POLITECNICO DI MILANO

School of Civil and Environmental Engineering

Master of Science in
Environmental and Land Planning Engineering

# Trading off food security and environmental impacts: the Water Footprint of food production in the Gaza Strip

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# Compromesso tra sicurezza alimentare e impatti ambientali: calcolo della Water Footprint della produzione di cibo nella Striscia di Gaza

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Ai nonni, all’asino vivo. . . ai miei genitori, i quali hanno creduto nel dottore e ad Andrea, perché é Andrea

— Francesca —

# CONTENTS

# LIST OF FIGURES

## LIST OF TABLES

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# ACRONYMS

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| | |
|---|---|
| AR | Application Rate |

| | |
|---|---|
| BAU | Business As Usual |
| CMWU | Coastal Municipalities Water Utility |
| CoWU | Consumptive Water Use |
| CRU | Climate Research Unit |
| CWR | Crop Water Requirement |
| CWU | Crop Water Use |
| DWU | Degradative Water Use |
| eggplant4 | eggplant grown for 4 months |
| eggplant5 | eggplant grown for 5 months |
| EWASH | Emergency Water Sanitation-Hygiene Group |
| FAO | Food and Agriculture Organization |
| FCE | Food Conversion Efficiency |
| GS | Gaza Strip |
| IAA | Integrated Agriculture and Aquaculture |
| Kc | Crop Coefficient |
| LCA | Life Cycle Assessment |
| MDGs | Millennium Development Goals |
| NIS | New Israeli Shenkel |
| NPP | Net Primary Production |
| oPt | occupied Palestinian territories |
| pea3 | pea grown for 3 months |
| pea4 | pea grown for 4 months |
| pepper4 | pepper grown for 4 months |
| pepper5 | pepper grown for 5 months |
| PNA | Palestinian National Authority |
| PDF | Potentially Disappeared Fraction of species |
| PNA | Palestinian National Authority |
| PWA | Palestinian Water Authority |
| SRF | Strongly Regulated Flows |

| | |
|---|---|
| SWI | salt water intrusion |
| UAWCA | Union of Agriculture Work Committees Association |
| VF | Variation Factor |
| VPBD | Vulnerability of vascular Plant species Biodiversity |
| WB | West Bank |
| WF | Water Footprint |
| WFP | World Food Program |
| WHO | World Health Organization |
| WSI | Water Stress Index |
| WTA | Withdrawals To Availability |
| WWTP | Waste Water Treatment Plant |

# ABSTRACT

The sustainability of food production systems is a fundamental issue in a global development context. Its importance is even increased in an area like the Gaza Strip, where natural resources are scarce and extremely exploited and the population density is one of the highest in the world. Furthermore, the United Nations claim that, with respect to the MDGs, the GS is affected by both food insecurity and environmental sustainability. These two aspects are jointly analyzed in this study: in fact, the general goal of this work concerns the sustainability assessment of some existing protein production systems in GS. The adopted methodology consists in the assessment of the WF, of other environmental impacts (using Life Cycle Assessment), and of the proteins production related to some existing agricultural systems, including aquaculture.

The main outcomes show that, even though the analyzed systems could quantitatively provide the required amount of proteins, they exploit the groundwater resources in an unsustainable way. Furthermore, aquaculture affects the water consumptions more than other livestock activities, and for this reason, investing on that activity is not convenient. Concerning the Gazians' diet, the proteins requirement is mainly satisfied thanks to vegetables: this means that, each person would eat a portion of vegetables ten times bigger than the recommended one, assuming the proteins amount recommended by the Food and Agriculture Organization. For this reason, trade mechanisms are suggested to improve the quality of the diet for the population, and to take advantages from virtual water trade. Also the methodology adopted in this study can be evaluated, in light of the results: integrating WF and Life Cycle Assessment (LCA) a complete impacts assessment, considering both local and global perspectives, can be obtained . Moreover, for a better integration of these methodologies, the evaluation of damages to human health, to ecosystem, and to resources, related to water consumption for the arid areas, should be included in the LCA method. Estimating impacts and damages caused by the analyzed agricultural systems, their sustainability referred to natural resources in the GS assessed.

# SOMMARIO

La sostenibilitá dei sistemi di produzione di cibo é un punto cruciale nel contesto dello sviluppo globale. La sua importanza viene enfatizzata in un'area come la striscia di Gaza, nella quale le risorse naturali sono scarse e giá estremamente sfruttate e la densitá demografica é una delle piú alte al mondo. Inoltre, le Nazioni Unite sostengono che, riferendosi ai MDGs la Striscia di Gaza é interessata sia da insicurezza alimentare che da mancanza di sostenibilitá ambientale. Questi due aspetti vengono analizzati in maniera congiunta in questo studio: infatti, l'obiettivo generale del lavoro riguarda la valutazione della sostenibilitá di alcuni sistemi di produzione di proteine presenti nella Striscia di Gaza. Il procedimento consiste nella stima della WF, di altri impatti ambientali (usando LCA) e della produzione di proteine di sistemi agricoli esistenti nella Striscia di Gaza, che prevedono l'acquacoltura.

