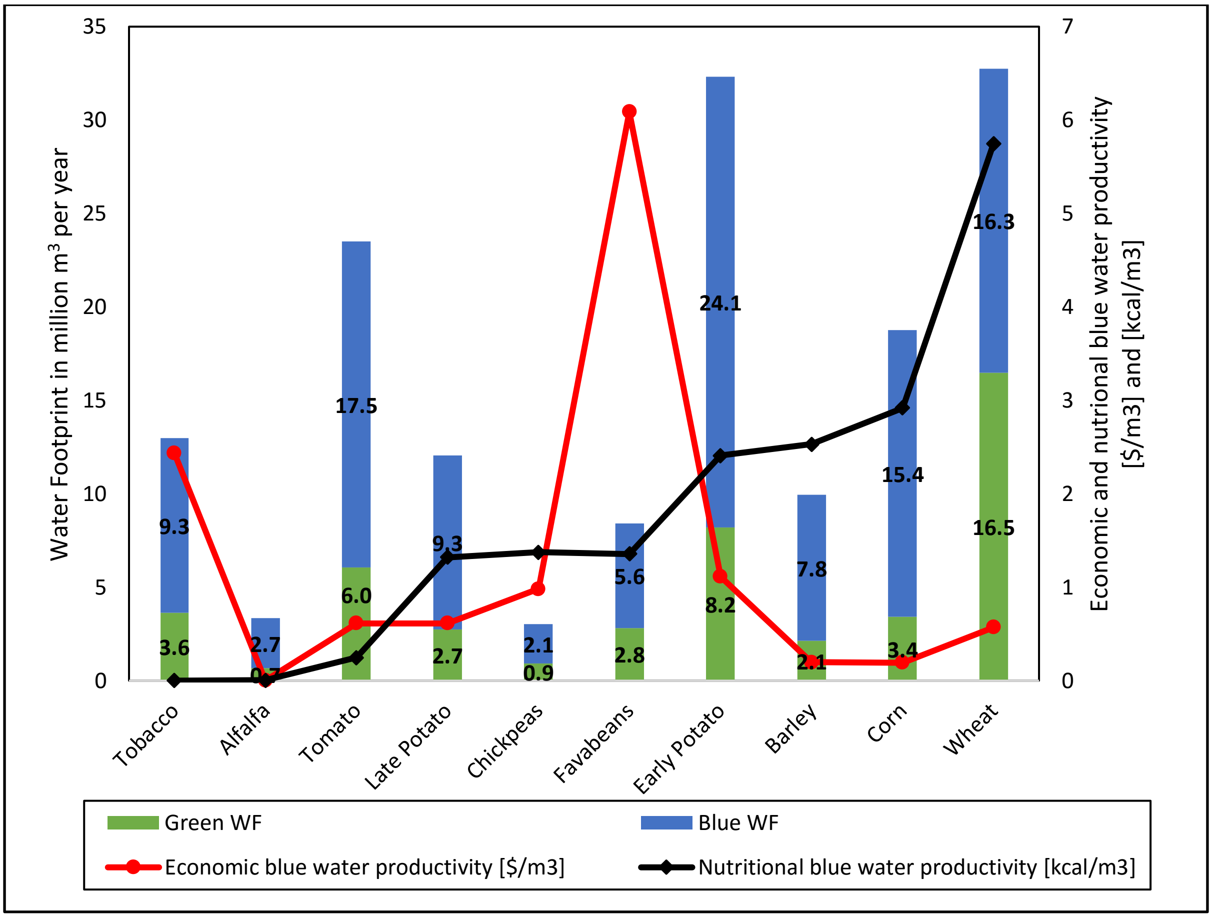

Figure 14 – Annual green and blue WF of crops in the ULB and their nutritional blue water productivity (NBP) and economic blue water productivity (EBP).

Period: 2011-2016.

Interesting result was obtained for the NBP and EBP of tomato. USAID (2014) stated that this crop is mainly grown for its high value. Considering the summer crops, tomato had indeed the highest amount of US$ per tons. However, the EBP is very low due to high blue WF. Moreover, tomato performs also low on the nutritional productivity. Production of corn results in a higher amount of kcal per m^3 of irrigation water. However, corn is mainly used as feed for livestock and does not directly contributes to the human food demand. This is also the case for alfalfa. To discuss thoroughly, we divided the crops into three groups of cash crops, (human) food crops and feed crops. Cash crops include favabeans, tomato and tobacco; food crops include early potato, late potato, chickpeas, barley and wheat; feed crops include alfalfa and corn. As it was mentioned in the introduction, this research aims to produce enough food to feed the basins population, and that the remaining water must be used for high value crops. Feed crops represent thus lowest value, since they are mainly used for production of an un-necessary product such as meat and dairy that do not contributes to the food cash production.

The basins annual food demand that should came from crops was defined at 193 537 million kcals. The current food production was estimated at 186 094 million kcals, which is lower than the basins demand. The cash production in the current situation is 67 million US$. Both the food and cash production per crop type are shown in Figure 15. The relatively low share of tomato on the cash production could be noticed compared to its high annual blue WF. The high NBP of wheat in relation to its high annual blue WF was expressed in a high share of wheat in the total food production.

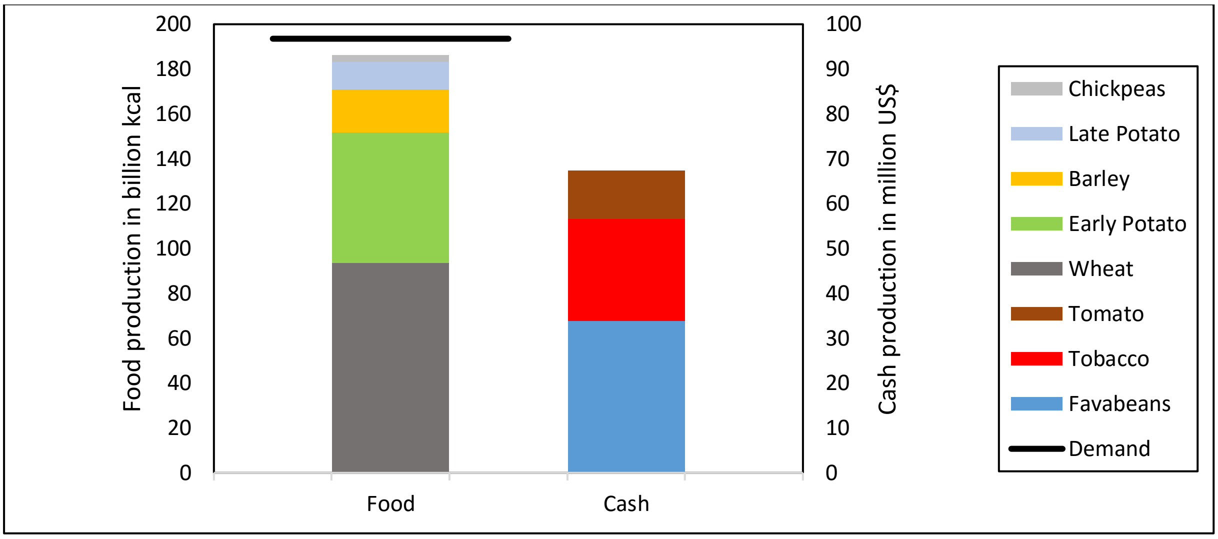

Figure 15 - Annual food and cash production of major crops in the ULB.

Period: 2011-2016.

The product analysis shows that corn, alfalfa and tomato are of low value for the ULB. The food production can be increased most efficiently by producing more wheat. Higher food production is necessary since the basins food demand is not met currently. Tobacco and favabeans delivers the most US$ per m^3 of water.

4.3 Blue water scarcity [Geographic perspective]

The monthly water footprint for all crops from 2011 to 2016 were summed and compared with the calculated availability$^+$ in section 3.3.4. Figure 16 shows the average monthly blue WF and the relevant water fluxes. It can be noticed that water shortages occur from May till October, resulting in an average fossil water abstraction of 37 million m^3 per annum. A water abstraction of 10 million m^3 per annum was considered as an acceptable rate, so the annual overexploitation of water is 27 million m^3. Table 10 shows the rate of the monthly blue water scarcity in the period 2011-2016. The ULB faces 3 months of severe water scarcity per year, mainly in the summer. In the winter is low water scarcity and in the spring, is moderate to significant water scarcity.

Table 10 - Water scarcity for all months in the ULB.

Year	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
2011	0.31	0.58	0.42	0.32	0.58	0.86	1.09	1.20	1.71	1.80	2.28	0.99
2012	0.67	0.59	0.38	0.37	0.52	1.01	1.13	1.30	1.68	1.82	2.25	0.55
2013	0.64	0.56	0.39	0.35	0.60	0.77	0.93	1.21	1.50	1.75	2.10	0.85
2014	0.60	0.56	0.44	0.38	0.63	0.86	0.90	1.28	1.70	1.88	2.12	0.77
2015	1.07	0.68	0.43	0.37	0.63	0.81	0.97	1.20	1.65	1.81	2.12	0.49
2016	0.31	0.62	0.44	0.44	0.64	0.97	0.98	1.30	1.61	1.92	1.90	0.52
Mean	0.60	0.60	0.42	0.37	0.60	0.88	1.00	1.25	1.64	1.83	2.13	0.70

Low scarcity (≤ 1) 44 months	Moderate (1 – 1.2) 5 months	Significant (1.2 – 1.4) 5 months	Severe (> 1.4) 18 months

Blue water scarcity is the ratio of total blue WF in the ULB over the adjusted water availability based on EFR of 60%, irrigation supply from Canal 900 and allowed fossil abstraction.

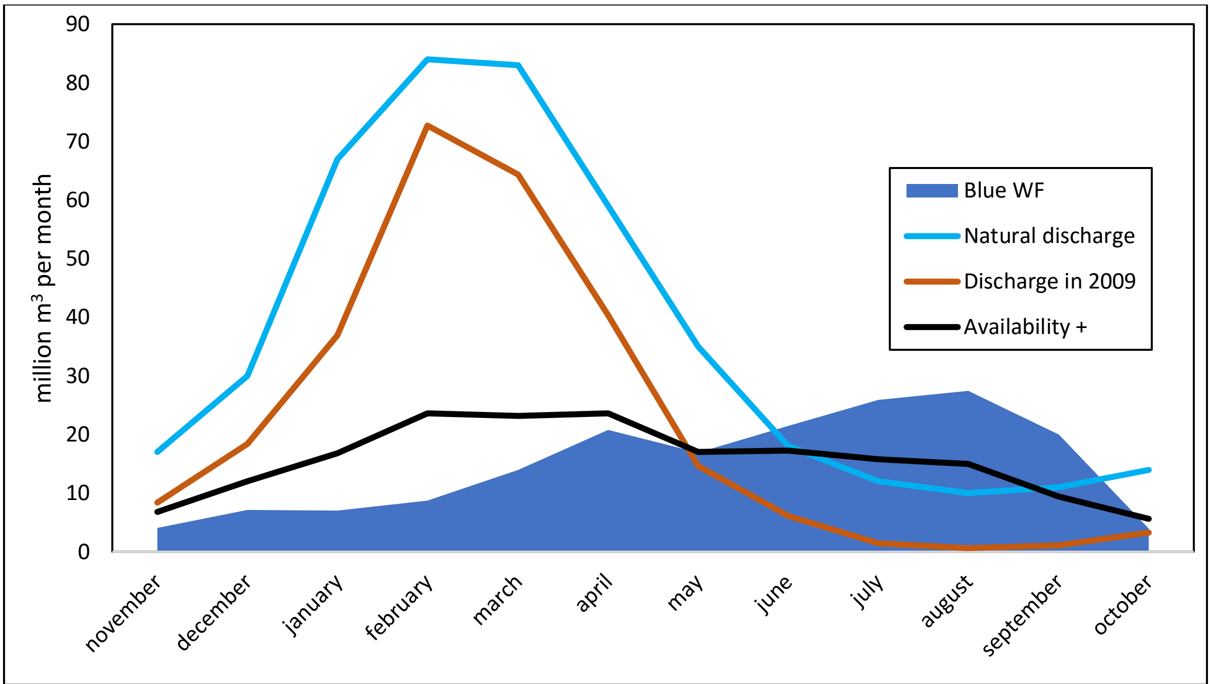

Figure 16 - Monthly blue WF in the ULB for reference [a)]; natural [b)] and measured [c)] flows types and adjusted [e)] sustainable water availability.

Period: 2011-2016. Sources: [a & b)] USAID (2014); [c)] based on EFR of 60 % and including 30 million m^3 of irrigation water supply from Canal 900 and allowed fossil water abstraction of 10 million m^3 per year.

A safety margin of 20% of the blue water WF of crops was included to account for some additional loses from the system. These loses including irrigation loses because of windy conditions, illegal water extractions and the water use for lettuce which represents the remaining 6% of the total harvested area. The total blue water consumption of crops per annum is 127 million m^3. The total blue water consumption is 177 million m^3 which is lower than what was estimated by USAID (2014) and Jaafar and King-Okumu (2016) as shown in the overview in Table 11.

The differences between this study and USAID can be explained because they overestimated the crop water demands. They used very rough estimations about mm/ha/year for crop types from FAO and assumed optimal conditions for crop development, without considering the actual crop yields. The relation between crop water use and biomass was expressed in AquaCrop with Equation 2.2 & 2.3. A high biomass production needs more water as for the same crop but with lower biomass production. The crops in this study were parameterized to correct for observed yields (Appendix C.2). The actual crop water use was thus lower because biomass production in the ULB was not optimal and crops used less water. Further, their estimations did not consider crop rotations as in this study. From Figure 13, we knew that irrigated water in one season is not entirely lost in the next season. The irrigation demands should therefore not simply be summed since these demands will decrease due to irrigation events in earlier seasons.

Table 11 - Total water usages per group in this study and previous studies.

Annual blue WF [million m^3]	Per user type			Per source		Total
	Domestic	Trees	Crops	Renewable	Fossil	
USAID (2014) [a)]	20	25	165	140	70	210
Jaafar and King-Okumu (2016) [b)]	60	-	332	305	87	392
This study [c)]	25	25	127	140	37	177

Accounting period: [a)] 2011; [b)] 2016; [c)] 2011-2016.

The average monthly blue water consumption per user type is shown in Figure 17. The areas in the figure represents blue WF of crops. It can be noticed that more blue water could be abstracted from the system from November to May. These results are in line with results from previous section, that annual blue WF of summer crops is highest (Figure 14). It can be derived from the figure that low value crops including tomato, corn and alfalfa has a high blue WF, while the availability is low in that period. In contrast, there is a potential to enhance blue water consumption for winter crops.

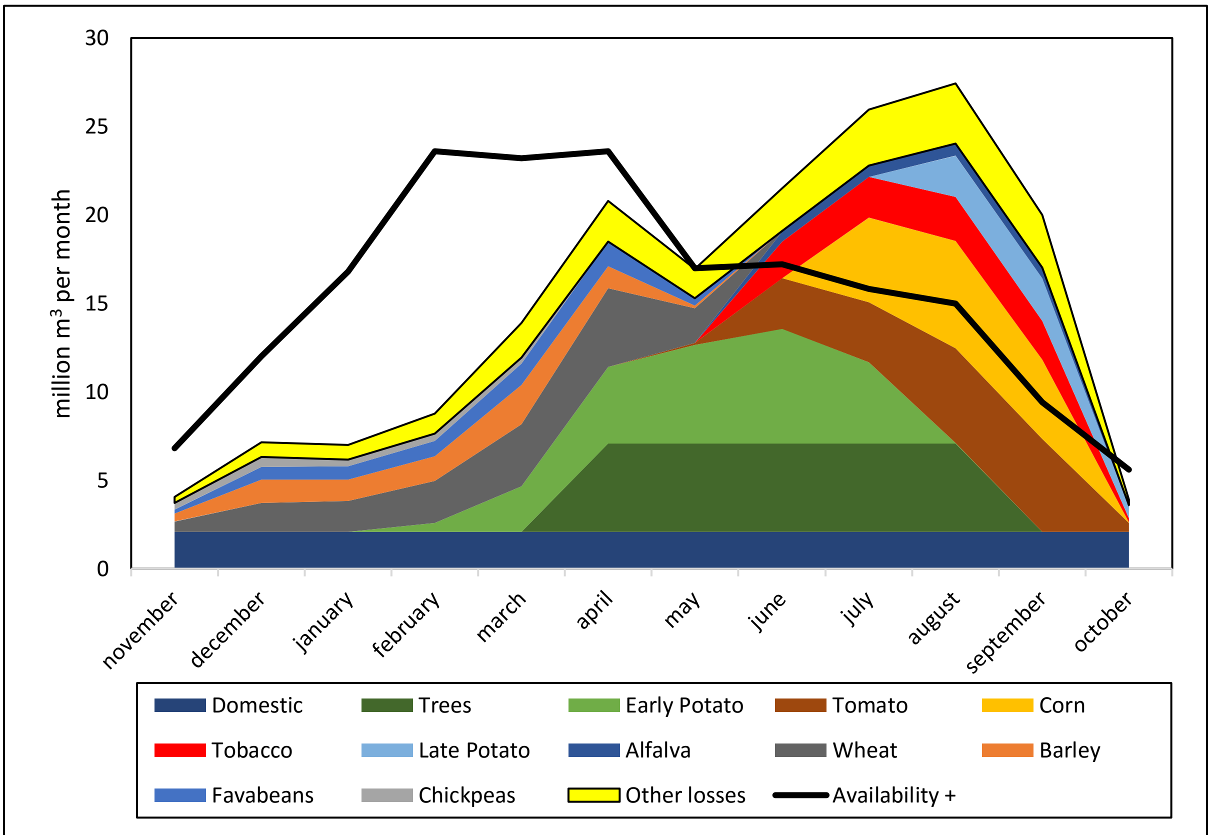

Figure 17 –Monthly blue WF per user type in the ULB and the sustainable availability [a)] of blue water in reference situation.

Period: 2011-2016. Source: [a)] USAID (2014).

4.4 Response scenarios

The effects of the three scenarios to save water in the ULB were introduced to the AquaCrop-OS model. The first scenario was to add mulches for all crops. In the second scenario were drip irrigation techniques for summer crops added to the mulching practices. The third scenario was about the relocation of high value crops based on the effects of the first and second scenarios and the analysis in the previous chapter.

- Scenario 1: Mulching for all crops
- Scenario 2: S1 + drip irrigation for all summer crops
- Scenario 3: S2 + relocation of crops

4.4.1 Scenario 1

The effects of scenario 1 on blue water reduction are 6.30 million m^3 per year. This is a relative blue WF reduction of 3.6%. The safety margin decreases a little bit as well, because of the decrease in total crop water use. This is justified because the safety margin represents irrigation loses and the water use of lettuce. The latter is a summer crop, and all improvements are applied to this crop too. The fossil water abstraction of 37 million m^3 reduces to 31 million m^2, which is a reduction of 16.9%.

4.4.2 Scenario 2

The additional water saving effects of drip irrigation are 2.06 million m^3 per year. The total effects of scenario 2 on blue water reduction are 8.36 million m^3 per year. This is a relative blue WF reduction of 4.7%. As in Scenario 1, the safety margin decreases a little bit as well. The fossil water abstraction of 37 million m^3 reduces to 29 million m^2, which is a reduction of 22.4%.

An overview of the effects of scenario 1 and 2 is shown in Table 12. There was an annual amount of 37 million m^3 that comes from fossil groundwater. This overexploitation can decrease by 16.9% in scenario 1 and by 22.4% in scenario 2. The current overexploitation is very intense for minimal 3 months per year in which the blue WF exceeds the natural runoff even twice. A water saving is achievable by modest adaptive strategies like mulching or replacing current irrigation techniques to drip irrigation. The current cropping pattern with a large focus on summer crops remains unsustainable that needs an urgent action taking into account the severe water scarcity challenges.

Table 12 – Blue water saving effects of scenario 1 and scenario 2.

	Scenario 1[a)]		**Scenario 2[b)]**	
Crop type	**million m^3**	**%**	**million m^3**	**%**
Alfalfa	0.29	10.8	0.41	15.1
Barley	1.04	13.1	*1.04*	*13.1*
Chickpeas	0.27	12.8	*0.27*	*12.8*
Corn	1.94	12.6	2.96	19.3
Favabeans	0.08	1.5	*0.08*	*1.5*
Early Potato	0.42	1.8	1.39	5.8
Late Potato	0.30	3.2	0.53	5.7
Tobacco	1.20	12.8	1.68	18.1
Tomato	1.30	7.4	2.11	12.1
Wheat	0.49	3.0	*0.49*	*3.0*
Other losses	1.05	4.9	1.39	6.6
Total	**6.30**	**3.6**	**8.36**	**4.7**
Fossil	**6.3**	**16.9**	**8.36**	**22.4**

[a)] Mulching for all crops; [b)] S1 + drip irrigation for all summer crops.

4.4.3 Scenario 3 [Formulation]

Implementation of scenario 1 and 2 had positive but limited impact on water savings in the ULB and further action is required to maximize efficiency of water usage in the ULB. The crops were relocated by looking at the analysis in chapter 4 (Figure 14). The crops corn and alfalfa had large blue WF in times when the water scarcity is in its most. Both crops are grown as feed for livestock and has less priority. Tomato had also a large annual blue WF compared to its contribution to food or economic production. If these crops were replaced by those which have higher economic and/or nutritional values, like tobacco in the summer and wheat in the winter, the ULB could save substantial amount of water. Further was some additional land cultivated with wheat, since there was a gap between blue WF and availability in winter. An overview of the relocation of crops is given in Table 13.

Table 13 - Relocation of crops overview.

Reference			Scenario 3		Area [ha]
Summer	Winter		Summer	Winter	
Favabeans	Alfalfa	→	Favabeans	Tobacco	700
Favabeans	Corn	→	Favabeans	Tobacco	800
Fallow	Corn	→	Wheat	Fallow	700
Wheat	Corn	→	Wheat	Fallow	2 300
Fallow	Tomato	→	Wheat	Fallow	4 300
Fallow		→	Wheat	Fallow	2 580

A total of 6 500 hectares is currently fallow whole year and could be relocated to agriculture without a larger impact on nature lands. We knew from Figure 12 that there was no zone where the environmental conditions were optimal. Therefore, the current area of cultivated wheat (12 900 ha) is increased with 20% (2 580 ha). The new cropping pattern is shown in Table 14.

Table 14 - Land use types in Scenario 3.

#	Area[ha]	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
1	4 400	**Fallow**			**Early Potato**						**Fallow**		
2	15 480	**Wheat**								**Fallow**			
3	500	**Favabeans**							**Fallow**				
4	3 200	**Barley**								**Late Potato**			
5	2 800	**Chickpeas**							**Tobacco**			**Fallow**	
6	1 500	**Favabeans**							**Tobacco**			**Fallow**	
7	3 920	**Fallow**											
Total harvested land			**32 700 ha**										

Source: USAID (2014).

4.4.4 Scenario 3 [Effects]

The blue WF is below the sustainable water availability whole year round in scenario 3. The total blue WF and the abstraction of fossil water are reduced from 177 to 141 million m^3 and from 37 million m^3 to 1 million m^3, respectively. The adopted flows and total monthly blue WF for scenario 3 are shown in Figure 18.

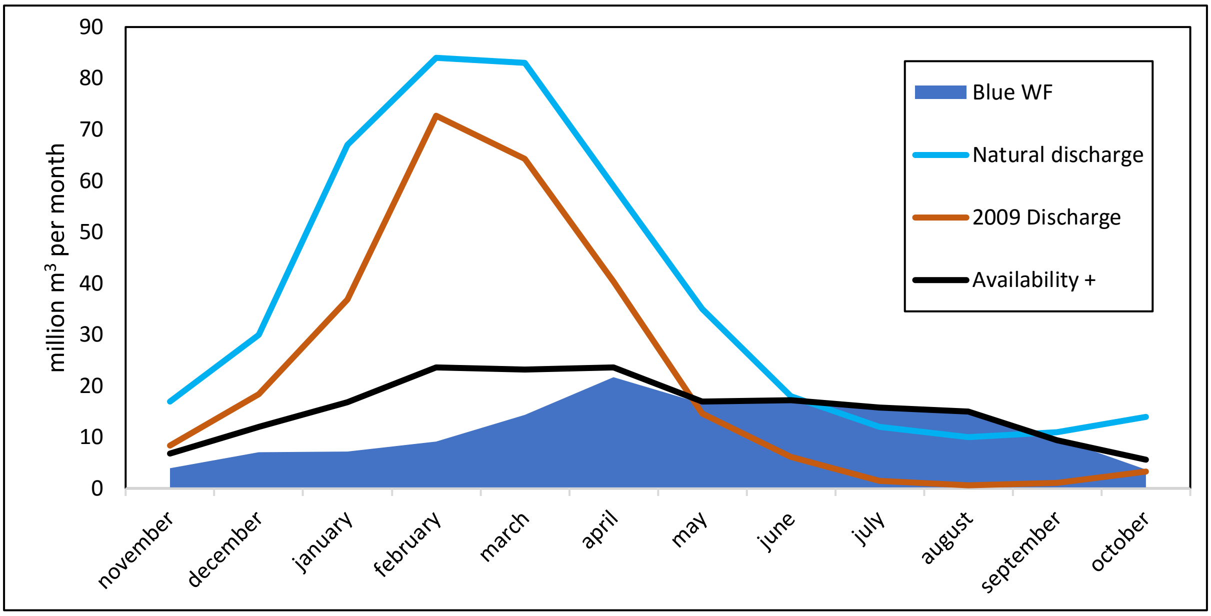

Figure 18 - Monthly blue WF in ULB in scenario 3 [a)] and sustainable blue water availability [b)].

Period: 2011-2016. Sources: [a)] Relocation of crops + drip irrigation for summer crops + mulching for all crops; [b)] USAID (2014).

Monthly changes in the blue WF for different users are demonstrated in Figure 19. It can be observed that the areas representing wheat and tobacco had increased and that the crops of tomato, corn and alfalfa were removed. Also, the blue WF in winter months had increased but is still below the sustainable availability. So, the increase of blue WF in that period does not caused extra water shortages.

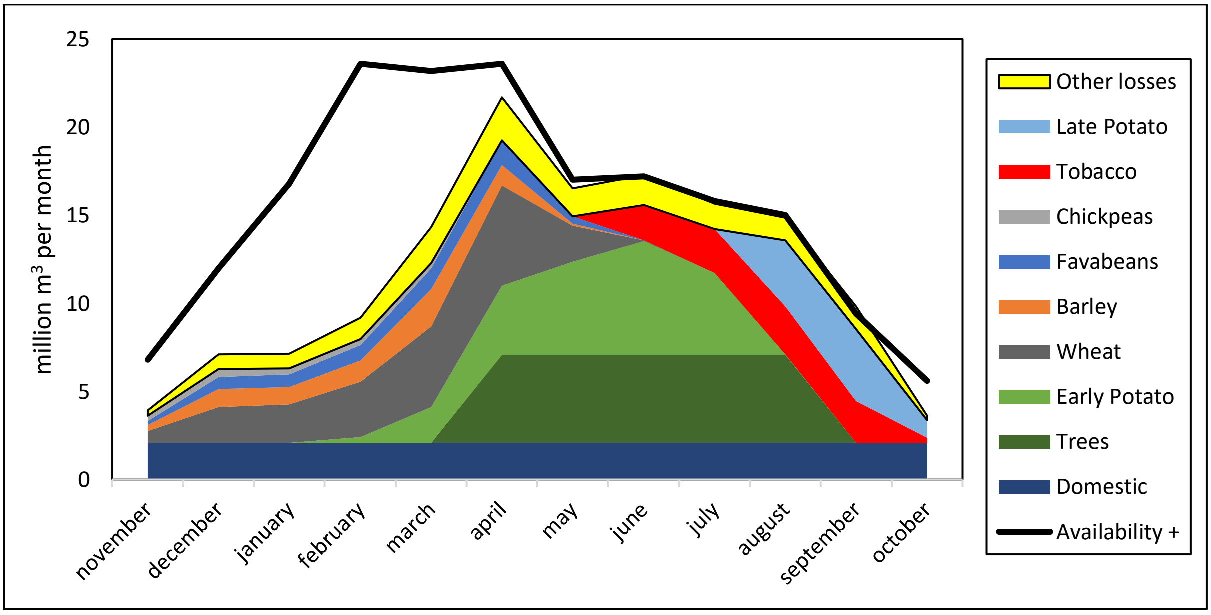

Figure 19 - Monthly blue WF in the ULB per user type in scenario 3[a)] + sustainable blue water availability [b)].

Period: 2011-2016. Sources: a) Relocation of crops + drip irrigation for summer crops + mulching for all crops; b) USAID (2014).

Achieving blue water savings without lower production were mainly fulfilled by increasing green WF. By far the most rainfall falls in winter and using it more efficiently can happen by producing more winter crops. Figure 20 shows the green WF in the reference and scenario 3, and the monthly rainfall. The green WF could exceeds the rainfall in a month because of rainwater storage in the soil.

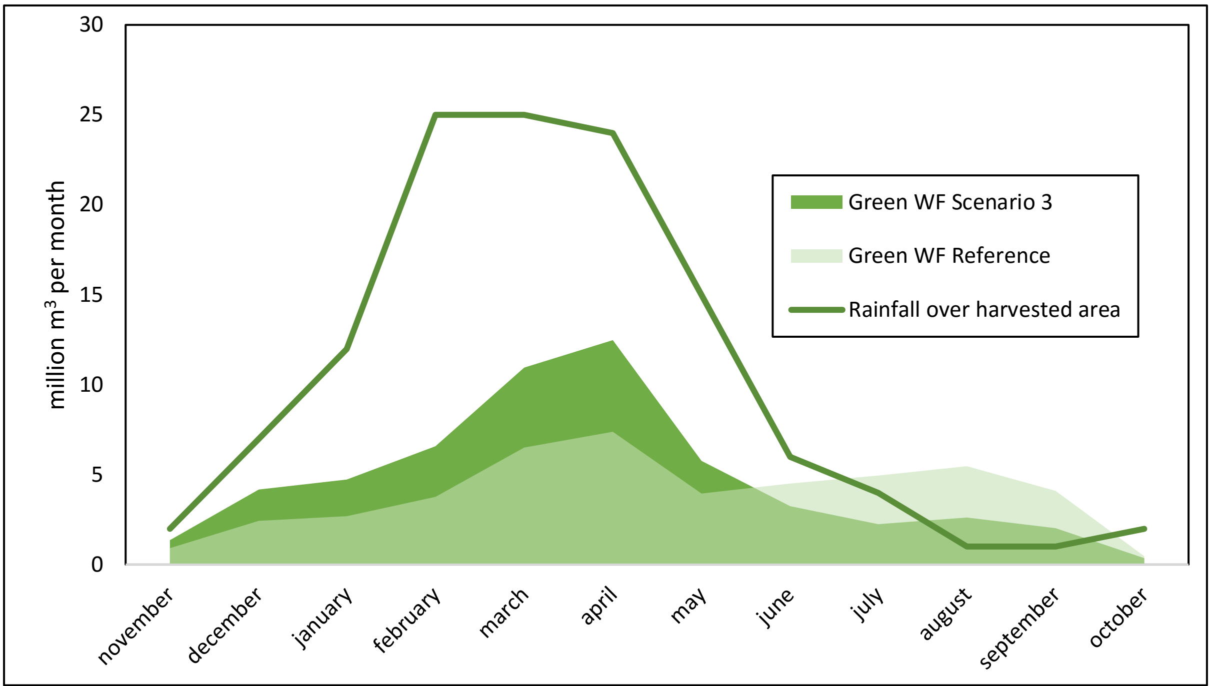

Figure 20 - Monthly green WF in the ULB in the reference [a] and in scenario 3 [b] + total monthly rainfall [c] on croplands [d].

Period: 2011-2016. Sources: [a] Actual situation; [b]) relocation of crops + drip irrigation for summer crops + mulching for all crops; [c] LARI (2017); [d] USAID (2014).

4.4.5 All scenarios compared

The current cropping pattern results in overexploitation of fresh water availability in the ULB. Practically, the Litani River is almost dried because of these effects during summer. In addition, the survey shows that farmers tend to over fertilizing their farmlands for production of early potatoes. This trend was also mentioned for other crops by FAO (2012a). USAID (2014) stated that the river was polluted from hazardous, organic and industrial effluent too. The impacts of crop production in the ULB are thus ambiguous. The runoff and assimilation capacity are decreased but the assimilation demand is increased. It can be assumed that the current runoff is not capable to assimilate the pollutions. The effects of agriculture on water quality are thus another problem that should be addressed.

The effects of proposed measures as mulching and drip irrigation were studied in Scenario 1 and 2. Both had positive but limited effects on water saving. These scenarios had mainly positive effects on the reduction of fossil groundwater, not on the surface runoff. The problems about water quality were therefore almost unchanged in these scenarios.

In scenario 3, the cropping pattern was changed by focusing on high value crops and more efficient use of rainwater. Crops like corn, alfalfa and tomato represents low value and were replaced by tobacco and wheat. This means a reduction of the harvested area during summer and an increase during winter. The contribution of green water is higher since winter crops use more rainwater for its development.

The effects of all scenarios are shown in Table 15. The focus on more effective use of rainwater and high value crops had positive effects for the ULB. It reduces the stress on fresh water resources without negative economic or nutritional effects. The production of food and cash represented by crops will even increase. The water quality will also increase due to a higher runoff and reduction of fertilizers during summer.

Table 15 - Annual WF and production for reference and three scenarios.

Annual WF / production	Reference [a]	Scenario 1 [b]	Scenario 2 [c]	Scenario 3 [d]
Green WF [million m^3]	47	46	48	71
Blue WF [million m^3]	177	171	169	141
Fossil abstraction [million m^3]	37	31	29	1
Blue WF saving [million m^3]		6	8	36
Food [billion kcal]	186	190	190	196
Cash [million US$]	67	67	68	102

[a] Actual situation; [b] mulching for all crops; [c] drip irrigation for summer crops + S1; [d] relocation crops + S2.

The wet winters and dry summers resulting in respectively supplementary and full irrigation schemes. Winter crops should mainly use rain water and summer crops are depended of irrigation water. The analysis to effective use of rainwater and irrigation water should therefore be limited to the corresponding season. The total green WF and rainwater in winter for all seasons is shown in the left side of Figure 21. The availability of rainfall in scenario 3 is larger because the harvested area increased. It can be noticed that the green WF is highest in scenario 3 compared to the other scenarios. The effective use of rainfall is thus highest in scenario 3. The blue WF from renewable water and available irrigation water during summer is shown on the right side of Figure 21. The blue WF exceeds sustainable water availability in the reference and scenarios 1 and 2. In scenario 3, the average blue WF from renewable sources is below sustainable demands. The assimilation capacity of the river will increase in this scenario. The use of fertilizers will decrease because of less summer crops.

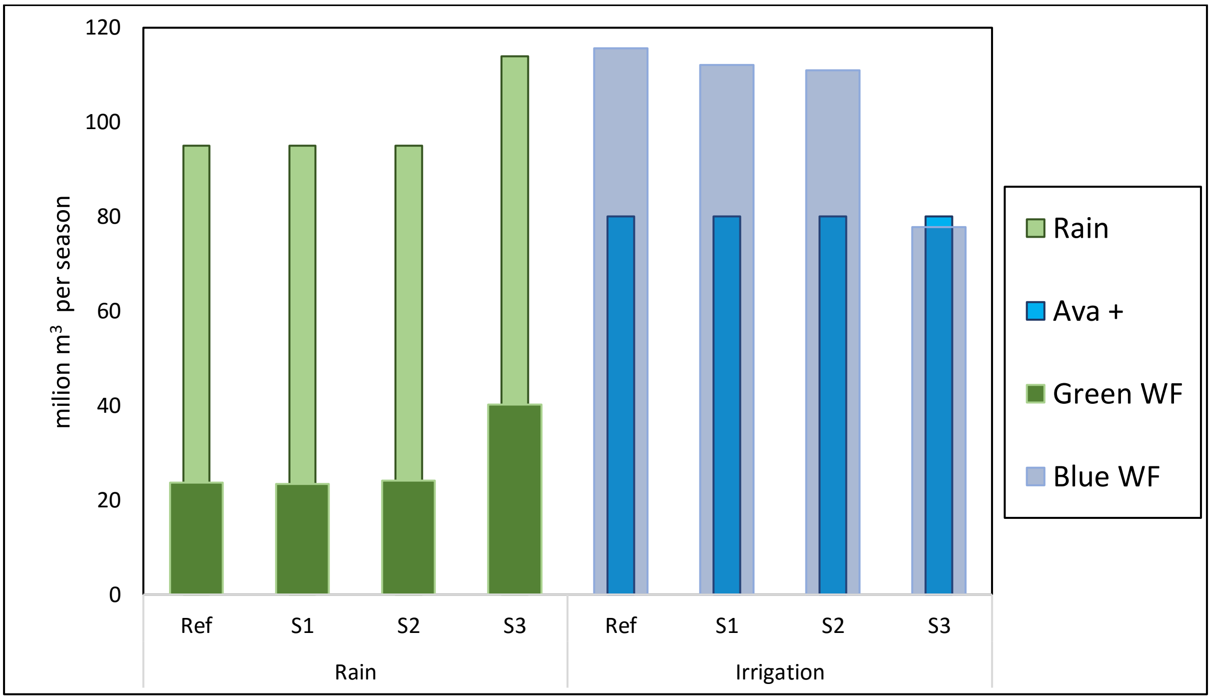

Figure 21 - Seasonal consumptive use of available rain [a] (winter) and irrigation [b] (summer) water in the ULB for the reference [c] all scenarios [e),g),f)].

Period 2011-2016. Sources: [a] LARI (2017); [b] USAID (2014); [c] Actual situation; [d] Scenario 1: Mulching for all crops; [e] Scenario 2: S1 + drip irrigation for summer crops; [f] Scenario 3: S2 + relocation of crops.

The food production for the reference and scenarios 1 and 2 is below the assumed food demands in the ULB. Wheat is the crop that represents the highest share in food production. The harvested area of wheat is increased scenario 3 in order to produce more food. This focus results in higher food production and achieving the food demand. The economic production increased too in scenario 3 because of the focus on tobacco. The food and cash production for all scenarios are shown in Figure 22.

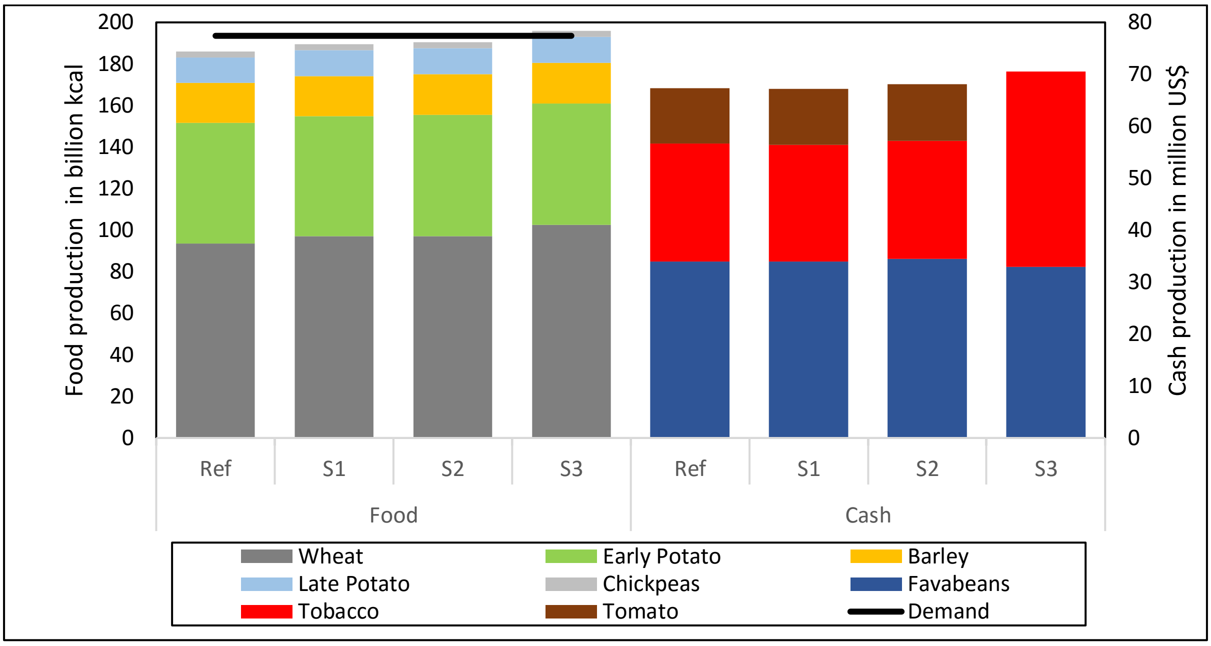

Figure 22 –Food and cash production per crop type for reference a) and all scenarios b),c),d) .

Period 2011-2016. Sources: a) Actual situation; b) Mulching for all crops; c) S1 + drip irrigation for summer crops; d) S2 + relocation of crops.

The rate of blue water scarcity for the reference and all scenarios is given in Table 16. Without relocation of crops, water scarcity is happening during four months per year. The ULB faces severe water scarcity during three months per year with the actual cropping pattern, no matter which techniques are used. By relocating the crops, low water scarcity can be achieved the whole year round. Table 16 shows that the ratio blue WF over availability during winter months is small increased but remains below the scarcity threshold.

Table 16 - Water scarcity for all scenarios for months in the ULB.

Year	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Ref a)	0.60	0.60	0.42	0.37	0.60	0.88	1.00	1.25	1.64	1.83	2.13	0.70
S1 b)	0.55	0.54	0.39	0.35	0.58	0.87	0.99	1.20	1.53	1.79	2.09	0.72
S2 c)	0.55	0.54	0.39	0.35	0.56	0.85	0.97	1.15	1.47	1.79	2.15	0.76
S3 d)	0.58	0.59	0.43	0.39	0.62	0.92	0.97	1.00	0.99	0.99	1.00	0.65

Low scarcity (≤ 1)	Moderate (1- 1.2)	Significant (1.2 -1.4)	Severe (> 1.4)

Blue water scarcity is the ratio of total blue WF in the ULB over the adjusted water availability based on EFR of 60%, irrigation supply from Canal 900 and allowed fossil abstraction.
Period: 2011-2016. Scenarios: a) Actual situation; b) Mulching for all crops; c) S1 + drip irrigation for summer crops; d) S2 + relocation of crops.

Chapter 5

Discussion

This chapter discusses obtained results. In Section 6.1, the methodology of accounting the water consumption is discussed. In Section 6.2, limitations in the sustainability assessment are described. The formulation and effects of the scenarios are discussed in Section 6.3.

5.1 Water footprint accounting

This study estimated the internal human water consumption in the ULB through three sectors of domestic and industries, perennial crops (trees) and herbaceous crops. The results differ from previous studies that estimated the water consumption in the ULB (AquaStat, 2008; Jaafar & King-Okumu, 2016; USAID, 2011). All of them used very rough assumptions for water demand for crop types and assumed optimal conditions for crop development, without considering the actual crop yields.

This study used the crop simulation model of AquaCrop-OS to estimated crop water use and then the water demand of crops is divided into green and blue compartment. This approach is of much larger level of detail compared with previous studies because the water consumption is estimated individually per crop, based on environmental conditions and corrected for observed yields. FAO (2014a) stated minimal requirements about data that for a reliable simulation in AquaCrop-OS. The historical data of soil, climate and cropping patterns satisfies these minimal requirements. The technical information about crop development and management types were limited.

The crop and management settings were based on literature and most sensitive parameters were revised based on observed yields from FAOStat and survey's outcome. For the validation of AquaCrop modelling, we run a field survey for two major crops of early potato and wheat in their harvesting time in summer. The surveys provided technical information about soil, irrigation, fertilization, groundwater and yield; these data were partially employed in the simulation process and partially in the validation process. For instance, field data made it possible to use pre-defined irrigation settings instead of assessing the net irrigation requirement. The latter method is commonly used in WF studies but is less realistic since it allows the model to apply irrigation any day, based on a certain threshold. In reality, farmers do not irrigate based on real life monitoring of soil water balance, they use a fixed interval as learned from the surveys.

There are still different sources of biases and uncertainties in the simulation of major crops in the ULB because inadequacy of data. No systems are installed that could monitoring long-term crop development. For instance, data on canopy cover, above-ground biomass, root depth, planting density, irrigation application and several types of stresses during simulation period could increase the reliability. Estimated values from literature were used instead and stresses were not considered. The other uncertainty could be from cropping pattern. In this study, the cropping pattern of 2011 was used for the period 2011-2016, temporal and spatial variation of potential changes were ignored.

So, the results must not be taken too literal in a quantitative way because there are too much uncertainties in the underlying data and assumptions. However, the AquaCrop-OS model had proved to perform well in estimating crop water use by using only limited amount of data. Most used datasets exceeded the minimal requirements for a reliable simulation. The study gives thus a clear indication of the water house holding in the ULB over the period 2011-2016. The water accounting may be not exactly correctly but can be seen as improvement to the current insights. It shows the temporal variability of water consumption which was missing in previous studies.