I risultati mostrano che, anche se i sistemi analizzati potrebbero produrre la quantitá di proteine necessaria a soddisfare il fabbisogno della popolazione, per farlo sfrutterebbero le risorse idriche in maniera non sostenibile. L'acquacoltura, inoltre, presenta consumi idrici maggiori rispetto alle altre attivitá di allevamento, e per questo motivo, non risulta un investimento conveniente. A proposito della dieta della popolazione di Gaza, il fabbisogno di proteine é principalmente soddisfatto grazie alle verdure: tuttavia ció significa che ogni persona deve assumere una porzione giornaliera di vegetali dieci volte maggiore di quella consigliata, per raggiungere la quota minima di proteine raccomandata dalla Food and Agriculture Organization (FAO). Per questo motivo meccanismi di mercato estero potrebbero migliorare la qualita' della dieta della popolazione a Gaza e portare benefici in termini di virtual water.

Alla luce dei risultati ottenuti, anche la metodologia adottata puo' essere valutata: integrando WF e LCA, vengono stimati impatti a livello sia locale sia globale. Inoltre, per migliorare l'integrazione tra le due metodologie, é stata inclusa nella LCA la valutazione dei danni, causati dai consumi idrici, alla salute umana, alla qualitá degli ecosistemi e alle risorse.

# Part I

# METHODOLOGY AND CASE STUDY

# 1

# INTRODUCTION

'Food security exists when all people at all times have both physical and economic access to sufficient, safe and nutritious food that meets their dietary needs for an active and healthy life. People who have better access to water tend to have lower levels of undernourishment. The lack of water can be a major cause of famine and undernourishment, in particular in areas where people depend on local agriculture for food and income [. . . ] The lack of water limits farmers' ability to produce enough food to eat or earn a living. South Asia, East Asia and the Middle East for example are already close to their resources limits, and their population is still growing.' (UN and FAO, World Water Day, 2012). This sentences completely explain the importance of water in food security issues. Given the relevance of this topic, the goal of this study is to assess the environmental sustainability of food production systems, especially in terms of water consumption, in an area whose natural resources are already extremely exploited and the population density is one of the highest in the world: the GS.

The critical situation concerning food security and environmental sustainability is reported also by FAO (FAO, 2012 [15]) and UNDP (UNDP, 2011 [40]): data show that families employed in the agriculture sector face levels of food insecurity significantly higher than their average level (75% versus 52% average value). Moreover, among the MDGs, the eradication of extreme poverty and hunger and ensuring environmental sustainability are unlikely to be achieved by 2015 in the oPt. These critical conditions are caused by both political and environmental difficulties affecting the area, i.e. the perennial conflict with Israel, and the climatic conditions characterized by aridity.

Since agriculture has an important role in Palestinian economy, and the majority of food insecure population lives in the rural area, several international organizations in collaboration with local partners are working on projects that aim at improving the living conditions of these citizens without, at the same time, compromising the environmental component integrity. From the collaboration with one of these organizations, Overseas NGO, the idea of this study originated: this organization is involved in a project concerning the introduction of aquaculture in the existing water ponds, and its operators are interested in the assessment of advantages and impacts of this activity. Broadening this analysis to the adopted agricultural systems in the GS, we assess the sustainability of food production systems. This topic is emerging as fundamental point in development issues in fact the FAO has decided to dedicate the World Food Day (16 October 2013) to 'Sustainable Food Systems for Food Security and Nutrition'.

This work is a first analysis regarding the consumption of natural resources in food production in the GS, and its main goals concern the evaluation of existent agricultural systems in the GS in terms of WF, environmental impacts and proteins productions. With this study we evaluate whether some existing agricultural systems can produce the required nutrients (especially proteins) for a balanced diet for the whole Gazian population, exploiting local natural resources in a sustainable way. In particular, we want to evaluate whether aquaculture and its product are better than other animal products or crops, in terms of both proteins production and environmental sustainability. Moreover, with this work we want to analyze whether the natural resources in the GS (especially freshwater and land) are sufficient to produce the main nutrients for a balanced diet for the whole population, or trade mechanisms are necessary to cope with food security.

A proper methodology was created by the author of this study, in order to pursue all the mentioned goals. It is composed by the following three steps: WF, LCA, quantification of nutrients provided to population, under the constraint that the balanced diet for each person must be respected. Firstly, the WF of different agricultural products and systems is evaluated; LCA is sequentially used to have a wider evaluation in terms of both environmental impacts for the considered area: the analyzed impact categories concern local, regional and global impacts; finally, these environmental aspects are coupled with proteins and food production. Furthermore, apart from WF, other indicators concerning water consumption and its related impacts are calculated and evaluated.