5.2 Sustainability assessment

The sustainability assessment of the water consumption in the ULB was studied from three perspectives including process, product and geographic perspective. From the process perspective were the water footprints of crops for different environmental and management conditions compared. The obtained results were in line with what we learned from literature. The WF of major crops in the ULB showed sensitivity to climate conditions but not to soil physical properties. Our finding was in line with what was stated by Zhuo et al. (2014). Furthermore, reduction of WF in case of mulching and/or drip irrigation compared to no mulching and sprinkler or surface irrigation practices were observed. This was also reported by Chukalla et al. (2015).

The economic and nutritional blue water productivity depends on the underlying data regarding economic and nutritional value. These data were derived from trustable resources like FAOStat and the Dutch Food Centre, but these resources were limited. The EBP and NBP give us only qualitative insights in the identification of high and low value crops.

The geographic sustainability was assessed using the estimated blue water consumption and blue water availability. The uncertainty in blue water consumption was discussed in Section 6.1. The water availability was estimated using historical discharges and some assumptions to derive the sustainable water availability. Climate change was not taken into account but might have significant influenced on the temperature, ET, precipitation and the natural runoff. The potential increased availability due to the irrigation canal C900 was assumed to happen but in reality, this canal is still under construction. The rate of blue water scarcity is thus uncertain because of limitations in the estimation of both the water consumption as the water availability. Another limitation was that the basin is considered as one big homogeneous region and all spatial variations in water availability were neglected. The distance of a farm to groundwater springs and irrigation canal C900 may influence the availability of blue water that was not included in our study.

5.3 Adoptive strategies

Three response scenarios were formulated based on the sustainability assessment for the reference situation and proposed measures in earlier studies: Scenario 1: (Mulching for all crops); Scenario 2: (S1 + Drip irrigation for all summer crops); Scenario 3: (S2 + Relocation of crops). The effects of scenario 1 and 2 were assessed using the AquaCrop-OS model. The are some uncertainties involved in the outcomes for similar reasons that were discussed in Section 6.1 and 6.2 for the reference scenario which mainly was a practice of sprinkler irrigation and no mulching. USAID (2014) stated that farmers who changed from sprinkler to drip irrigation saw their yields increasing. These effects are missing in this study because the net irrigation amount was constant for all irrigation techniques. The variation was modelled by changing total irrigation amount, efficiency and percentage of wetted surface. It only models thus water saving effects but not potential increasing yields which are in reality also observed.

Scenario 3 was about the relocation of crops, based on their value and impact on blue water resources. The focus was on solving blue water scarcity, rather than water efficiency, green water scarcity or water quality. According to Hoekstra (2016), the water scarcity should also be addressed by looking to green and grey WF and their efficiency since all types of depletion are relevant to each other.

However, the adopted strategy is justified since the main problem in the ULB was the blue water scarcity during summer. It pointed out that by focusing on blue water scarcity, other aspects will be improved as well. In particular, the efficiency had increased because of mulching and drip irrigation. The efficiency of rain water use had increased due to replacement of some summer crops by winter crops. Finally, the decreased number of crops during summer will have positive effects on water quality. This is because fertilizers and blue water consumption will decrease and river runoff and assimilation capacity will increase. The river will thus be cleaner because of a lower concentration of fertilizers.

This study researched the technical aspects of blue water scarcity, but did not considered the feasibility in formulation of scenarios. Implementation of mulching and drip irrigation techniques are costly, while the ULB is one of the poorest regions in Lebanon according to AquaStat (2008). If farmers do have the cash to invest in new techniques, they still have to be convinced about the advantages. USAID (2014) stated that only a part of a selected group of farmers was willing to corporate in a pilot to switch to drip irrigation, even when they did not have to pay by themselves. It can be simply assumed that the willingness of farmers to replace summer crops by winter crops will be challenging. There were large water problems identified in the ULB, but these are mainly at basin level. Individual farmers may not feel the need of a change to other crop types or techniques. It is thus a major challenge of the Litani River Authority to facilitate the implementation of the adopted scenarios.

Chapter 6

Conclusions and recommendations

This chapter describes the obtained conclusions from this study and recommendations for further research about sustainability and efficiency of water consumption in the ULB. This study shows that the ULB faces severe water scarcity during summer. This can be improved by using more efficient techniques and relocate the cropping pattern. These practices could have positive impacts on the economic and nutritional production by focusing on high value crops and more efficient use of rainwater.

6.1 Conclusions

Goal of this study was to assess the efficiency and sustainability of the green and blue water consumption in the ULB and to evaluate potential improvements through formulating a few water-sustainable scenarios to achieve food security. The water footprint (WF) of 10 major crops, representing 94% of the harvested area of the catchment, was accounted using AquaCrop-OS for the period 2011-2016. The total water consumption was divided into a green WF that comes from rainwater and a blue WF that comes from irrigation water. The blue WF of domestic, industrial and trees obtained from literature were added to the calculated crop water uses.

The sustainability was assessed by comparing the blue water consumption to the blue water availability. The total annual blue WF was estimated at 177 million m^3, from which 127 million m^3 comes from crops. The ULB faces severe water scarcity for minimum of 3 months per year from July till September. The natural availability during summer was too low for such a high rate of blue water consumption, so a significant part of the blue WF, 37 million m^3, comes from fossil groundwater or stored water from previous months which is not a sustainable source of water. Due to overexploitation, the river runs in its minimum with a high potential to dry out during summer and the assimilation capacity is very limited. Field surveys learned that farmers over fertilize their farms to achieve a higher yield that resulted in negative impact on the groundwater quality.

The food and cash production were estimated based on the blue water productivity and the amount of kcal and US$ per volume of water. The food demand was based on the forecasted population in 2030 and the average needs per capita that should be provided by crops. Achieving the food demand is of major importance for countries in the NENA region since recent famines had resulted in social crises in Syria and the horn of Africa (FAO, 2014b; Gleick, 2014). The estimated food demand for the ULB is about 193 537 million kcal. The current amount of food and cash production are respectively 186 094 million kcal and 67 million US$.

The current cropping pattern results in low river flows but with a high rate of pollution. This means food security for the forecasted population growth in 2030 is not achievable with the scenario of "business as usual". Three scenarios were formulated to improve blue water scarcity and food and cash production:

- Scenario 1: Mulching for all crops
- Scenario 2: S1 + drip irrigation for all summer crops
- Scenario 3: S2 + relocation of crops

Figure 23 shows a summary of the green and blue WF and food and cash production for the reference and three adoptive scenarios. Both scenario 1 and 2 had water saving effects. The total blue WF will decrease with 5 and 8 million m^3 respectively. The scenarios reduced fossil water abstraction by 16.9 and 22.4 percent. Implementation of scenario 1 and 2 had positive effects, but further action is required to maximize performance of water use. In scenario 3, low value crops were replaced by high value crops. Further, summer crops were replaced by winter crops because of the high blue water scarcity during summer, while there is potential to use more water during winter. It means that the crops of maize, tomato and alfalfa were replaced because of its low economic and nutritional blue water productivities. These crops were replaced by tobacco and wheat which had high economic and nutritional blue water productivity respectively. In addition, some available lands which is currently fallow were replaced by wheat.

The blue WF savings in scenario 3 were 38 m^3. Winter farming will increase the efficiency of green water resources (rainwater use). The green WF increases from 47 to 71 million m^3 in scenario 3. The focus on the high value crops resulted in an increase of 5% in the food and cash production. In particular, the food production in scenario 3 is 195 925 million kcal that led to food security.

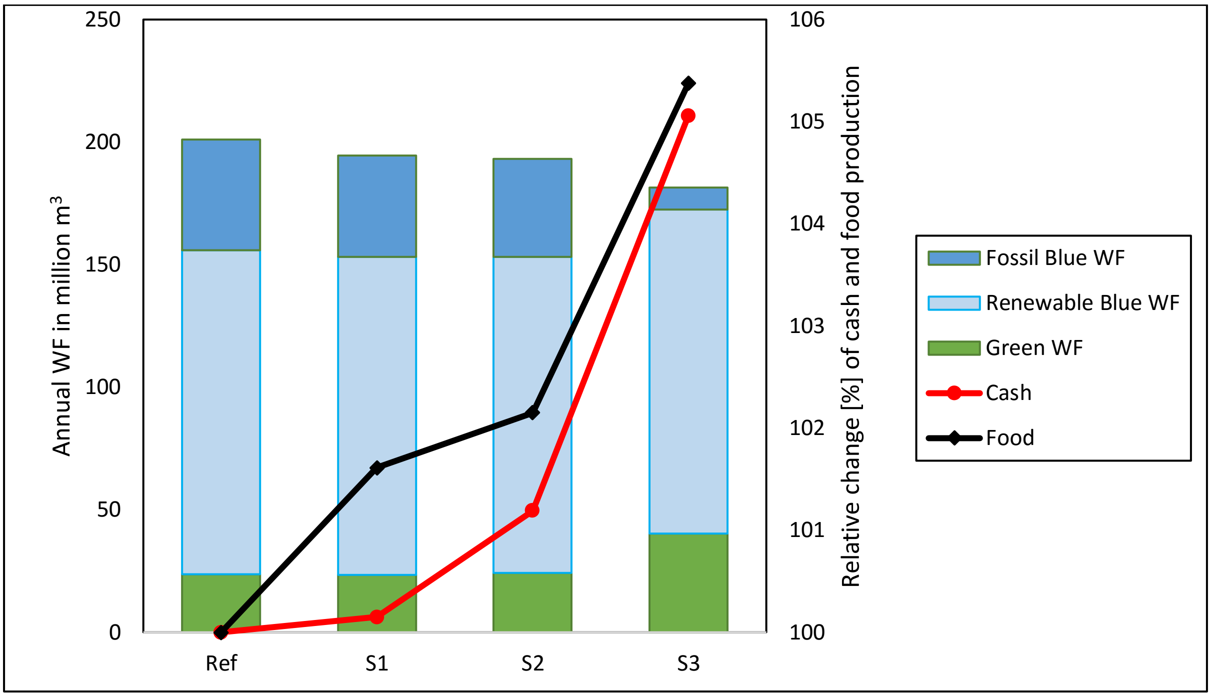

Figure 23 - Comparison of annual green and blue WF and food and cash production in the ULB for the actual situation [a] and all scenarios [b), c), d)].

Period: 2011-2016. Scenarios: [a] actual situation; [b] mulching for all crops [c]; S1 + drip irrigation for all summer crops [d]; S2 + relocation of crops.

6.2 Recommendations

This study is the first research in Lebanon to study the WF of major crops in the Upper Litani catchment. It also included domestic and industrial WF to evaluate sustainability. We identified that there is a severe blue water scarcity during summer that has a large impact on the food security of the region and the country. Compared to previous studies, this study is more comprehensive analysis of the water consumption of different user types in the ULB. It has been already known that the cropping pattern in the ULB is not sustainable, but there was no published quantitative study on the temporal variability of water scarcity. This study identified that the blue water scarcity is most urgent during summer. This can partly be solved by use of more efficient farming techniques such as mulching and drip irrigation. In addition, the cropping pattern was suggested to be changed in order to meet water sustainability. However, social aspects of these adoptive strategies need to be studied.

The crops of maize, tomato and alfalfa have important roles in the scarce water resources but are of low values compared to their blue WF. Further research is needed to be taken to evaluate the impact of other crops (out of this study) for replacement that represents high economic or nutritional blue water productivity. It is recommended to replace parts of summer crops by winter crops, in order to use available green water resources more efficiently, however, further study is needed.

Limited data was available to this study, more data could potentially improve this research. However, all used data is provided in the appendices of this report. This study shows that the employed method is able to provide some insights in the water house holding in the ULB. These results will be more comprehensive by including water house holding data.

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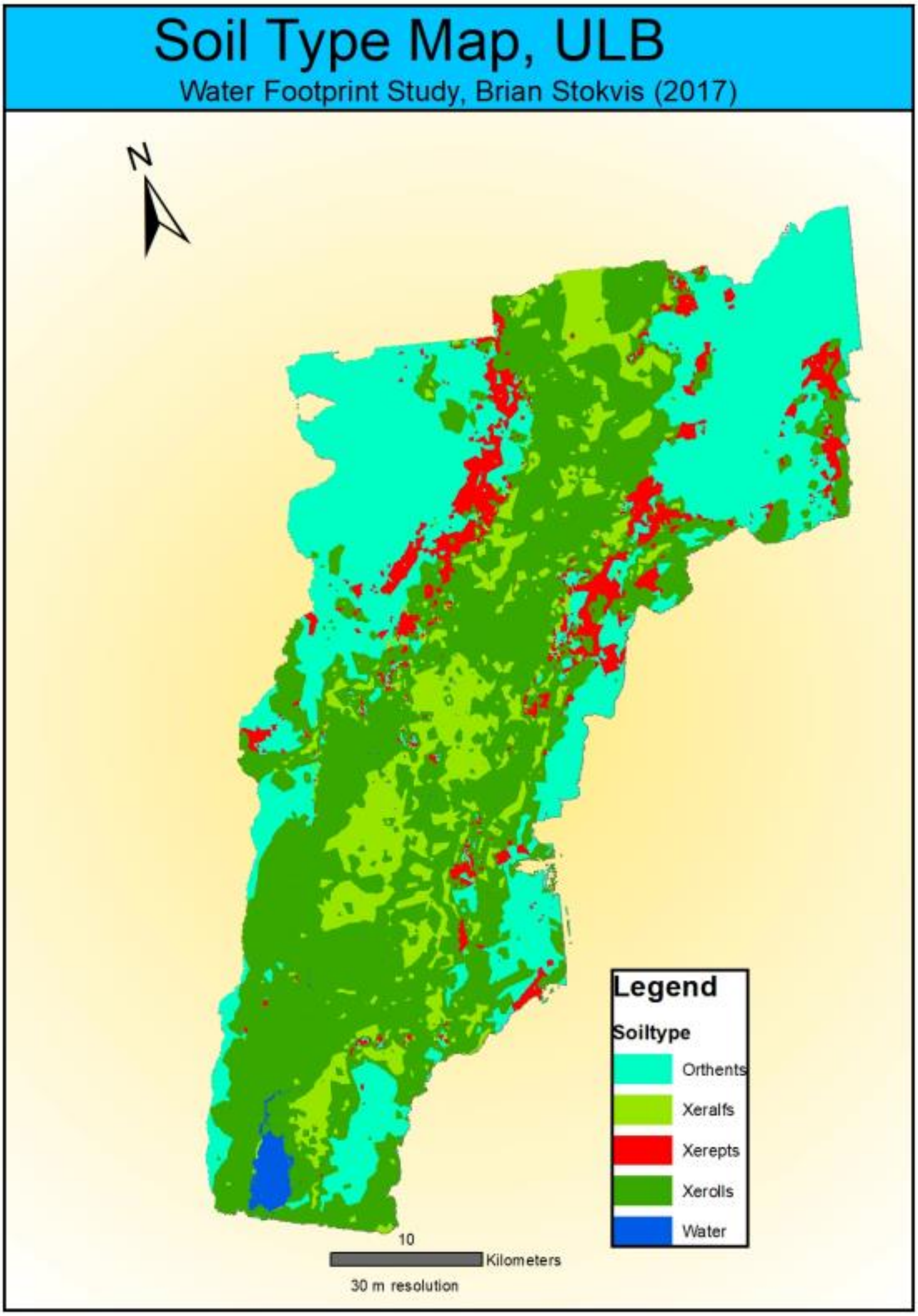
Appendices

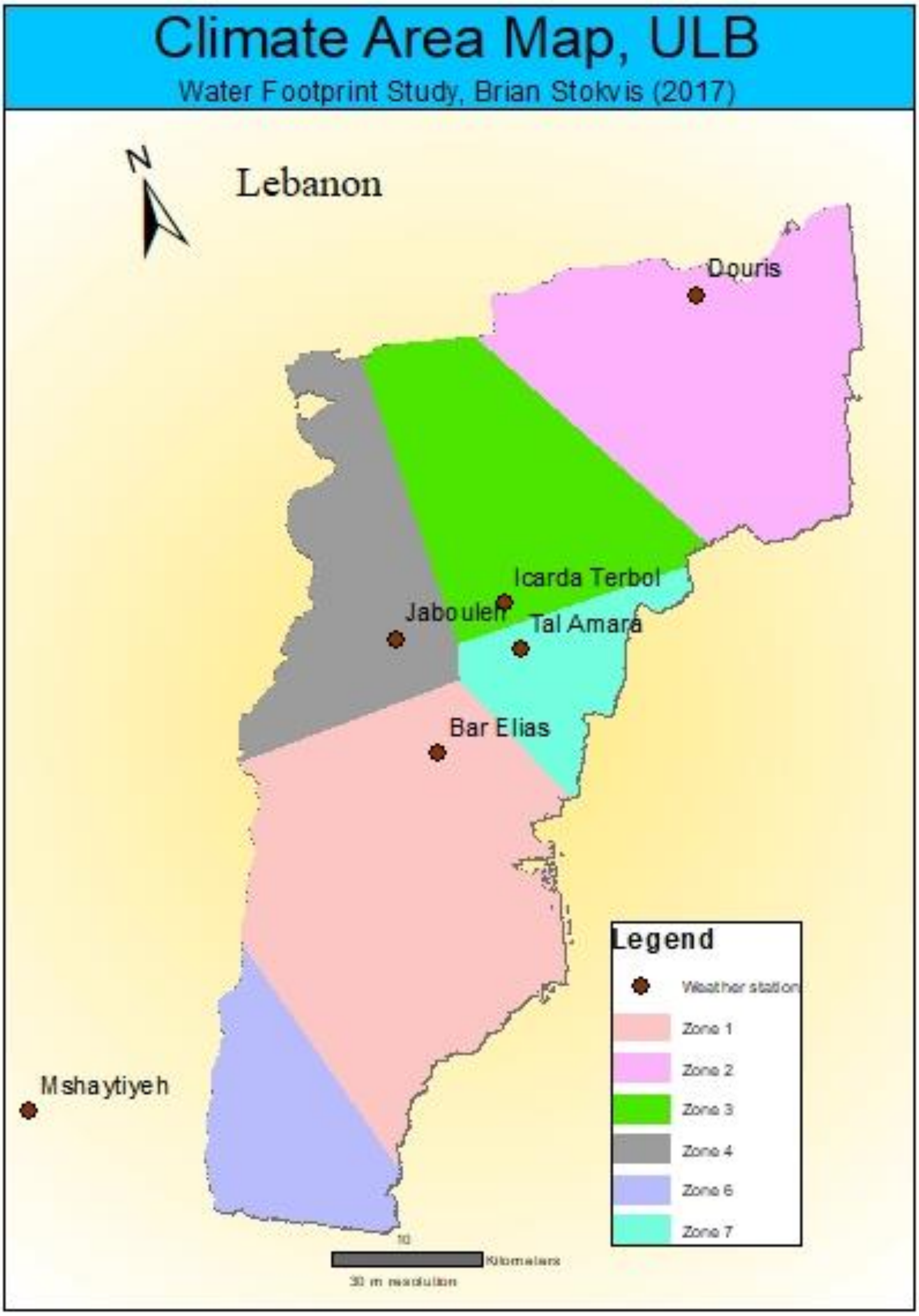
Appendix A

Input data

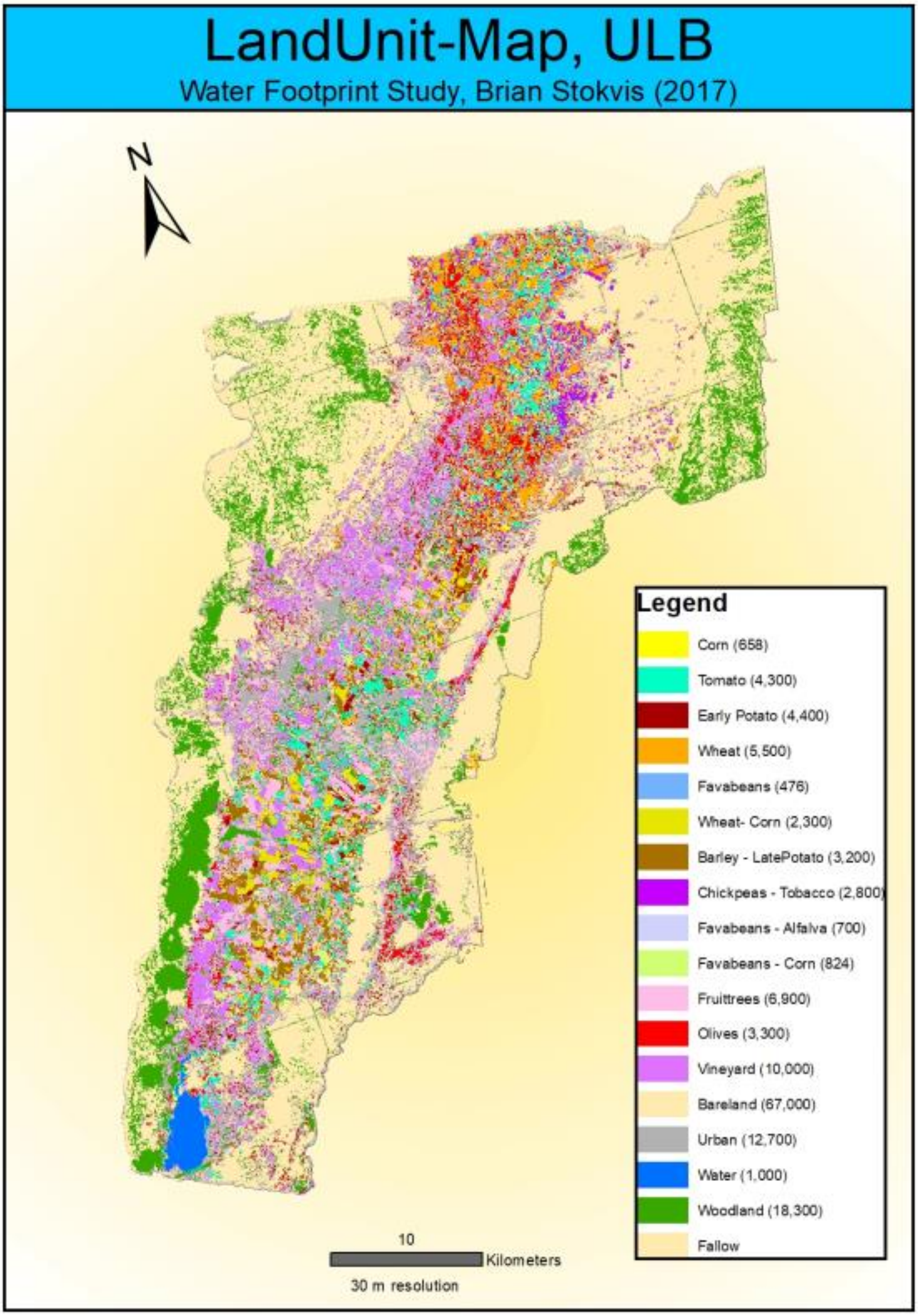
A.1 Soil map



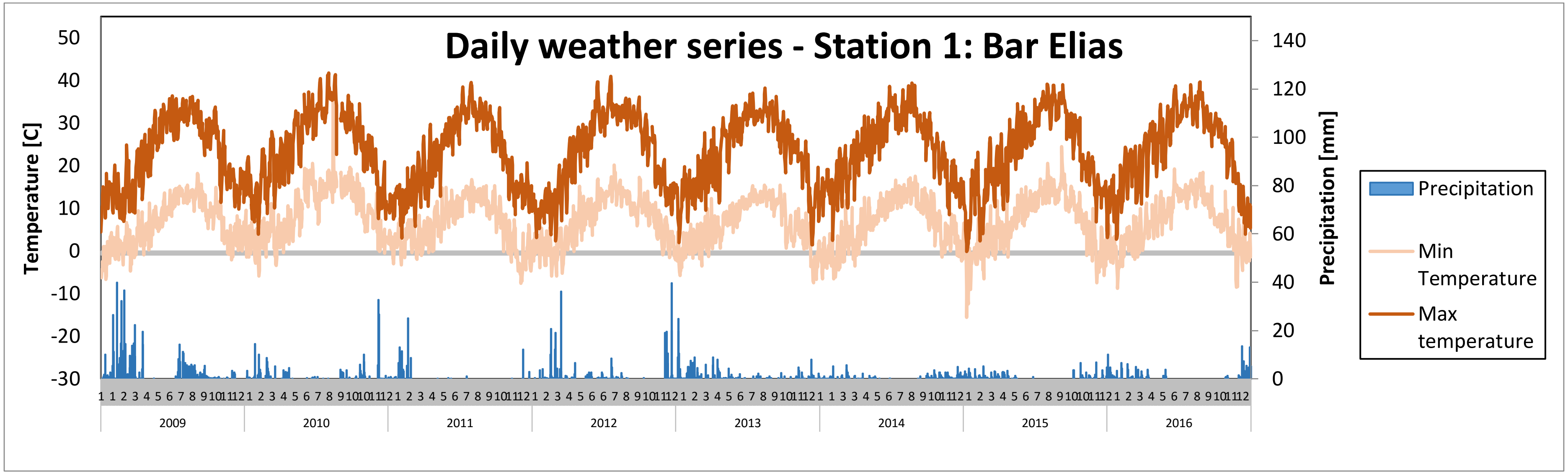
A.2 Climatic map

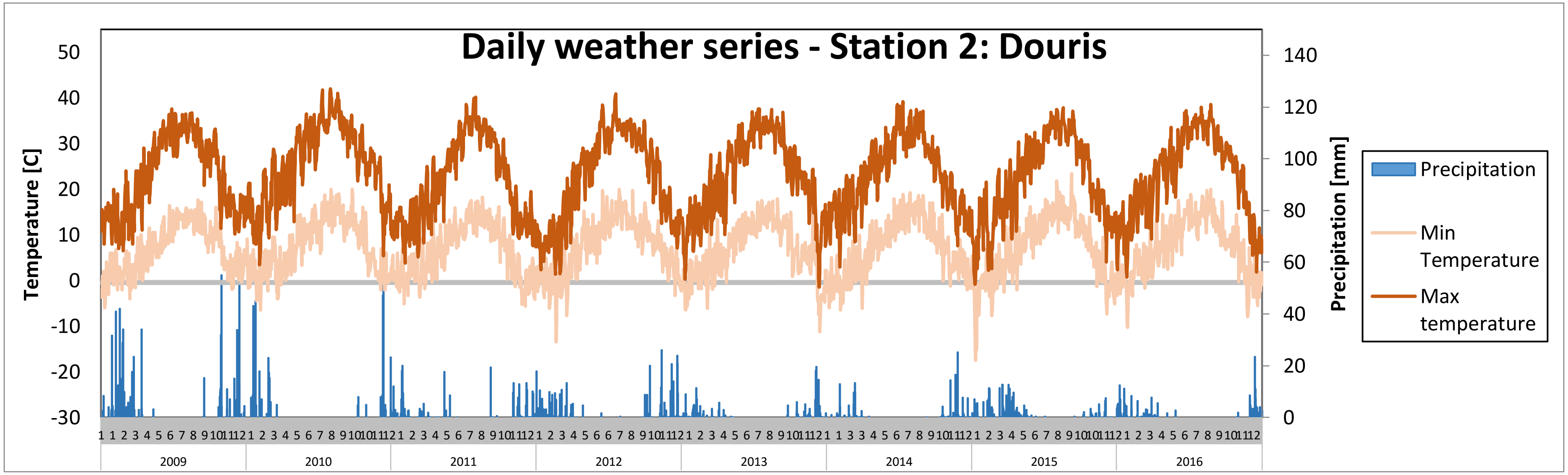


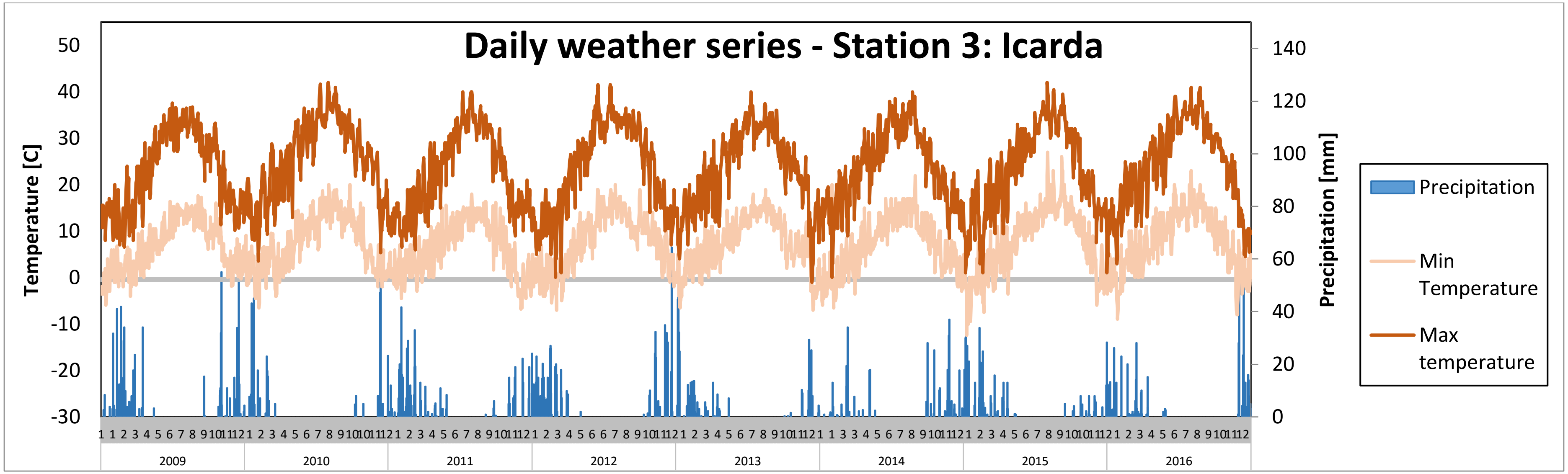
A.3 LandUnit map

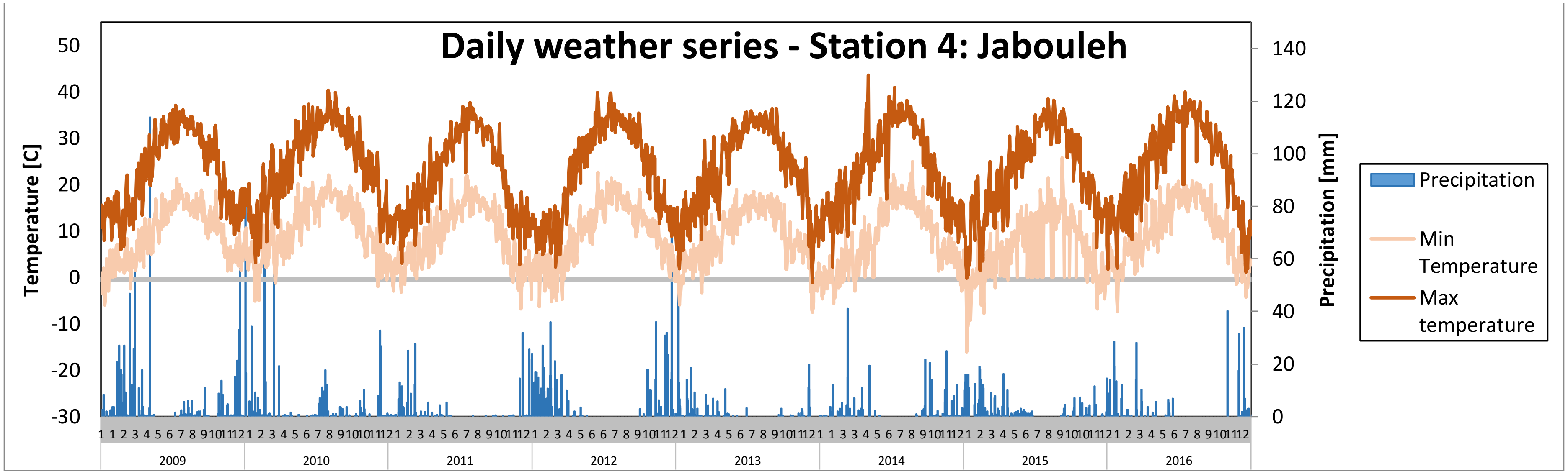


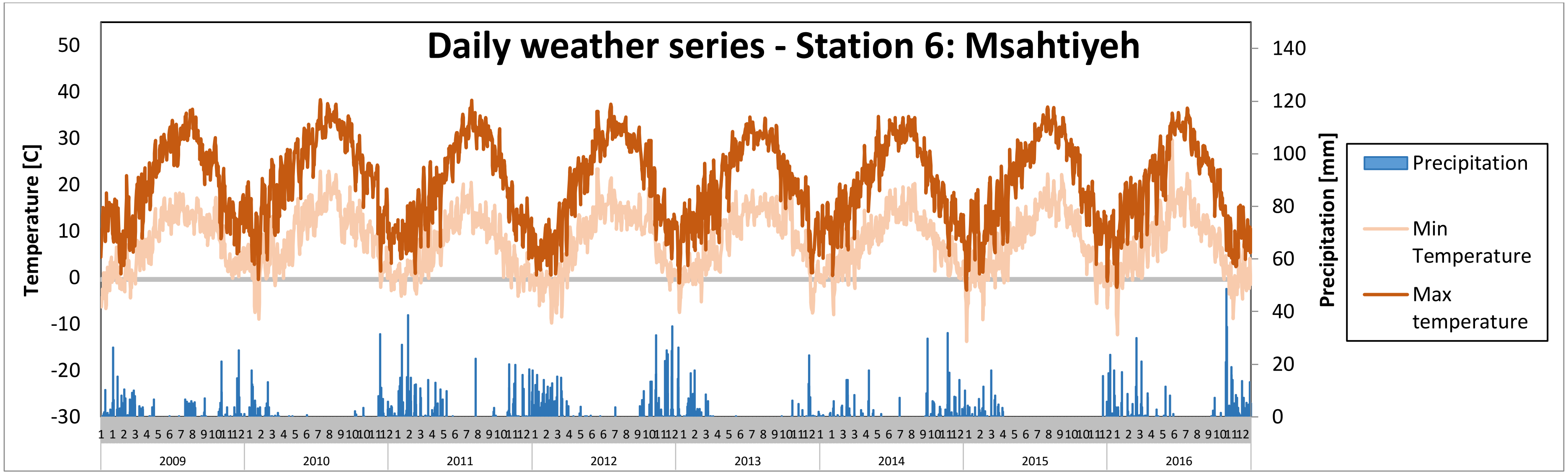
A.4 Climate data per station

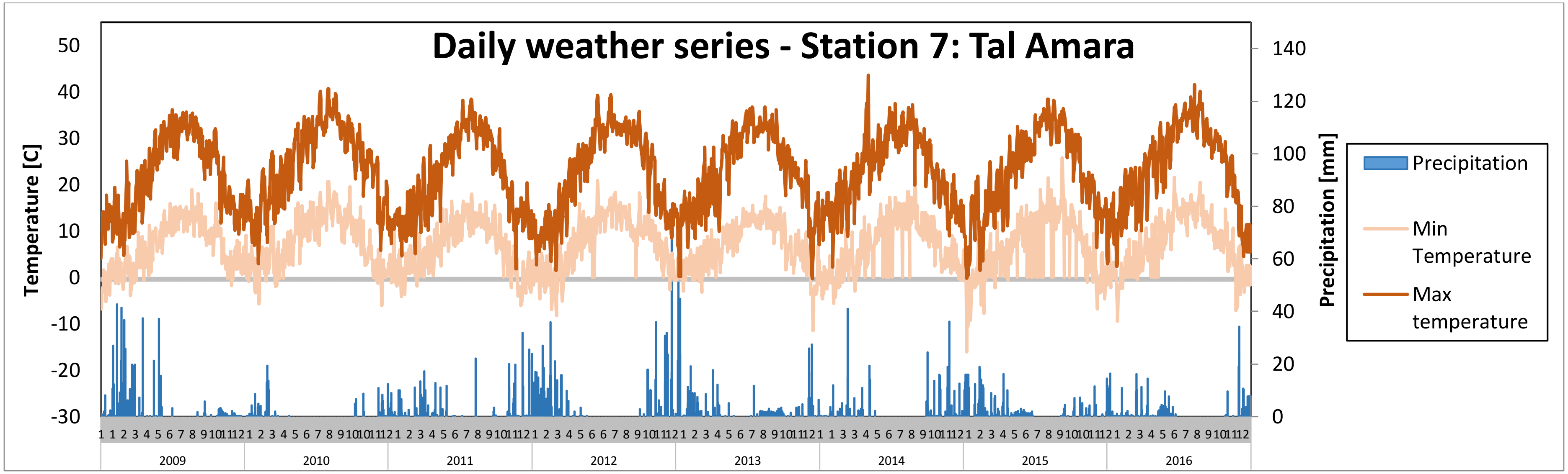





Daily weather series - Station 3: Icarda
Temperature [C]
Precipitation [mm]
Precipitation
Min Temperature
Max temperature
2009
2010
2011
2012
2013
2014
2015
2016


Daily weather series - Station 4: Jabouleh
Temperature [C]
Precipitation [mm]
Precipitation
Min Temperature
Max temperature
2009
2010
2011
2012
2013
2014
2015
2016


Daily weather series - Station 6: Msahtiyeh
Temperature [C]
Precipitation [mm]
Precipitation
Min Temperature
Max temperature
2009
2010
2011
2012
2013
2014
2015
2016


Daily weather series - Station 7: Tal Amara
Temperature [C]
Precipitation [mm]
Precipitation
Min Temperature
Max temperature
2009
2010
2011
2012
2013
2014
2015
2016

A.5 Land Units

LU [#]	Land Use[#]	Soil [#]	Climate [#]	Area [ha]	LU [#]	Land Use[#]	Soil [#]	Climate [#]	Area [ha]	LU [#]	Land Use[#]	Soil [#]	Climate [#]	Area [ha]
1	1	1	1	18	**21**	1	4	3	89	**41**	2	3	7	2
2	1	1	2	1	**22**	1	4	4	14	**42**	2	4	1	1094
3	1	1	3	8	**23**	1	4	6	8	**43**	2	4	2	1064
4	1	1	4	19	**24**	1	4	7	41	**44**	2	4	3	348
5	1	1	6	1	**25**	2	1	1	30	**45**	2	4	4	47
6	1	1	7	10	**26**	2	1	2	30	**46**	2	4	6	213
7	1	2	1	57	**27**	2	1	3	3	**47**	2	4	7	117
8	1	2	2	33	**28**	2	1	4	14	**48**	3	1	1	52
9	1	2	3	20	**29**	2	1	6	1	**49**	3	1	2	104
10	1	2	4	3	**30**	2	1	7	1	**50**	3	1	3	76
11	1	2	6	7	**31**	2	2	1	702	**51**	3	1	4	131
12	1	2	7	7	**32**	2	2	2	329	**52**	3	1	6	41
13	1	3	1	7	**33**	2	2	3	80	**53**	3	1	7	3
14	1	3	2	1	**34**	2	2	4	55	**54**	3	2	1	390
15	1	3	3	19	**35**	2	2	6	55	**55**	3	2	2	158
16	1	3	4	2	**36**	2	2	7	64	**56**	3	2	3	160
17	1	3	6	0	**37**	2	3	1	15	**57**	3	2	4	35
18	1	3	7	10	**38**	2	3	2	15	**58**	3	2	6	38
19	1	4	1	132	**39**	2	3	3	18	**59**	3	2	7	41
20	1	4	2	169	**40**	2	3	4	2	**60**	3	3	1	13

LU [#]	Land Use[#]	Soil [#]	Climate [#]	Area [ha]	LU [#]	Land Use[#]	Soil [#]	Climate [#]	Area [ha]	LU [#]	Land Use[#]	Soil [#]	Climate [#]	Area [ha]
61	3	3	2	31	**81**	5	3	1	8	**101**	6	2	4	4
62	3	3	3	98	**82**	5	3	2	176	**102**	6	2	6	5
63	3	3	4	27	**83**	5	3	3	247	**103**	6	2	7	4
64	3	3	7	10	**84**	5	3	4	12	**104**	6	3	1	2
65	3	4	1	1044	**85**	5	3	7	2	**105**	6	3	2	12
66	3	4	2	486	**86**	5	4	1	258	**106**	6	3	3	33
67	3	4	3	885	**87**	5	4	2	1611	**107**	6	3	4	3
68	3	4	4	147	**88**	5	4	3	1057	**108**	6	3	7	4
69	3	4	6	304	**89**	5	4	4	62	**109**	6	4	1	74
70	3	4	7	124	**90**	5	4	6	1	**110**	6	4	2	65
71	5	1	1	34	**91**	5	4	7	127	**111**	6	4	3	65
72	5	1	2	373	**92**	6	1	1	7	**112**	6	4	4	16
73	5	1	3	148	**93**	6	1	2	25	**113**	6	4	6	15
74	5	1	4	77	**94**	6	1	3	15	**114**	6	4	7	31
75	5	1	7	11	**95**	6	1	4	9	**115**	7	1	1	25
76	5	2	1	103	**96**	6	1	6	6	**116**	7	1	2	5
77	5	2	2	803	**97**	6	1	7	1	**117**	7	1	3	1
78	5	2	3	350	**98**	6	2	1	31	**118**	7	1	4	1
79	5	2	4	10	**99**	6	2	2	32	**119**	7	1	6	1
80	5	2	7	30	**100**	6	2	3	15	**120**	7	1	7	1

LU [#]	Land Use[#]	Soil [#]	Climate [#]	Area [ha]	LU [#]	Land Use[#]	Soil [#]	Climate [#]	Area [ha]	LU [#]	Land Use[#]	Soil [#]	Climate [#]	Area [ha]
121	7	2	1	644	**141**	8	1	4	4	**161**	9	1	1	9
122	7	2	2	92	**142**	8	1	6	2	**162**	9	1	2	434
123	7	2	3	13	**143**	8	1	7	2	**163**	9	1	3	73
124	7	2	4	10	**144**	8	2	1	764	**164**	9	1	4	24
125	7	2	6	7	**145**	8	2	2	41	**165**	9	1	6	1
126	7	2	7	28	**146**	8	2	3	37	**166**	9	1	7	6
127	7	3	1	3	**147**	8	2	4	18	**167**	9	2	1	56
128	7	3	2	4	**148**	8	2	6	8	**168**	9	2	2	291
129	7	3	3	1	**149**	8	2	7	58	**169**	9	2	3	45
130	7	3	4	1	**150**	8	3	1	7	**170**	9	2	4	2
131	7	3	7	2	**151**	8	3	2	1	**171**	9	2	6	4
132	7	4	1	761	**152**	8	3	3	4	**172**	9	2	7	18
133	7	4	2	303	**153**	8	3	4	1	**173**	9	3	1	0
134	7	4	3	129	**154**	8	3	7	12	**174**	9	3	2	96
135	7	4	4	25	**155**	8	4	1	1549	**175**	9	3	3	102
136	7	4	6	19	**156**	8	4	2	125	**176**	9	3	4	6
137	7	4	7	223	**157**	8	4	3	179	**177**	9	3	7	1
138	8	1	1	18	**158**	8	4	4	39	**178**	9	4	1	131
139	8	1	2	1	**159**	8	4	6	34	**179**	9	4	2	1151
140	8	1	3	1	**160**	8	4	7	296	**180**	9	4	3	276

LU [#]	Land Use[#]	Soil [#]	Climate [#]	Area [ha]	LU [#]	Land Use[#]	Soil [#]	Climate [#]	Area [ha]	LU [#]	Land Use[#]	Soil [#]	Climate [#]	Area [ha]
181	9	4	4	21	**201**	10	4	1	269	**221**	11	4	1	393
182	9	4	6	11	**202**	10	4	2	29	**222**	11	4	3	6
183	9	4	7	44	**203**	10	4	3	45	**223**	11	4	4	22
184	10	1	1	13	**204**	10	4	4	20	**224**	11	4	6	59
185	10	1	2	2	**205**	10	4	6	49	**225**	11	4	7	71
186	10	1	3	2	**206**	10	4	7	63					
187	10	1	4	5	**207**	11	1	1	18					
188	10	1	6	6	**208**	11	1	3	2					
189	10	1	7	4	**209**	11	1	4	9					
190	10	2	1	103	**210**	11	1	6	16					
191	10	2	2	13	**211**	11	1	7	5					
192	10	2	3	9	**212**	11	2	1	158					
193	10	2	4	11	**213**	11	2	3	5					
194	10	2	6	16	**214**	11	2	4	6					
195	10	2	7	19	**215**	11	2	6	24					
196	10	3	1	3	**216**	11	2	7	9					
197	10	3	2	2	**217**	11	3	1	7					
198	10	3	3	7	**218**	11	3	3	1					
199	10	3	4	3	**219**	11	3	4	3					
200	10	3	7	9	**220**	11	3	7	11					

Appendix B

Field surveys

B.1 Potato

									Before season			During season		
ID	**Location**	**Farmer**	**Latitude**	**Longitude**	**Area [ha]**	**Yield [t/ha]**	**Start [m/dd]**	**Harvest [m/dd]**	**Mul.**	**Fert.**	**Irr,**	**Mul.**	**Fert.**	**Irr,**
p1	Terbol	Simon Kfowly	33.80623269	35.97281165	30		3/15	7/5	No	Yes	No	No	Yes	Yes
p2	Terbol	Riz-Kallah Fanaj	33.82990808	35.97789176	3.5	40	2/23	7/15	No	Yes	No	No	Yes	Yes
p3	Taleznob	Hani Jaafar	33.64989041	35.78088887	50	30	2/24	7/11	No	Yes	No	No	Yes	Yes
p4	Zanbutalfooani	Daher Company			25	35	3/1	7/15	No	Yes	No	No	Yes	Yes
p61a	Tahnish-Gharbieb	Albert Tami	33.69552852	35.79186011	26	40	3/10	7/12	No	Yes	No	No	Yes	Yes
P61b	Tahnish-Gharbieb	Albert Tami	33.69812745	35.78651816	17	45	3/25	7/31	No	Yes	No	No	Yes	Yes
p62	Tahnish-Gharbieb	Albert Tami	33.70052909	35.78843761	50	45	3/15	7/31	No	Yes	No	No	Yes	Yes
p63	Tahnish-Gharbieb	Albert Tami	33.69852438	35.79310566	12.5	40	3/10	7/12	No	Yes	No	No	Yes	Yes
p7	Tahnish-Gharbieb	Isam Iskaf	33.70366898	35.7628718	13	35	3/5	7/17	No	Yes	No	No	Yes	Yes
p8	MoDaurara	Daher Company	33.78323153	35.85760776	25	35	3/1	7/12	No	Yes	No	No	Yes	Yes
p9		‘’	33.70696299	35.81096247	25	35	3/15	7/20	No	Yes	No	No	Yes	Yes
p10		‘’	33.70405696	35.79680778	25	40	3/25	7/31	No	Yes	No	No	Yes	Yes
p11	Aana	‘’	33.68828586	35.78348793	35	35	2/28	7/25	No	Yes	No	No	Yes	Yes
p12	Central Bekaa	Mohammed Hallumah	33.82207764	36.01003233	22	40	2/15	7/11	No	Yes	No	No	Yes	Yes

p13	Terbol	Antoni Abu-Khater	33.83700009	35.99272639	25	40	2/20	7/10	No	Yes	No	No	Yes	Yes
p14	Terbol	Faisal Ramadan	33.82600577	35.97429525	16.5	40	2/20	7/10	No	Yes	No	No	Yes	Yes
P15	West Bekaa	Hamad Samir Ahsul	33.74110531	35.86151943	6	35	3/10	7/15	No	Yes	No	No	Yes	Yes
P16	Haouchomara	Skaff Company	33.7817741	35.89474127	20	40	3/10	28/7	No	Yes	No	No	Yes	Yes
P18	Mandara	Samir Sahid	33.78323153	35.85760776	2	40	3/8		No	Yes	No	No	Yes	Yes
P19	‘’	‘’	33.78442197	35.85782334	2.7	40	3/8		No	Yes	No	No	Yes	Yes
P20	‘’	‘’	33.78383678	35.857764	2	40	3/8		No	Yes	No	No	Yes	Yes
P22	Taj Akhdar	Tony Lebbos	33.76235483	35.82382098	24	40	3/17	7/13	No	Yes	No	No	Yes	Yes
P24	Housisher	Sami Dahdouch	33.78479537	35.87197836	34	40	3/20	7/17	No	Yes	No	No	Yes	Yes
P25	Houshoma district	Bashar Hbaro	33.82200773	35.89198027	20	45	2/20	7/7	No	Yes	No	No	Yes	Yes
P26		Salem Gagaoui	33.64774329	35.81167325	23.5	40	2/20	6/24	No	Yes	No	No	Yes	Yes

ID	Height [m]	Stress	Inter cropping	Pest/ disease	Irrigationwater Source	Depth of Resource [m]	Water quality [very low-very high]	Irrigation technique	Irrigation strategy	Irrigation interval
p1	1	No	No	Pesticide+flies	Groundwater	150	High	Sprinkler	Full	7
p2	0.6	No	No	No	Groundwater	17	High	Sprinkler	Full	7
p3	0.5	Heat	No	Conta	Groundwater		Very High	Sprinkler	Full	
p4	0.75	Heat	No	No	Groundwater		Very High	Sprinkler	Full	
p5										
p61a	1	No	No	weed	Ground+riverwater		Very High	Sprinkler	Full	
P61b	1	No	No	No	Ground+riverwater		Very High	Sprinkler	Full	
p62	1	No	No	No	Ground+riverwater		Very High	Sprinkler	Full	
p63	1	No	No	No	Ground+riverwater		Very High	Sprinkler	Full	
p7	0.65	No	No	No	Groundwater		Very High	Sprinkler	Full	6-7
p8	0.75	Heat	No	No	Groundwater		Very High	Sprinkler	Full	
p9	0.75	Heat	No	No	Ground+riverwater		Very High	Sprinkler	Full	
p10	0.95	Heat	No	No	Ground+riverwater		Very High	Sprinkler	Full	
p11	0.75	No	No	No	Groundwater	0.7	Very High	Sprinkler	Full	
p12	0.4	No	No	No	Groundwater	300	Very High	Sprinkler	Full	
p13	0.5	Water	No	No	Groundwater		Very High	Sprinkler	Full	
p14	0.6	No	No	No	Groundwater	300	Very High	Sprinkler	Full	
P15	0.6	No	No	No	Groundwater	50	High	Sprinkler	Full	
P16	0.65	No	No	No	Surface water		High	Sprinkler	Full	
P18	1	No	No	No	Surface		Very high	Sprinkler	Full	
P19	1	No	No	No	Surface		Very high	Sprinkler	Full	
P20	1	No	No	No	Surface		Very high	Sprinkler	Full	
P22	>1	No	No	No	Groundwater		Very high	Sprinkler	Full	
P24	0.85	No	No	No	Groundwater		Very high	Sprinkler	Full	5-6
P25	0.8	Cold	No	No	Groundwater		Very high	Sprinkler	Full	
P26	0.8	No	No	No	Groundwater		Very high	Sprinkler	Full	

ID	Irrigation events	Irrigation Amount [mm]	Soil type	Soil layers	Groundwater level at start [m]	Groundwater level at end [m]	Groundwater decrease [m]
p1	8		Silty clay	1	40	110	70
p2	7	5.4	Black soil	1	17	25	8
p3	8		Sandy clay	1	150	160	10
p4	9	4.5	Clay	1			
p5							
p61a	13		Clay	1	50	100	50
P61b	13		Clay	1	50	100	50
p62	13		Clay	1			
p63	13		Clay	1	50	100	50
p7	8	5.4	Clay	1			
p8	9	4.5	Clay	1			
p9	9	4.5	Clay	1			
p10	9	4.5	Clay	1			
p11		4.5	Clay	1			
p12			Silt	1	300		
p13			Sand	1	70	170	100
p14			Sand	1	300		
P15			Black soil	1	50		
P16	8	4.5	Clay loam	1			
P18	11		Gravel	1			
P19	11		Gravel	1			
P20	11		Gravel	1			
P22			Clay	1			
P24			Clay	1			
P25			Clay	1			
P26							

ID	Fertilizer initial – Type [kg/ha]	Fertilizer during season – Type [kg/ha]
p1	10-10-17 [1500], Ammonium sulfate [400] Phosphorus [50],	20-20-20 [50] Solphur Urea[50],
p2	12-11-18 [1250] 20-20-20 [100] Phosphate [50] Organic [1000] Solphur Urea [400] Amalgus [70]	
p3	11-22-16 [1500],	20-20-20 [100] Phosphate [100] Solphur Urea [500],
p4, p8, p9, p10, p11	Di-Ammonium Phosphate [350] Chicken manure [8000] Potassium sulfate [500]	20-20-20 [Sprinkler] Ammonium sulfate [400] Potassium sulfate [100] sulfate [100]
p61a, p61b, p62, p63	Ammonium sulfate [500] Phosphate [1500] Organic [2000] Potassium [1000] Triple [2000]	20-20-20 [100] 5-5-5 [3 times] Ammonium sulfate [500] Potassium sulfate [150] Abidas [400]
p7	15-15-15 [1800] Organic [2000]	20-20-20 [200] Nitrogen [1000]
p12	European Urea [500]	
p13		
p14	European Urea [2000] Soil energy [33000],	Soil energy [2 events]
P15	Di-Ammonium Phosphate [1000] Micro organic comple [5000] potassium sulfate [250]	12-61-0 [50] Organic [10000]
P16	Organic 11 -22 -16 [1000]	Phosphate Potassium nitrate [250]
P18, p19, p20	Organic 15-15-15 [2000] Chicken manure [30]	Ammonium sulfate [400] Urea sulfate [300] Potassium sulfate [70] 20-20-20 [150]
P22	Di-Ammonium Phosphate [1250]	Ammonium sulfate [500] Amidas [250] Potassium nitrate [50]
P24	11-22-16 [1200]	Ammonium sulfate [150] Potassium sulfate [150]
P25	Potassium sulfate [400] Di-Ammonium sulfate [400]	Potassium sulfate [250] Ammonium sulfate [250]
P26	Di-Ammonium Phosphate [1000] Potassium sulfate	Phosphate sulfate [100] 20-20-20 [100]

B.2 Wheat

									Before season			During season			
ID	**Location**	**Farmer**	**latitude**	**longitude**	**Area [ha]**	**Yield [t/ha]**	**Start [m/dd]**	**Harvest [m/dd]**	**Mul.**	**Fert.**	**Irr,**	**Mul.**	**Fert.**	**Irr,**	**Height [m]**
w1	Talznob	Hani Jaafar	33.64890185	35.77329487	50	1.2	28/11	6/28	No	No*	No	No	Yes	Yes	0.75
W2	Ammiq	Vayih Maarun	33.71878217	35.79317406	40	1.4	28/10	7/7	No	Yes	No	No	Yes	Yes	0.8
W4	Seifeddin	Mohammed Mohanto	33.70295995	35.80754131	21	1.1	01/12	-	No	Yes	No	No	Yes	Yes	0.5
W5	Tanish	George Kashish	33.70337025	35.77600926	25	1.2	20/11	7/7	No	Yes	No	No	Yes	Yes	0.75
W7	Berlias - Aujad	Mohammed Alarab	33.70174439	35.76586481	20	1.3	01/12	7/8	No	No	No	No	Yes	Yes	0.7
W8	‘’	‘’	33.77653497	35.95509399	8	‘’	‘’	‘’	‘’	‘’	‘’	‘’	‘’	‘’	‘’
W9	‘’	‘’	33.77572706	35.95766388	9	‘’	‘’	‘’	‘’	‘’	‘’	‘’	‘’	‘’	‘’
W10	West Bekaa	Samir Alrasul	33.74076323	35.86235024	12	1.1	28/11	7/8	No	Yes	No	No	Yes	Yes	0.6
W11	Dakwi	Foad Fraihah	33.69301069	35.86591154	17	1.4	10/11	7/15	No	No*	No	No	Yes	Yes	0.8
W12	Dakwi	Foad Fraihah	33.69468162	35.87207492	17	1.2	10/11	7/1	No	No	No	No	Yes	Yes	0.8
W13	-	Khaled Chuman	33.68775275	35.86515181	9	1.6	15/11	7/10	No	No*	No	No	Yes	Yes	1.2
W14	-	Khaled Chuman	33.70327095	35.87276794	90	1.5	01/11	7/14	No	No*	No	No	Yes	Yes	0.5

W15		Skaff company	33.78261456	35.89938048	45	1.5	10/?	7/14	No	No*	No	No	Yes	Yes	0.75
W16	Mandara	Samir Sahid	33.78378495	35.8561996	5	1.4	10/1	7/14	No	No	No	No	Yes	Yes	0.65
W17	“	“	33.78347452	35.85541036	3.3	‘’	“	“	“	“	“	“	“	“	“
W18	“	“	33.78386548	35.85685372	4	‘’	“	“	“	“	“	“	“	“	“
W19	“	“			4	‘’	“	“	“	“	“	“	“	“	“
W20	“	“	33.78128002	35.85730601	4.5	‘’	“	“	“	“	“	“	“	“	“
W21		Sami Bahdouh	33.75917556	35.81635941	11.5	1.05	11/20	7/12	No	No	No	No	Yes	Yes	0.9
W22	Tal Akhdar	Tony Lebbos	33.75187471	35.80235727	36	1.4	11/?	7/9	No	No	No	No	Yes	Yes	0.7
W23		Himed Tajishicker	33.81278095	35.88007327											
W25	Meksi	Hannah Smaha	33.79081057	35.86108357	3.5		1/1	5/17	No	Yes	No	No	No	No	0.4
W26		George Sakr	33.79656316	35.90337798		1.45			No	Yes	No	No	No	Yes	1

- Means that field is still well fertilized from previous crop

ID	Stress	Inter cropping	Pest/ disease	Irrigation water Source	Depth of Resource [m]	Water quality [very low-very high]	Irrigation technique	Irrigation strategy
w1	No	No	No	Groundwater	150	Very high	Sprinkler	Supplementary
W2	small grains	No	no	Surface water	-	Very high	Sprinkler	Supplementary
W4	No	No	No	Both	-	Very high	Sprinkler	Supplementary
W5	Water	No	Bugs	Groundwater	-	Very high	Sprinkler	Supplementary
W7	No	No	No	Groundwater	80	high	Sprinkler	Supplementary
W8	‘’	‘’	‘’	‘’	‘’	‘’	‘’	‘’
W9	‘’	‘’	‘’	‘’	‘’	‘’	‘’	‘’
W10	Heat	No	No	Both	50	Very high	Sprinkler	Supplementary
W11	No	No	Some	Groundwater	150	Very high	Sprinkler	Supplementary
W12	Cold	No	-	Groundwater	150	Very high	Sprinkler	Supplementary
W13	No	No	No	Groundwater	100	high	Sprinkler	Supplementary
W14	No	No	No	Groundwater	65	Very high	Sprinkler	Supplementary
W15	No	No	No	Surface water		High	Sprinkler	Supplementary
W16-w20	No	No	No	Surface water		High	Furrow	Supplementary
W21	Cold	No	No				Sprinkler	Supplementary
W22	No	No	No	Groundwater		Very high	Sprinkler	Supplementary
W23								
W25	No	No	No			High		
W26	No	No	No	Surface			Sprinkler	Supplementary

ID	Irr events	Irrigation Amount [mm]	Soil type	Soil layers	GW level at start [m]	GW level at end [m]	GWdecrease [m]
w1	3	4.5	Sandy clay	-	150	160	10
W2	1		Clay	1	-	-	-
W4	1		Clay	1	-	-	-
W5	1		Clay	1	-	-	-
W7	1		Clay	1	80	90	10
W8+9	‘’	‘’	‘’	‘’	‘’	‘’	‘’
W10	2		Clay	1	-	-	-
W11	3		Clay	1	-	-	-
W12	3		Clay	1	-	-	-
W13	2		Cay	1	-	-	-
W14	3		Silt clay	1	-	-	-
W15	3		Clay loam	1			
W16		125	Clay	1			
W17		“	“	“			
W18		“	“	“			
W19		“	“	“			
W20		“	“	“			
W21	1						
W22	1		Clay	1			
W23							
W25			Clay				
W26	2		Clay				

ID	Fertilizer initial – Type [kg/ha]	Fertilizer during season – Type [kg/ha]
w1		
W2	Ammonium sulphate [400 kg/ha]	Sulphate +Urea [400 kg/ha] – 1x
W4	Ammonium sulphate [500 kg/ha] Sulphate + Urea [500 kg/ha]	Ammonium nitrate [200kg/ha] 1x
W5	Ammonium sulphate [300 kg/ha]	Ammonium nitrate [500 kg/ha] 1x
W7	-	Ammonium sulphate [400 kg/ha Urea [500 kg/ha]
W8	‘’	‘’
W9	‘’	‘’
W10	15-15-15 [400 kg/ha]	Ammonium sulphate [250 kg/ha] Urea [500 kg/ha] Crop N 15 [400 kg/ha]
W11		Urea [500 kg/ha] 1x
W12		Urea [500 kg/ha] 1x
W13		Sulphate + Urea [350 kg/ha]
W14		Sulphate + Urea [400 kg/ha]
W15		Amidas [250]
W16, W17, w18, w19, w20		Ammonium sulfate [500] Sulfur [400]
W21		Ammonium sulfate [500] Ammonium nitrate [400]
W22		Ammonium sulfate [500] Urea [300]
W23		
W25	17-17-17 [300] Organic	
W26		Urea [250]

Appendix C
Technical information
C.1 AquaCrop-OS model

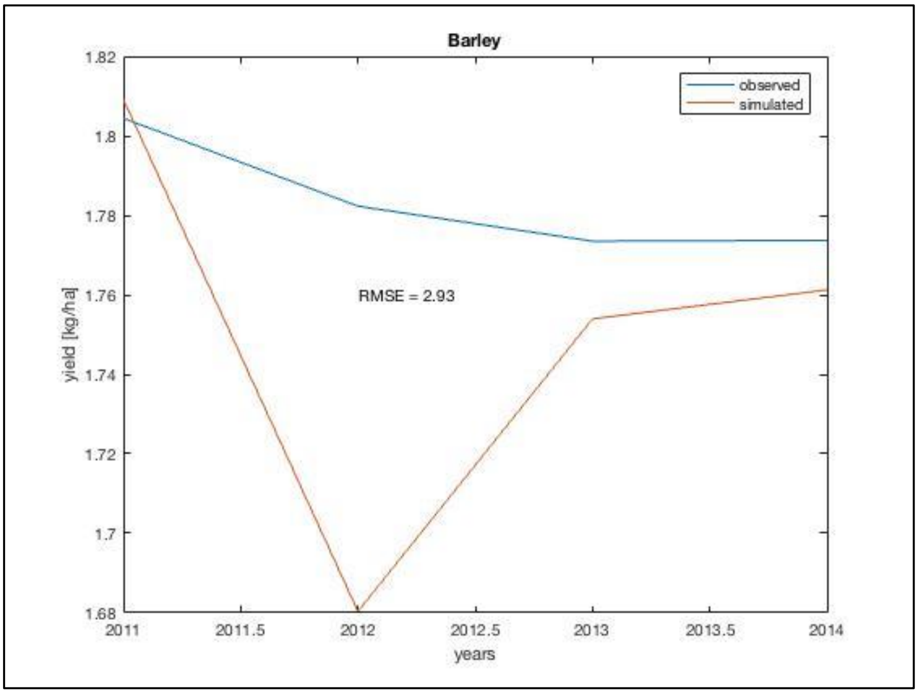
Conservative crop parameter	Non conservative crop parameter

Crop	Description
Crop type	Leafy vegetable, Root/tuber or Fruit/grain
Calendar type	Calendar days or Growing degree days (GDD)
Swtich GDD	Convert calendar to GDD mode
Planting date	
HarvestDate	
Emergence	GD/Calendar days from sowing to “emergence”
MaxRooting	‘’max rooting”
Senescence	“senescence”
Maturity	“maturity”
HIstart	“start yield formation”
Flowering	Duration of flowering in GD/calendar days
Yldform	Duration of yield formation “
GDDmethod	Calculation method (from manual)
Tbase	Base temperature below which growth does not progress
Tupp	Upper temperature above which crop development no longer increases
PolHeatStress	heat stress affects pollination (0:no, 1:yes)
Tmax_up	Max air temperature above which pollination begins to fail
Tmax_lo	Max air temperature above which pollination completely fails
PolColdStress	Cold stress affects pollination (0:no, 1: yes)
Tmin_up	Min air temperature below which pollination begins to fail
Tmin_lo	Min air temperature above which pollination completely fails
BioTempStress	Biomass production affected by temperature stress (0:no, 1: yes)
GDD_up	Minimum GDD (degC/day) required for full biomass production
GDD_lo	GDD (degC/day) at which biomass production occurs
Fshape_b	Shape factor describing the reduction in biomass production for insufficient GDD
PctZmin	Initial percentage of minimum effective rooting depth
Zmin	Minimum effective rooting depth (m)
Zmax	Maximum rooting depth (m)
fshape_r	Shape factor describing root expansion
fshape_ex	Shape factor describing the effects of water stress on root expansion
SxTopQ	Maximum root water extraction at top or the root zone
SxBotQ	Maximum root water extraction at the bottom of the root zone
a_tr	Exponent parameter for adjustment of Kcx once senescence is triggered
SeedSize	Soil surface area (cm2) covered by an individual seedling at 90% emergence
PlantPop	Number of plants per hectare
CCmin	Minimum canopy cover size below which yield formation cannot occur

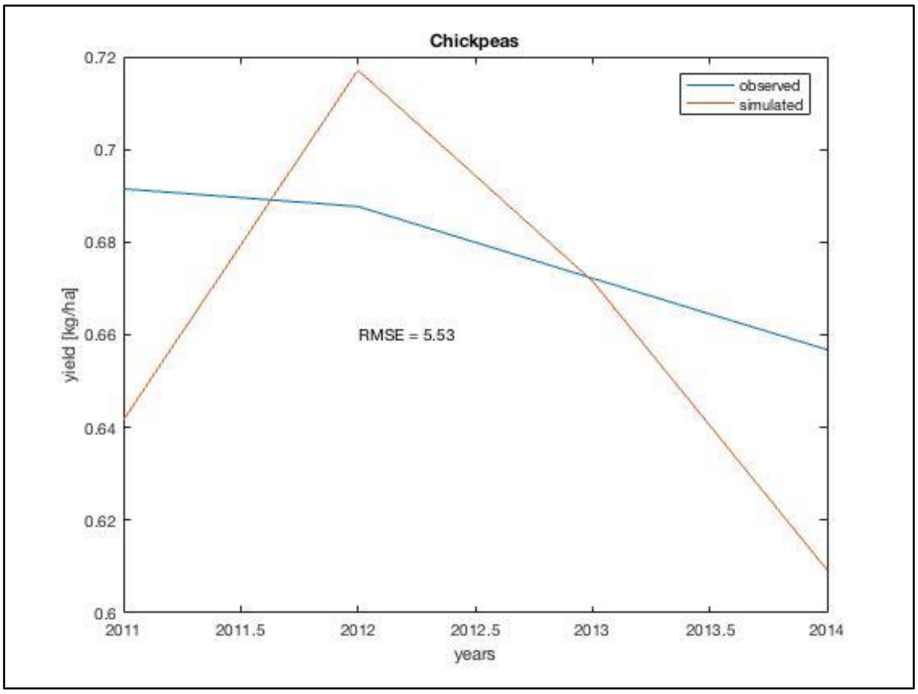
CCx	Maximum canopy cover (fraction of soil cover)
CDC	Canopy decline coefficient (fraction per GDD)
CGC	Canopy growth coefficient (fraction per GDD)
Kcb	Crop coefficient when canopy growth is complete but prior to senescene
fage	Decline of crop coefficient due to ageing (%/day)
WP	Water productivity normalized for ET0 and CO2 (g/m2)
WPy	Adjustment of water productvitiy in yield formation stage
fsink	Crop CO2 sink strength coefficient
bsted	WP CO2 adjustment parameter given by Steduto et al.2007
bface	WP CO2 adjustment parameter given by FACE experiments
HI0	Reference harvest index
HIini	Initial harvest index
dHI_pre	Possible increase of harvest index due to water stress before flowering
a_HI	Coefficient describing negative impact on harvest index of restricted vegetative growth during yield formation
b_hi	Coefficient describing negative impact on harvest index of stomatal closure during yield formation
dHI0	Maximum allowable increase of harvest index above reference
10Determinant	Crop determinancy (0: Indeterminant, 1: Determinant)
exc	Excess of potential fruits
MaxFlowPct	Percentage of total flowering at which peak flowering occurs
p_up1	Upper soil water depletion threshold for water stress effects on canopy “expansion”
p_up2	“stomatal control”
p_up3	“senescence”
p_up4	“pollination”
p_lo1	Lower soil water depletion threshold for water stress on canopy “expansion”
p_lo2	“stomatal control”
p_lo3	“senescence”
p_lo4	“pollination”
fshape_w1	Shape factor describing water stress effects on “canopy expansion”
fshape_w2	“stomatal control”
fshape_w3	“senescence”
fshape_w4	“pollination”
ETadj	Adjustment to water stress thresholds depending on daily ET0 (0: no, 1: yes)
Aer	Vol (%) below which saturation at which stress begins to occur due to deficient aeration
LagAer	Number of days lag before aeration stress affects crop growth
Beta	Reduction (%) to p_lo3 when early canopy senescence is triggered
GermThr	Proportion of toal water storage needed for crop to germinate

C.2 Parametrization

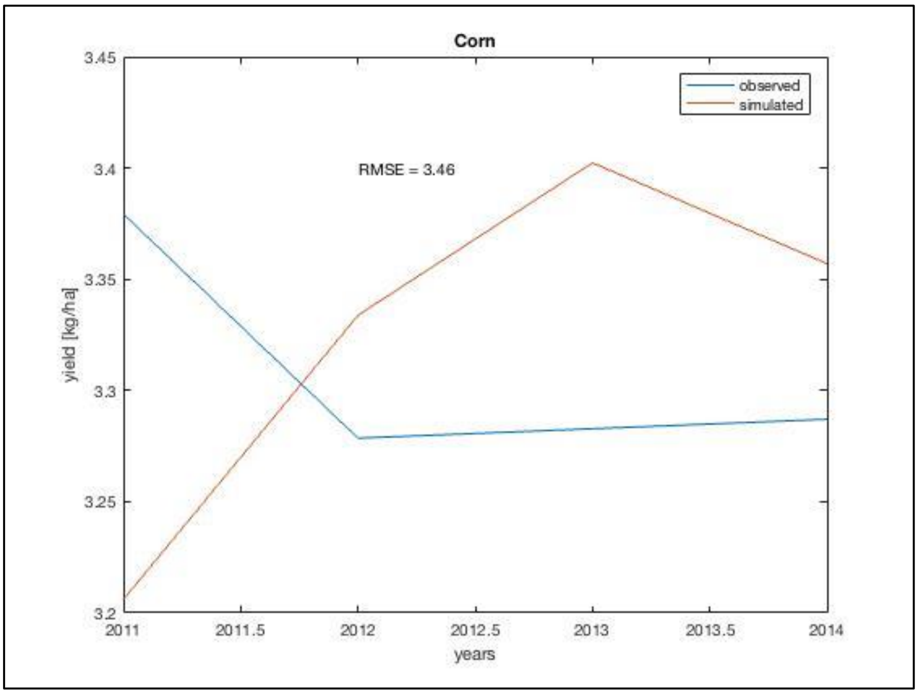
C.2.1Barley



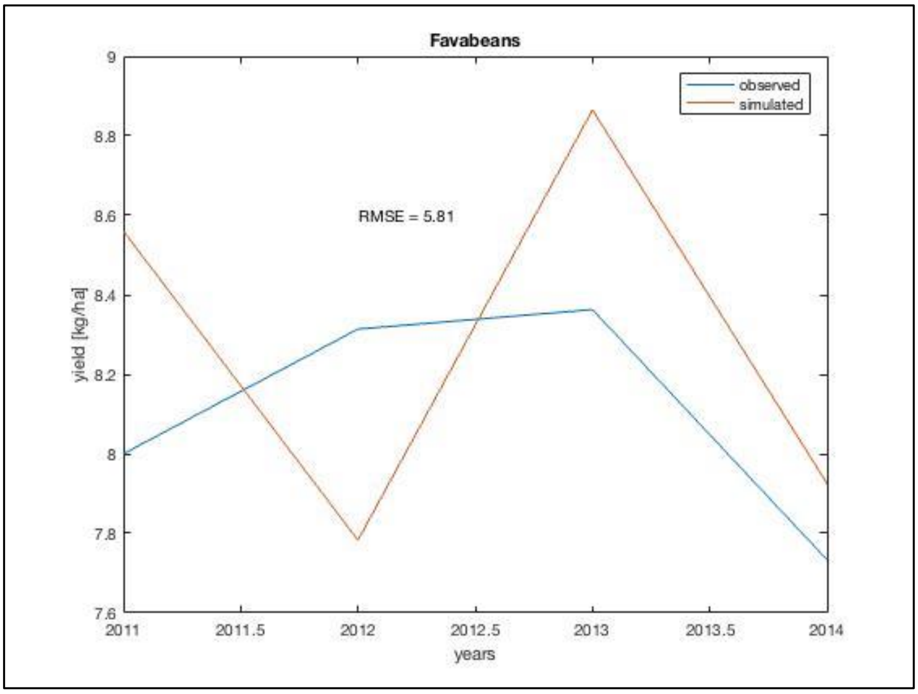
C.2.2Chickpeas



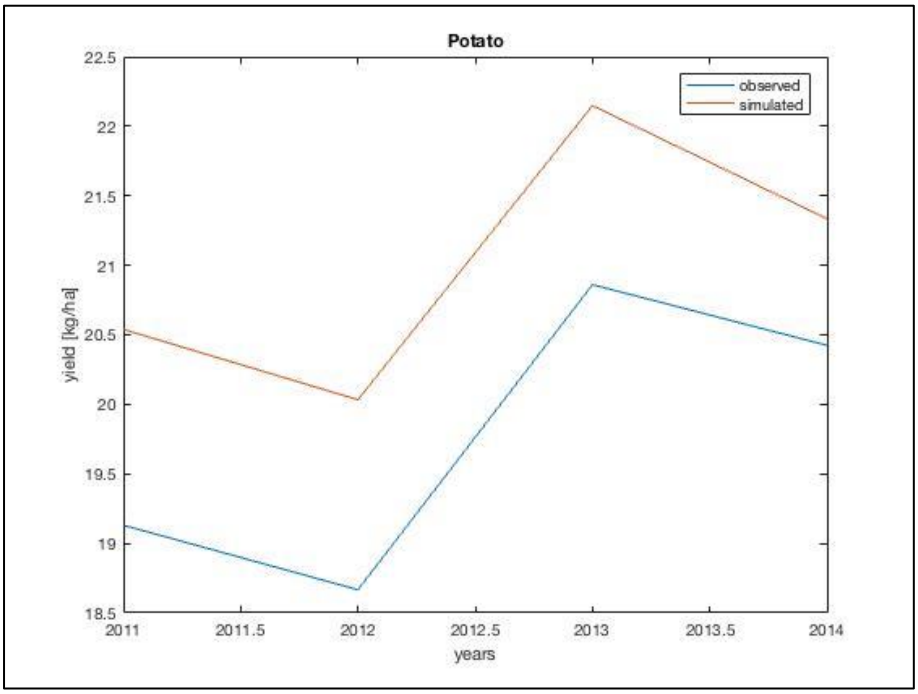
C.2.3Corn



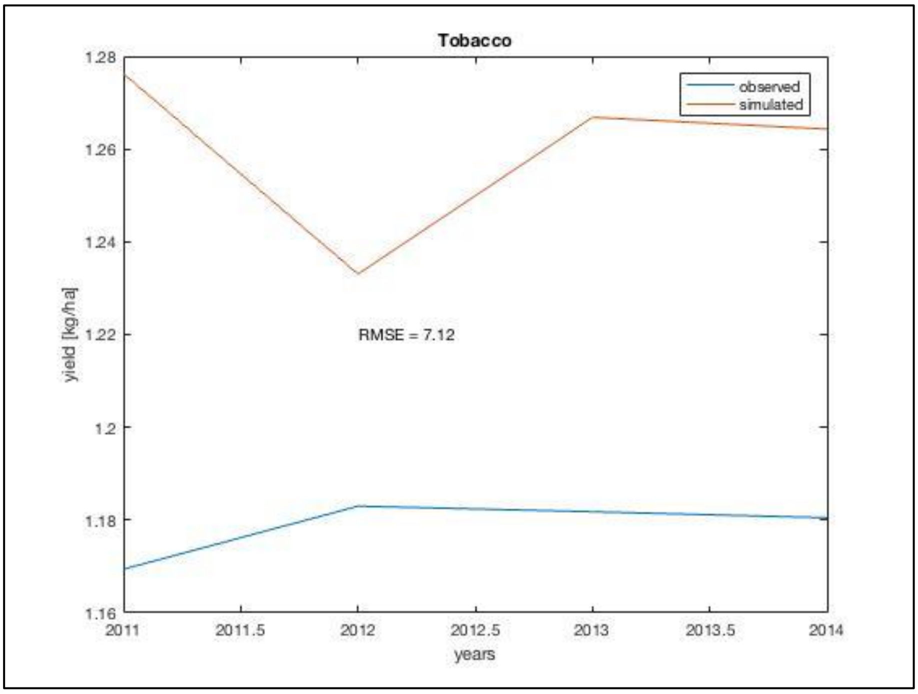
C.2.4Favabeans



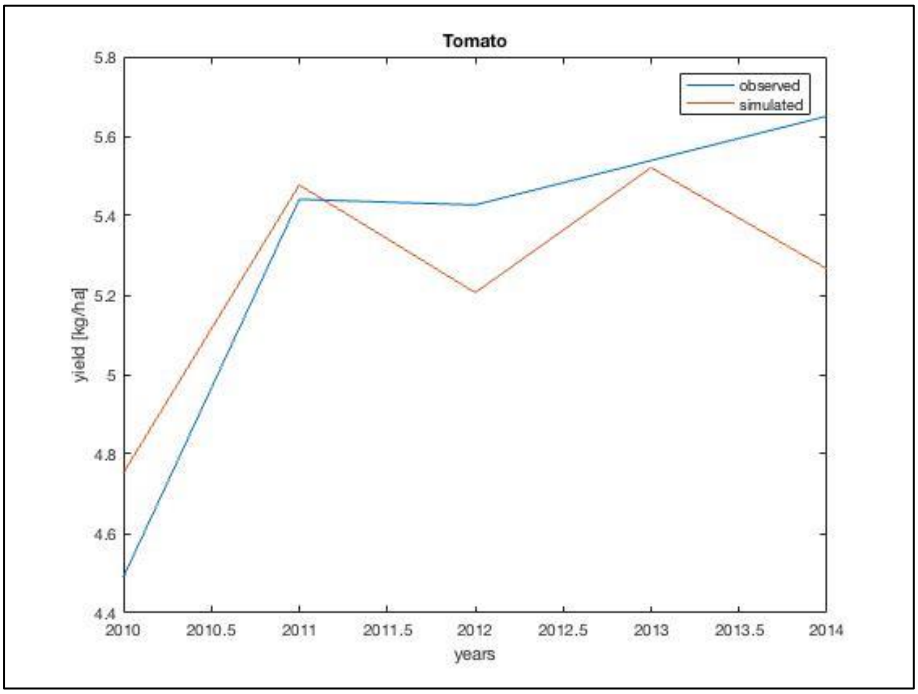
C.2.5Potato



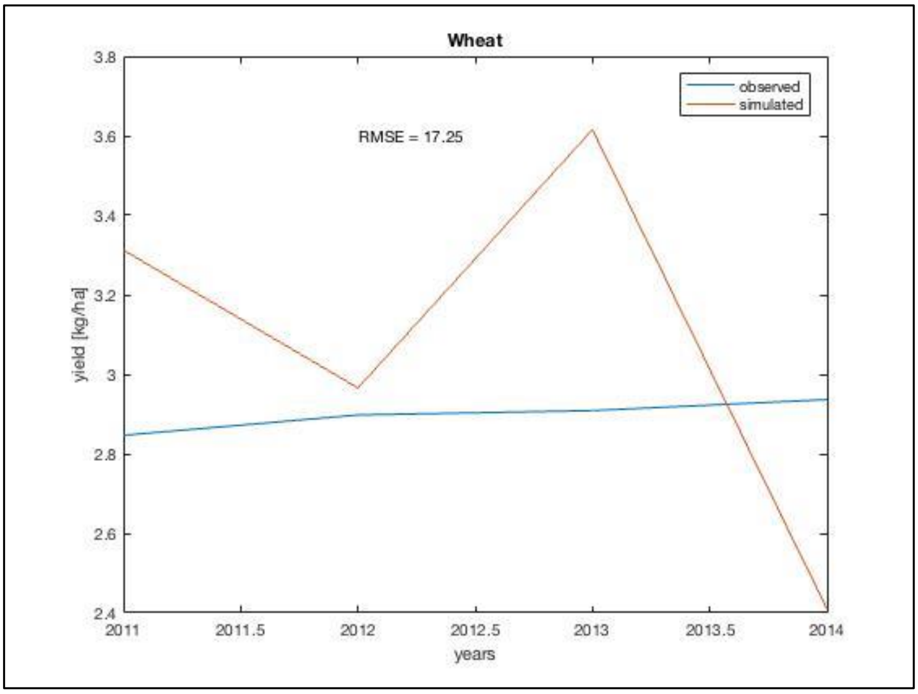
C.2.6Tobacco



C.2.7Tomato



C.2.8Wheat



C.3 Parameters in this study

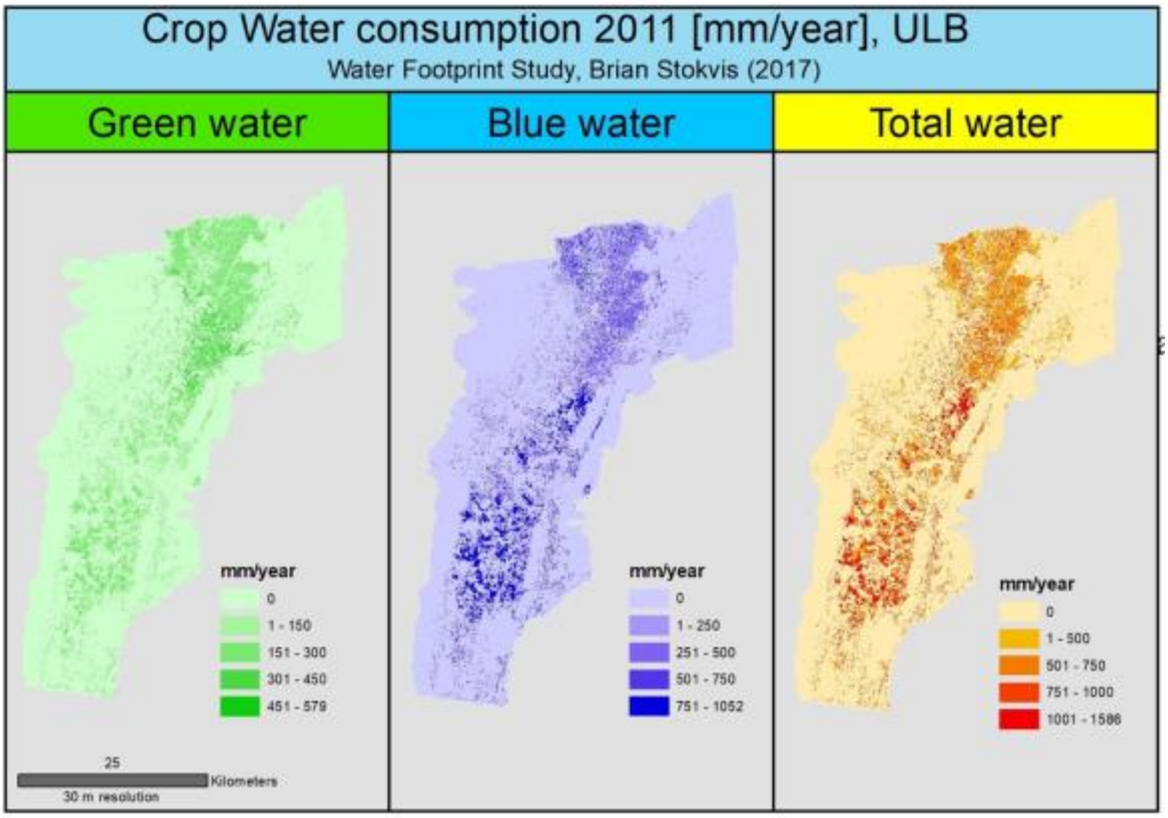
Conservative crop parameter					Non-conservative crop parameter					
Crop	**Alfalva**	**Barley**	**Corn**	**Chick peas**	**Fava beans**	**Early Potato**	**Late Potato**	**Tobacco**	**Tomato**	**Wheat**
Crop type	1	3	3	3	3	2	2	1	3	3
Calendar type	2	2	2	2	2	2	2	2	2	2
Swtich GDD	1	1	1	1	1	1	1	1	1	1
Planting date	may	nov	may	Nov	Nov/dec	May	Mar/Aug	May	May	Nov
HarvestDate										
Emergence	188	219	246	59	59	40	70	117	319	282
MaxRooting	958	741	1208	200	216	1900	1100	531	815	1096
Senescence	1327	1074	1028	242	357	2150	1000	941	1899	1570
Maturity	1551	1449	1208	274	522	2200	1200	1115	2443	2038
HIstart	700	741	426	190	247	400	600	313	449	1063
Flowering	-999	126	199	60	52	-999	-999	-999	793	171
Yldform	647	289	908	83	243	2200	400	457	1108	809
GDDmethod	1	1	1	1	1	1	1	1	1	1
Tbase	1	0	8	10	9	1	2	8	7	0
Tupp	35	15	30	33	30	26	26	35	28	26
PolHeatStress	0	1	1	1	1	0	0	0	1	1
Tmax_up		40	45	45	45				45	35
Tmax_lo		35	40	40	40				40	40
PolColdStress	0	1	1	1	1	0	0	0	1	0
Tmin_up		5	10	8	8				10	
Tmin_lo		0	5	3	3				5	
BioTempStress	1	1	1	1	1	1	1	1	0	1
GDD_up	12	14	12	12	12	12	7	12		14
GDD_lo	0	0	0	0	0	0	0	0		0

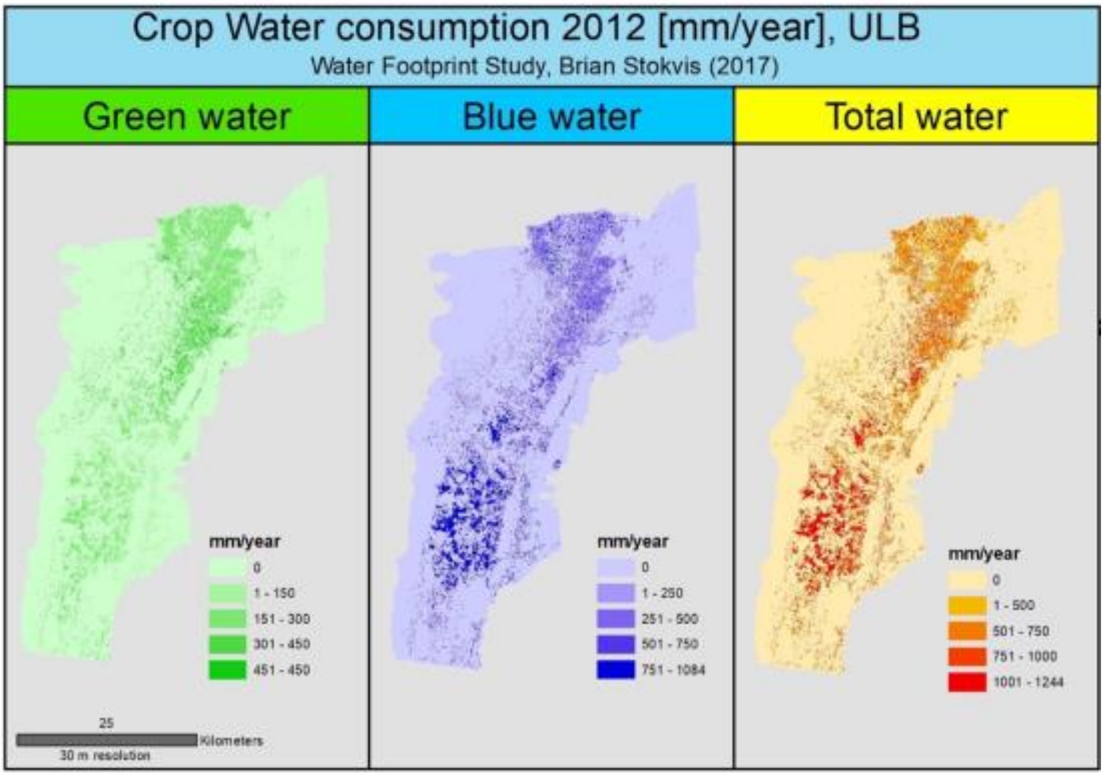
Fshape_b	13,8135	13,8135	13,8135	13,8135	13,8135	13,8135	13,8135	13,8135	13,8135	13,8135
PctZmin	70	70	70	70	70	70	70	70	70	70
Zmin	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3
Zmax	2	2,5	2,8	1,7	1,7	0.7	1,80	2	2	2,4
fshape_r	1,5	1,5	1,3	1,5	1,5	1,5	1,5	1,5	1,5	1,5
fshape_ex	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6
SxTopQ	0,024	0,048	0,045	0,024	0,024	0,024	0,048	0,024	0,048	0,048
SxBotQ	0,006	0,012	0,011	0,006	0,006	0,006	0,012	0,006	0,012	0,012
a_tr	1	1	1	1	1	1	1	1	1	1
SeedSize	15	1,5	6,5	5	10	5	20	5	1	1,50
PlantPop	40 000	2 000 000	60 000	300 000	132 000	300.000	60 000	300.000	50.000	4.500.000
CCmin	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
CCx	96	90	65	95	99	54	99	96	95	95
CDC	0,00286	0,006	0,01	0,00599	0,881	0.00145	0,002	0,00673	0,004	0,004
CGC	0,02108	0,008	0,012	0,00102	1,196	0.01107	0,018	0,00196	0,0075	0,006
Kcb	1,05	1,1	1,05	0,35	1,05	1,05	1,10	1,15	1,10	1,10
fage	0,15	0,15	0,3	0,15	0,15	0,15	0,15	0,15	0,15	0,15
WP	17	15	33,7	17	17	17	19	17	18	15
WPy	100	100	100	100	90	100	100	100	100	100
fsink	50	50	50	50		50	55	50	60	50
bsted	0,000138	0,000138	0,000138	0,000138	0,000138	0,000138	0,000138	0,000138	0,000138	0,000138
bface	0,001165	0,001165	0,001165	0,001165	0,001165	0,001165	0,001165	0,001165	0,001165	0,001165
HI0	2	40	48	52	40	80	90	55	50	48
HIini		0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01
dHI_pre		5	0	10	4	10	2		0	5
a_HI		10	7	10	0	10	0		0	10
b_hi		5	3	8	1	8	10		3	7
dHI0		15	15	15	10	15	5		15	15

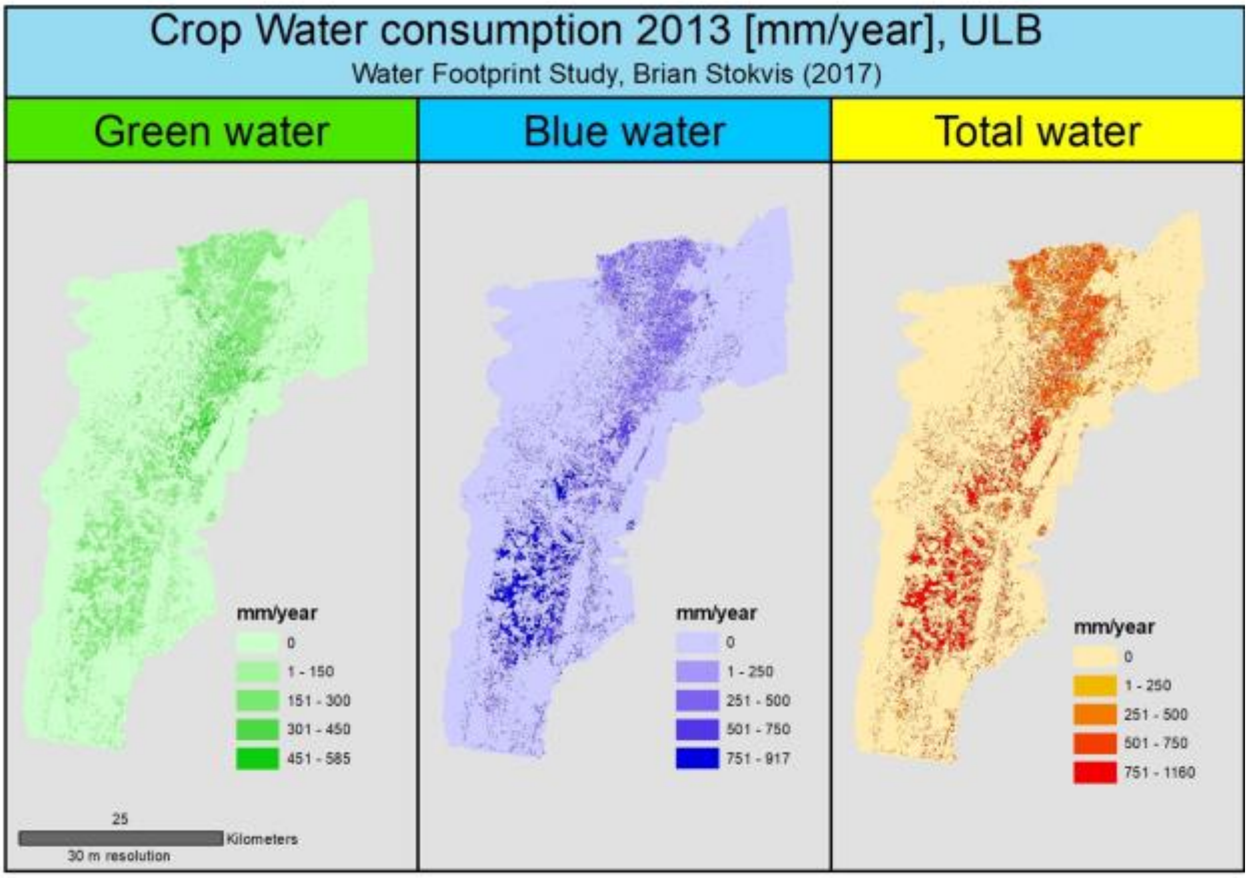
Determinant		1	1	1	1	0	0	0	0	1
exc	20	100	50	50	50	0		20	200	100
MaxFlowPct	33,33	33,33	33,33	33,33	33,33	33,33	33,33	33,33	33,33	33,33
p_up1	0,25	0,2	0,14	0,25	0,15	0,25	0,2	0,25	0,15	0,2
p_up2	0,5	0,6	0,69	0,5	0,6	0,5	0,55	0,5	0,5	0,65
p_up3	0,85	0,55	0,69	0,85	0,7	0,85	0,7	0,85	0,7	0,7
p_up4		0,85	0,8	0,9	0,9				0,92	0,85
p_lo1	0,55	0,65	0,72	0,55	0,65	0,55	0,6	0,55	0,55	0,65
p_lo2	1	1	1	1	1	1	1	1	1	1
p_lo3	1	1	1	1	1	1	1	1	1	1
p_lo4		1	1	1	1	0	0	0	1	1
fshape_w1	3	3	2,9	3	2,5	3	3	3	3	5
fshape_w2	3	3	6	3	1	3	3	3	3	2,5
fshape_w3	3	3	2,7	3	2,5	3	3	3	3	2,5
fshape_w4	1	1	1	1	1	1			1	1
ETadj	1	1	1	1	1	1	1	1	1	1
Aer	5	15	5	5	5	5	5	5	5	5
LagAer	3	3	3	3	3	3	3	3	3	3
Beta	12	12	12	12	12	12	12	12	12	12
GermThr	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2

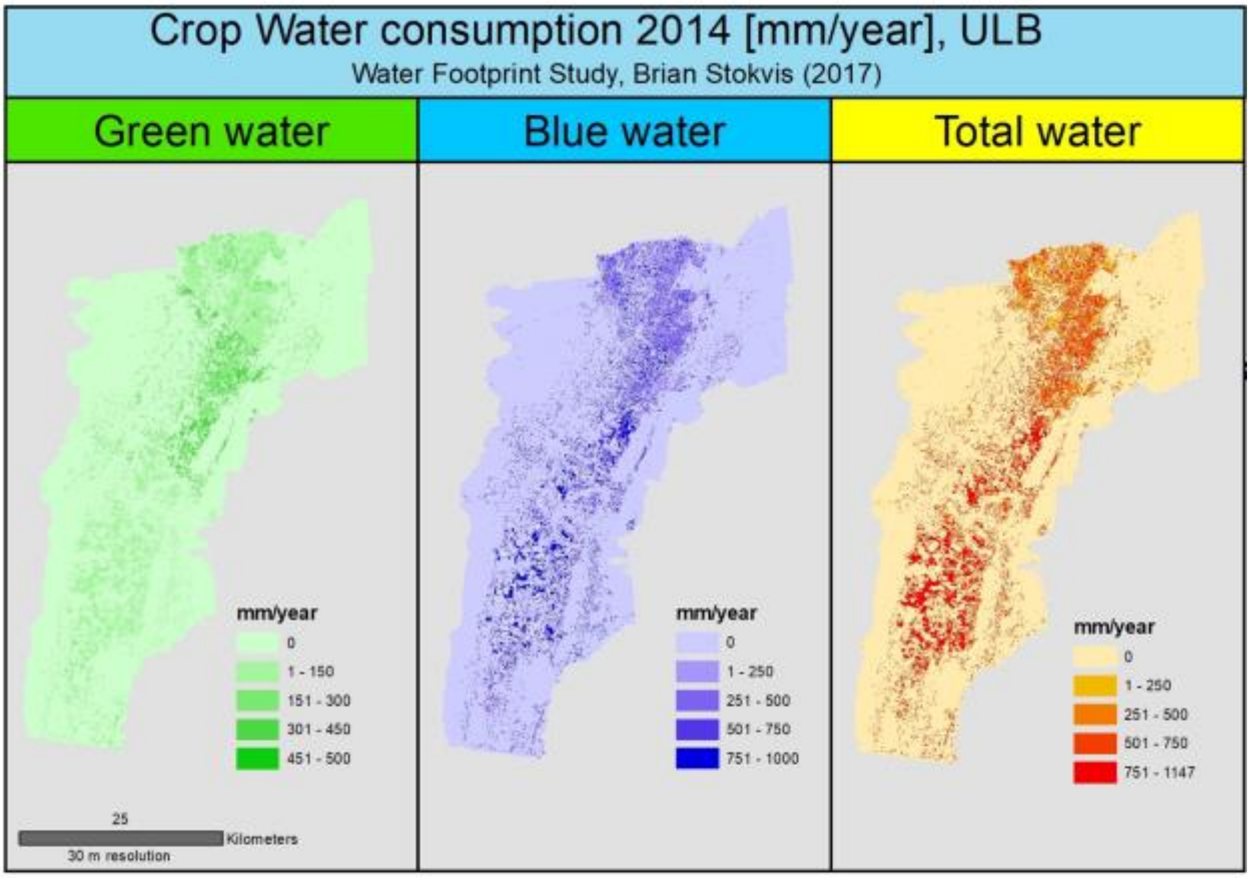
Output data

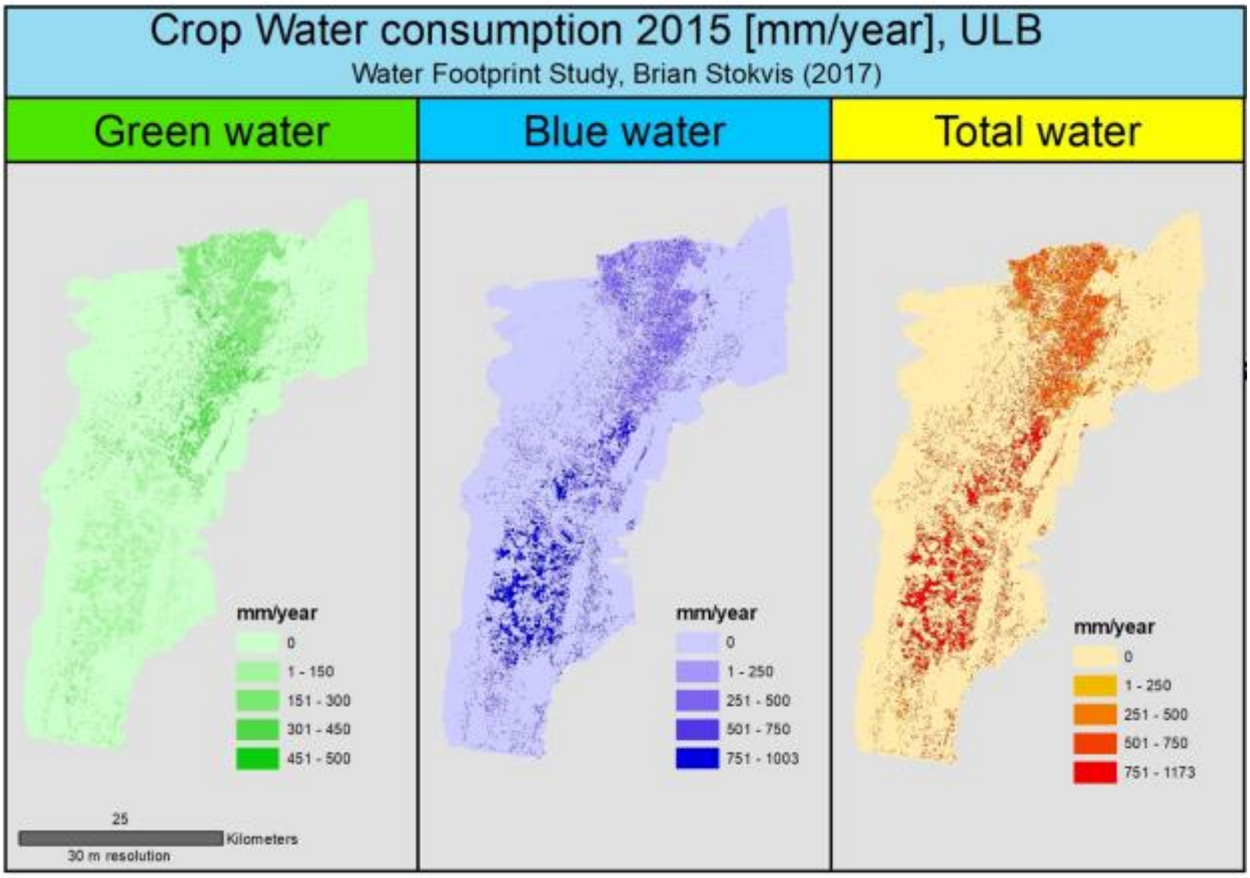
C.1 Crop Water consumption maps [2011 – 2016]

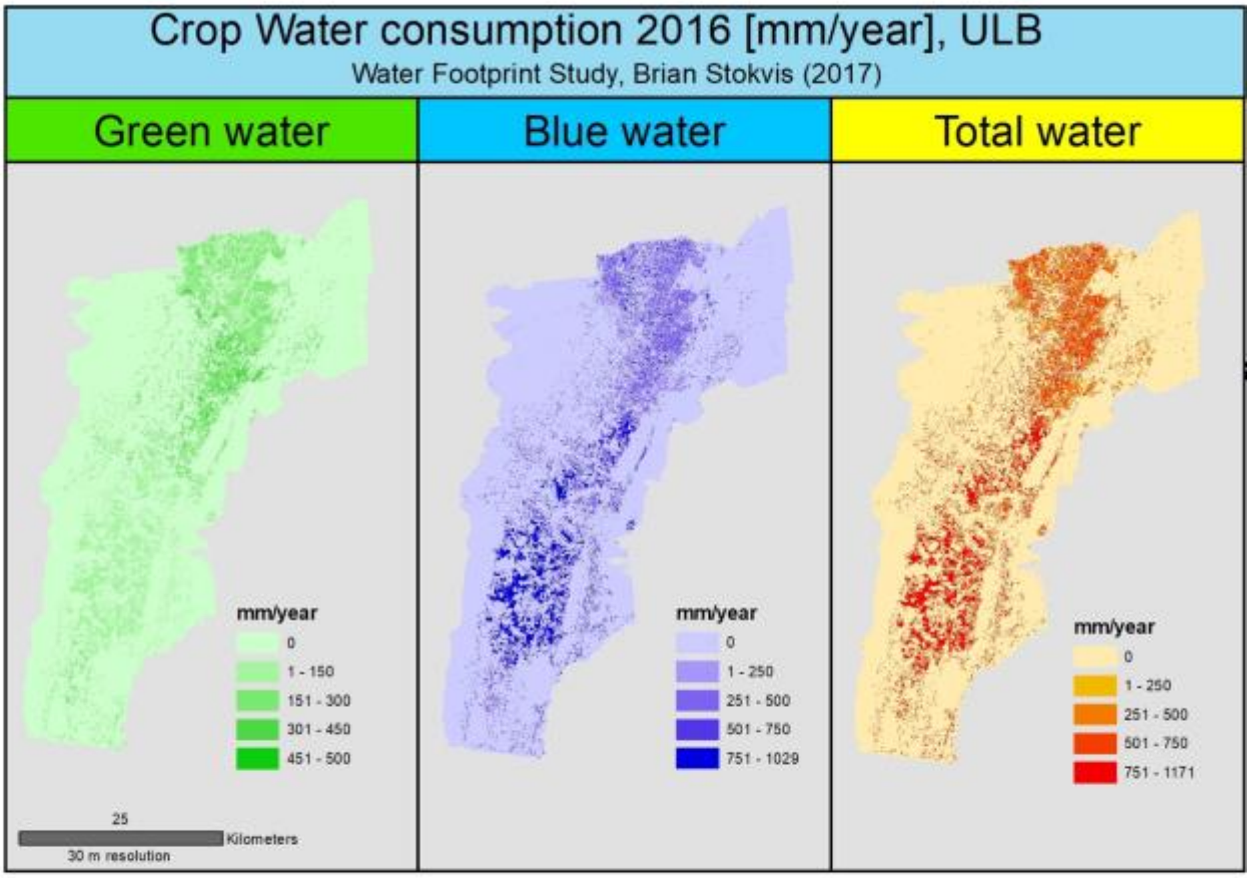




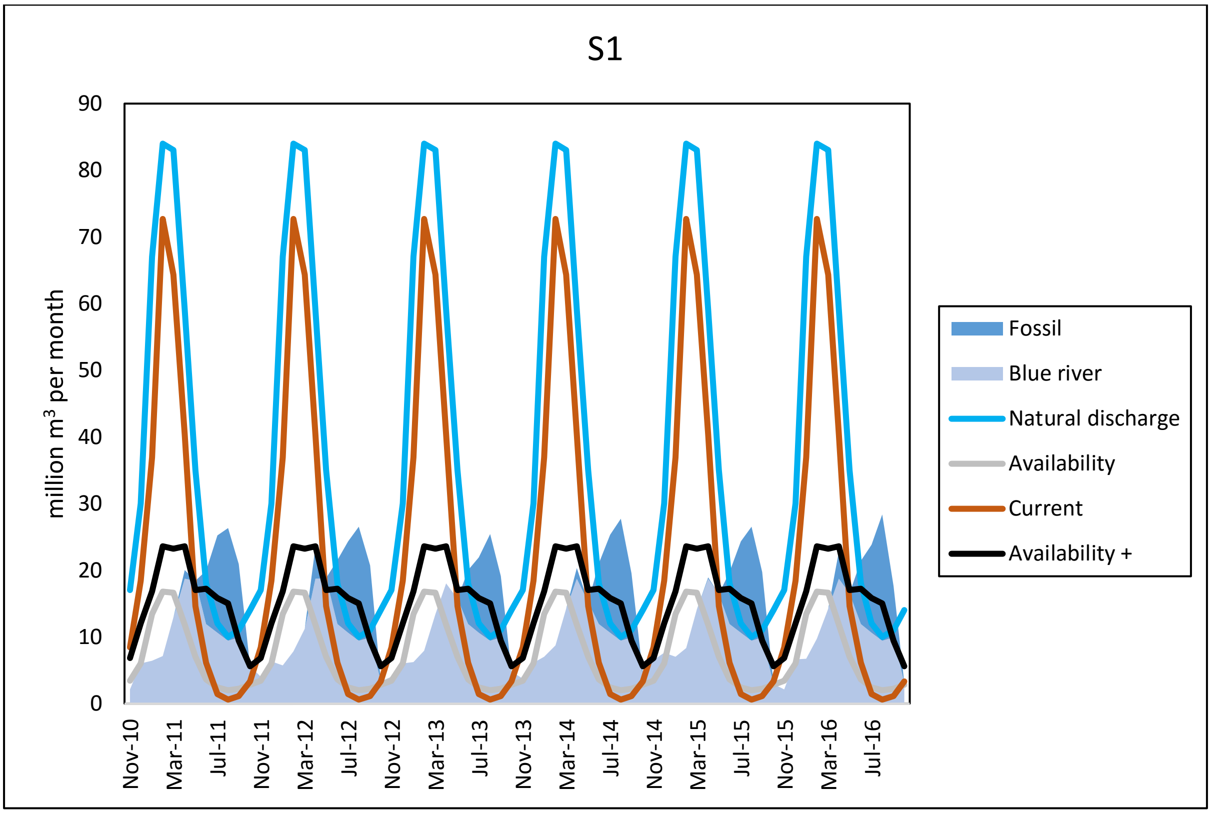

Crop Water consumption 2013 [mm/year], ULB
Water Footprint Study, Brian Stokvis (2017)
Green water
Blue water
Total water
mm/year
0
1 - 150
151 - 300
301 - 450
451 - 585
mm/year
0
1 - 250
251 - 500
501 - 750
751 - 917
mm/year
0
1 - 250
251 - 500
501 - 750
751 - 1160
25
Kilometers
30 m resolution

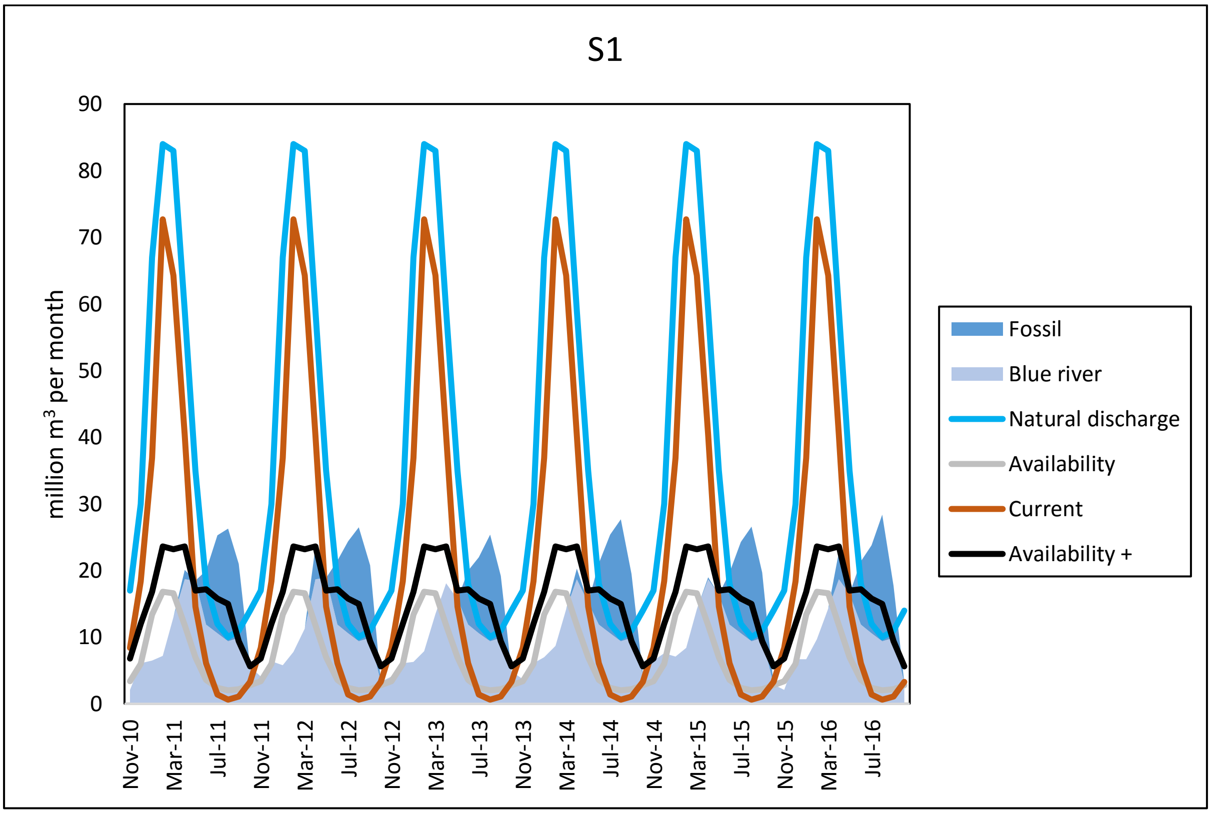

Crop Water consumption 2014 [mm/year], ULB
Water Footprint Study, Brian Stokvis (2017)
Green water
Blue water
Total water
mm/year
0
1 - 150
151 - 300
301 - 450
451 - 500
mm/year
0
1 - 250
251 - 500
501 - 750
751 - 1000
mm/year
0
1 - 250
251 - 500
501 - 750
751 - 1147
25
Kilometers
30 m resolution

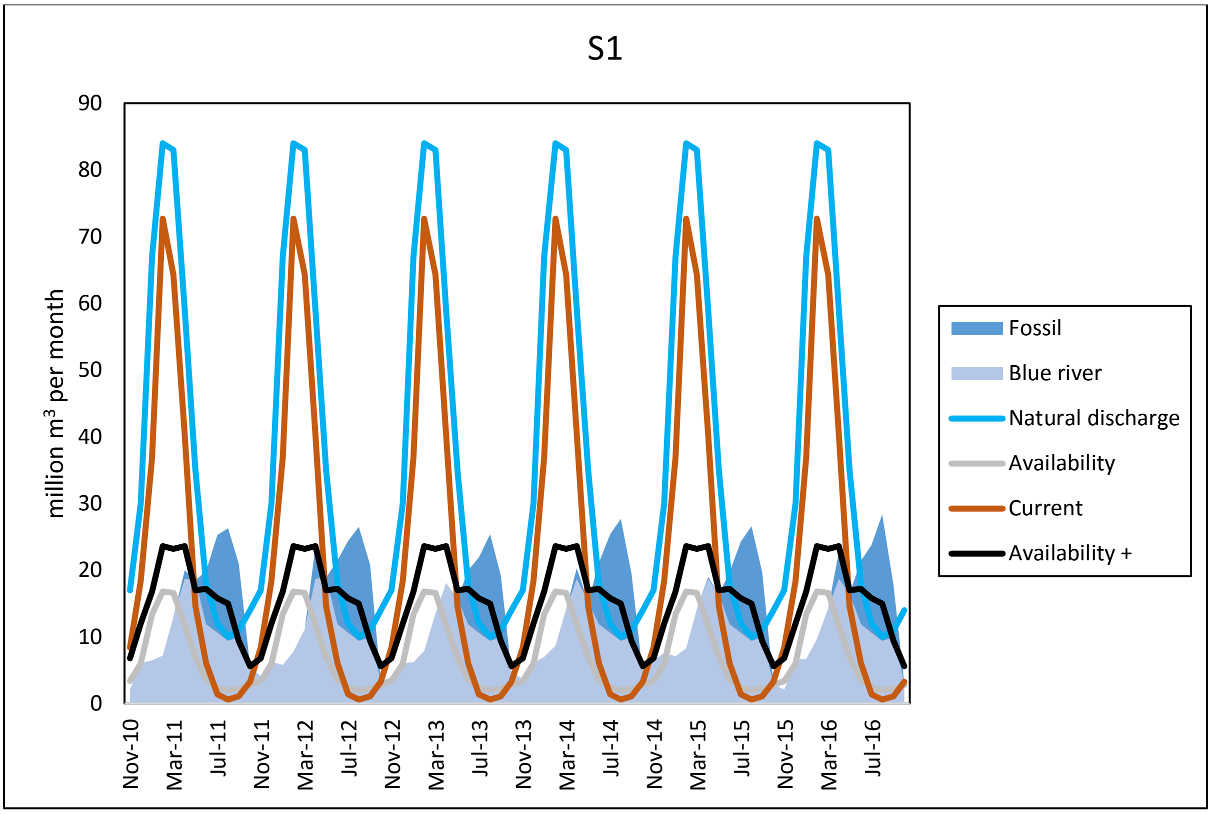

Crop Water consumption 2015 [mm/year], ULB
Water Footprint Study, Brian Stokvis (2017)
Green water
Blue water
Total water
mm/year
0
1 - 150
151 - 300
301 - 450
451 - 500
25
Kilometers
30 m resolution
mm/year
0
1 - 250
251 - 500
501 - 750
751 - 1003
mm/year
0
1 - 250
251 - 500
501 - 750
751 - 1173

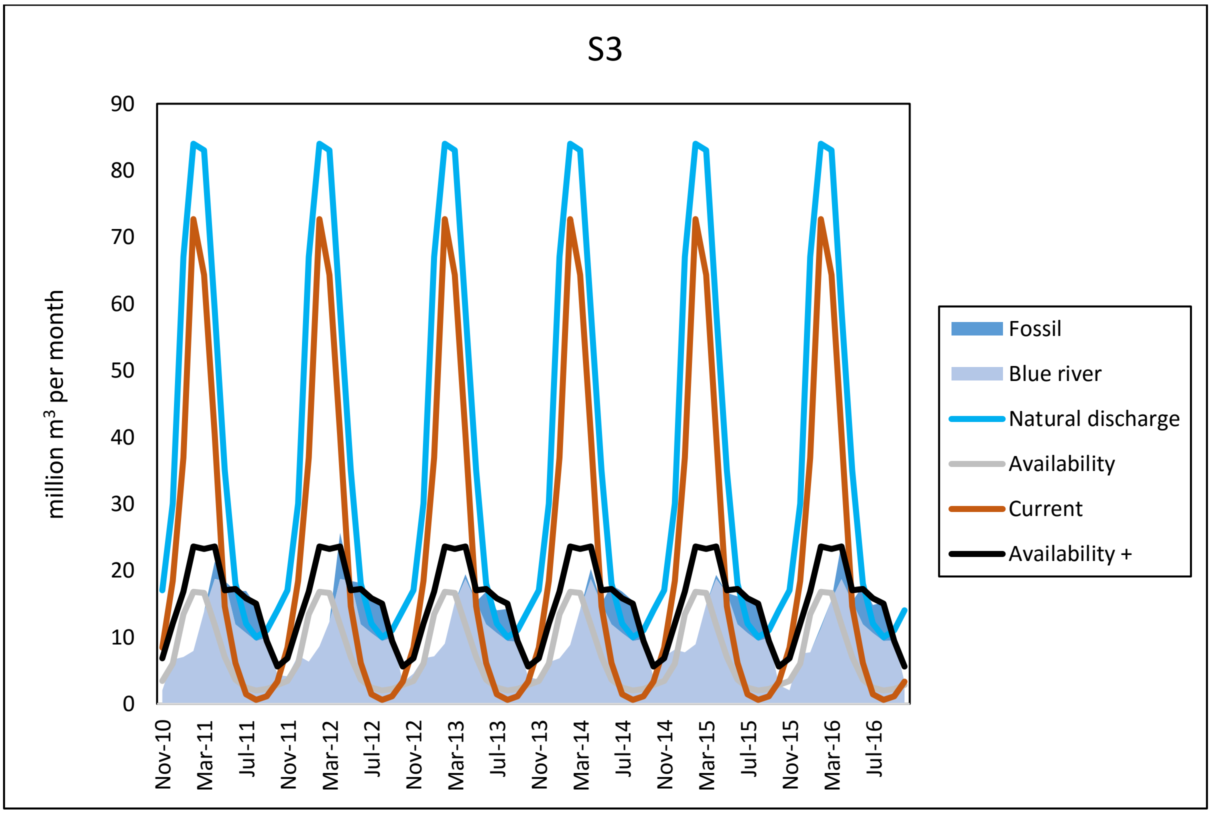

Crop Water consumption 2016 [mm/year], ULB
Water Footprint Study, Brian Stokvis (2017)
Green water
Blue water
Total water
mm/year
0
1 - 150
151 - 300
301 - 450
451 - 500
25
Kilometers
30 m resolution
mm/year
0
1 - 250
251 - 500
501 - 750
751 - 1029
mm/year
0
1 - 250
251 - 500
501 - 750
751 - 1171

C.2 Blue water consumption [2011 – 2016]

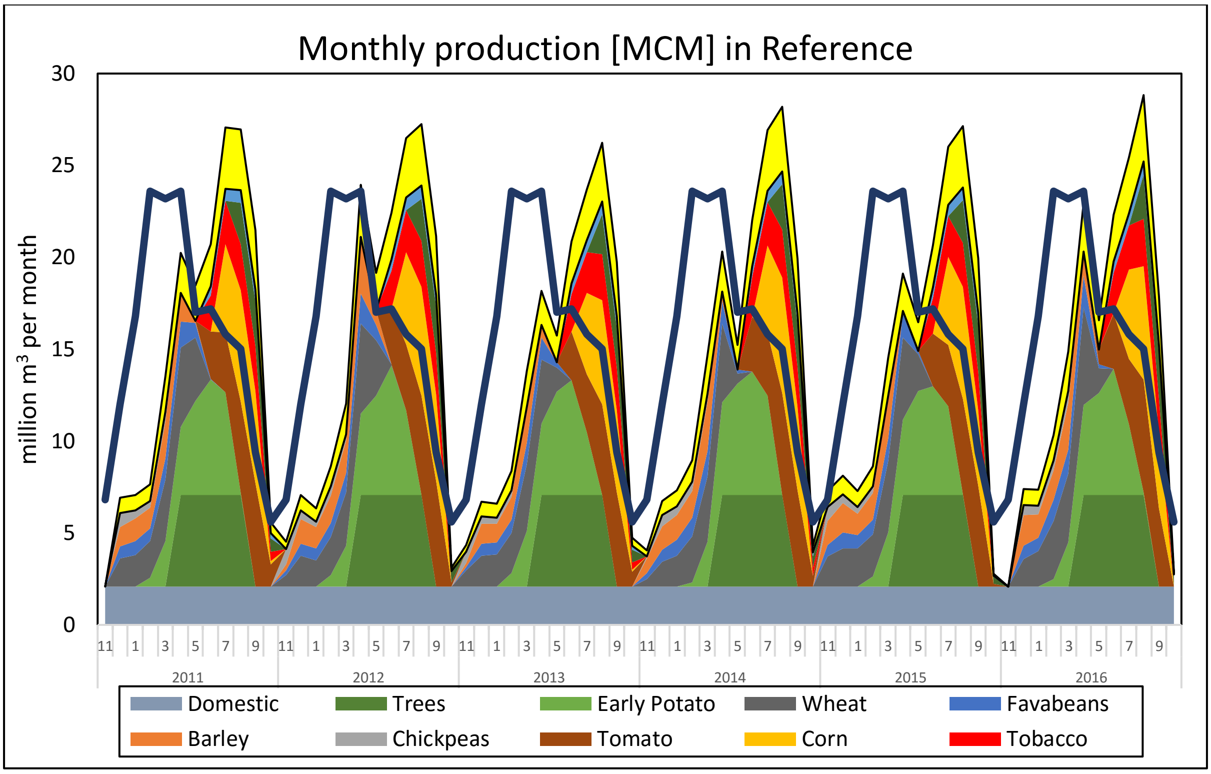


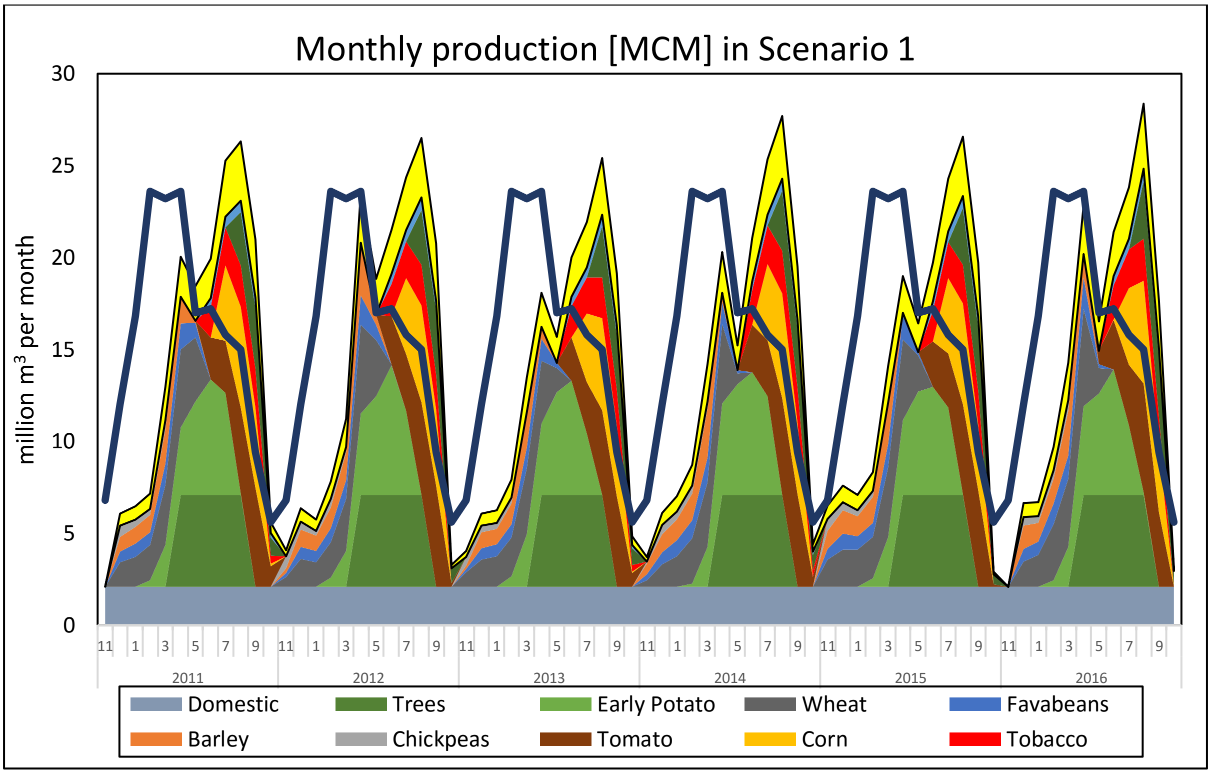


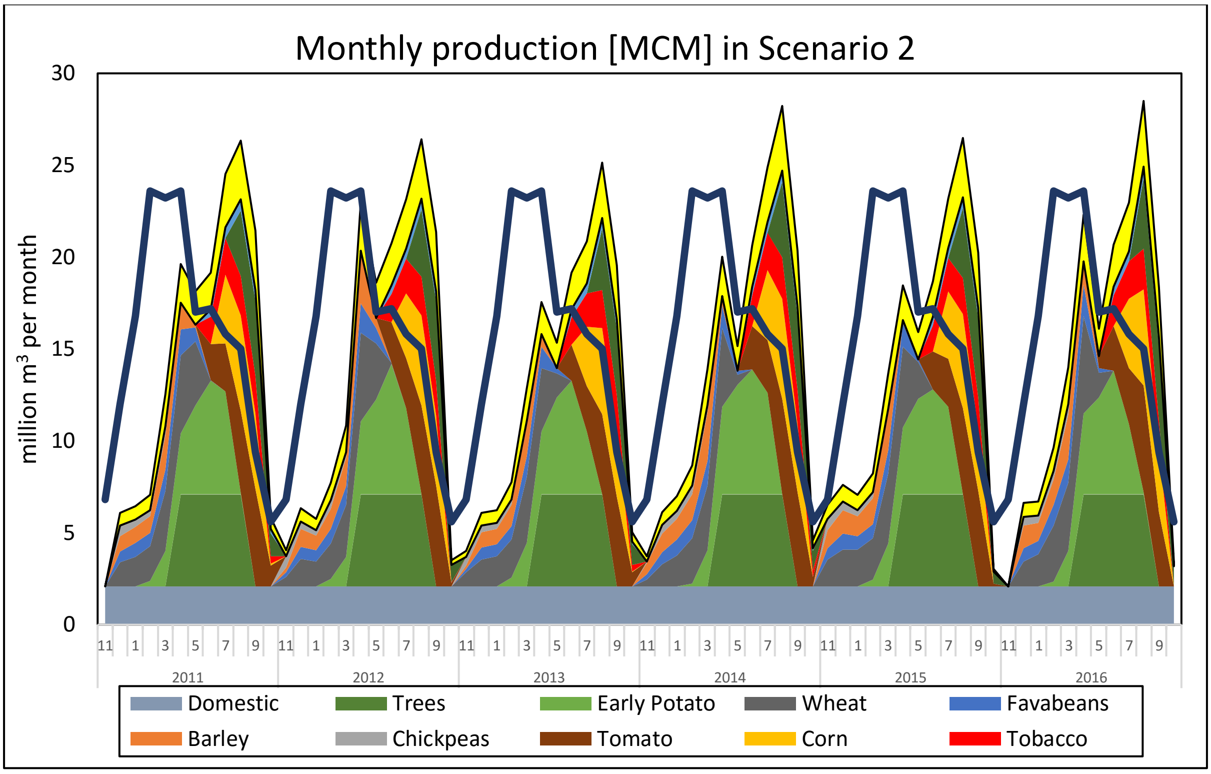

S1
million m³ per month
90
80
70
60
50
40
30
20
10
0
Nov-10
Mar-11
Jul-11
Nov-11
Mar-12
Jul-12
Nov-12
Mar-13
Jul-13
Nov-13
Mar-14
Jul-14
Nov-14
Mar-15
Jul-15
Nov-15
Mar-16
Jul-16
Fossil
Blue river
Natural discharge
Availability
Current
Availability +

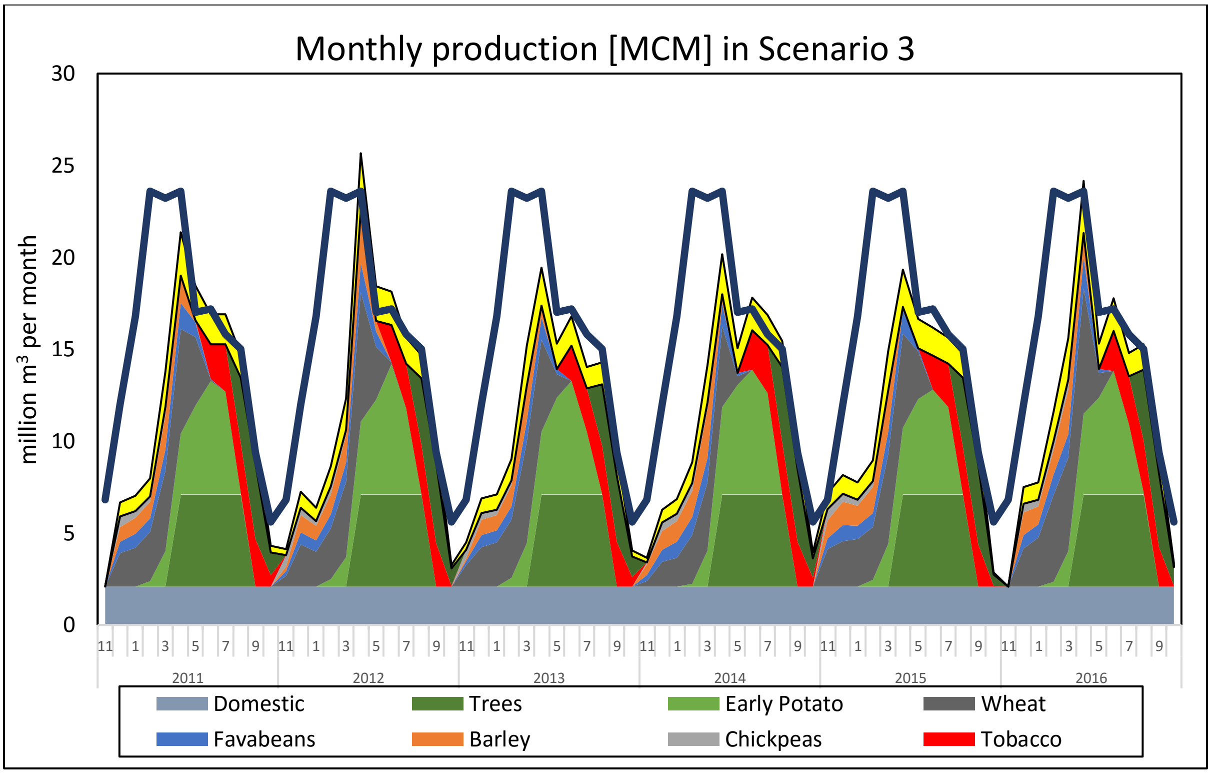

S3
million m³ per month
90
80
70
60
50
40
30
20
10
0
Nov-10
Mar-11
Jul-11
Nov-11
Mar-12
Jul-12
Nov-12
Mar-13
Jul-13
Nov-13
Mar-14
Jul-14
Nov-14
Mar-15
Jul-15
Nov-15
Mar-16
Jul-16
Fossil
Blue river
Natural discharge
Availability
Current
Availability +

C.3 Blue WF per crop type [2011 – 2016]






Monthly production [MCM] in Scenario 2
million m3 per month
30
25
20
15
10
5
0
11 1 3 5 7 9
2011
2012
2013
2014
2015
2016
Domestic
Trees
Early Potato
Wheat
Favabeans
Barley
Chickpeas
Tomato
Corn
Tobacco


Monthly production [MCM] in Scenario 3
million m3 per month
30
25
20
15
10
5
0
11 1 3 5 7 9
2011
2012
2013
2014
2015
2016
Domestic
Trees
Early Potato
Wheat
Favabeans
Barley
Chickpeas
Tobacco