The steps of this work correspond to the following chapters:

- Chapter 2: this chapter deals with a general description of the study area (the GS); it focuses on its hydrological resources, its historical events, and the attainment status of MDGs in the oPt.
- Chapter 3: this chapter focuses on the case study created for this analysis; the agricultural sector in the GS, and our partner for this work, Overseas NGO, are introduced.
- Chapter 4: it describes the theory of the adopted methodology, which is mainly composed by WF and LCA.
- Chapter 5: the data required for the different steps of the analysis are presented.
- Chapter 6: the results of the study are shown and interpreted following this order: WF accounting, proteins and food production in the GS and its related impacts, other indicators related to water consumption, and, finally, the LCA results.

- Chapter 7: the main conclusions of the study are presented together with the contribution to the field study and the future improvements.

# 2

# THE CHALLENGE OF THE GAZA STRIP: RESOURCE SCARCITY AND FOOD INSECURITY

In this chapter we present the case study area. In particular, data concerning geography, climate, topography and soil, and hydro-geology are presented. A focus is made on water resources in terms of availability and quality. Moreover, the critical historical events happened in the area of oPt and the level of MDGs indicators for the oPt are illustrated. Finally, the case study of the 'sample farm' is introduced.

## 2.1 THE GAZA STRIP

The Gaza Strip is a semi-arid region located on the Eastern coast of the Mediterranean sea between Egypt and Israel. Specifically, it is located between longitudes $34°2'0''$ and $34°25'0''$ east, and $31°16'0''$ and $31°45'0''$ north. It is part of the Palestinian coastal plain and covers a coastal area of about 365 $km^2$: its length along the coast is approximately 40 km and its width ranges from 6 to 12 km. The GS is subdivided into 5 governorates under the jurisdiction of the Palestinian National Authority (PNA). Population was estimated to be 1.77 million in July 2013 (CIA, 2013 [8]), with a density of about 4800 people/$km^2$, making the Gaza Strip one of the most overcrowded areas in the world. Considering the actual population growth rate of about 3.5%, by 2035 the population will reach a total number of about 3.7 million. This population growth and, consequently, the demand for resources, expecially water, is increasing : nowadays, the available resources cannot satisfy the need for water, and this fact is causing a huge deficit between water demand and supply [33]. Furthermore, the increase of the abstraction rates, due to inadequate water imports to Gaza, expanding population and drilling and use of unlicensed wells, causes saline intrusion. Moreover, the lack of wastewater treatment plants causes contamination of the shallow groundwater: the result is a scarce and polluted water resource, not suitable for any domestic use.

### 2.1.1 *Meteorological data*

The Gaza Strip is located in the transitional zone between a temperate Mediterranean climate in the west and north, and an arid desert climate of the Sinai Peninsula in the east and south. It has a semi-arid Mediterranean climate, characterized by a long and dry summer subject to drought, and a short, cool and rainy winter.

**Figure 2.1:** The Gaza Strip.

| **Month** | **Rainfall** (mm/-month) |
|---|---|
| Jan | 109.875 |
| Feb | 71.875 |
| Mar | 37.375 |
| Apr | 7.75 |
| May | 0 |
| Jun | 0 |
| Jul | 0 |
| Aug | 0 |
| Sep | 1.375 |
| Oct | 22.25 |
| Nov | 57.875 |
| Dec | 83.75 |
| TOT. | 392.125 |

**Table 2.1:** Monthly rainfall in mm/month; average values for the Gaza Strip (Al-Najar, 2011 [1])

#### 2.1.1.1 *Temperature, humidity and solar radiation*

The average mean daily temperature ranges from 26°C in summer and 12°C in winter. The annual mean of air temperature, annual mean of maximum air temperature, and annual mean of minimum air temperature are 19.8°C, 23.6°C and 16.1°C, respectively (PCBS, 2009). Temperature gradually changes throughout the year, and reaches its maximum in August (summer) and its minimum in January (winter); average monthly maximum temperature ranges from about 17.6 °C in January to 29.4 C °in August. The daily relative humidity fluctuates between 65% during the daytime and 85% during night in summer, and between 60% and 80% respectively in winter. The mean annual solar radiation amounts to 18 MJ $m^{-2}$ $day^{-1}$.

#### 2.1.1.2 *Rainfall*

Concerning the rainfall, two seasons are well defined in the Gaza Strip: the wet season, starting in October and extending into April, and the dry season, extending from May to September. Actually, the rainy season extends from about mid-October to the end of March, with essentially no rain falling in the remaining months. The 10-years average monthly amount of rainfall is shown in table 2.1.

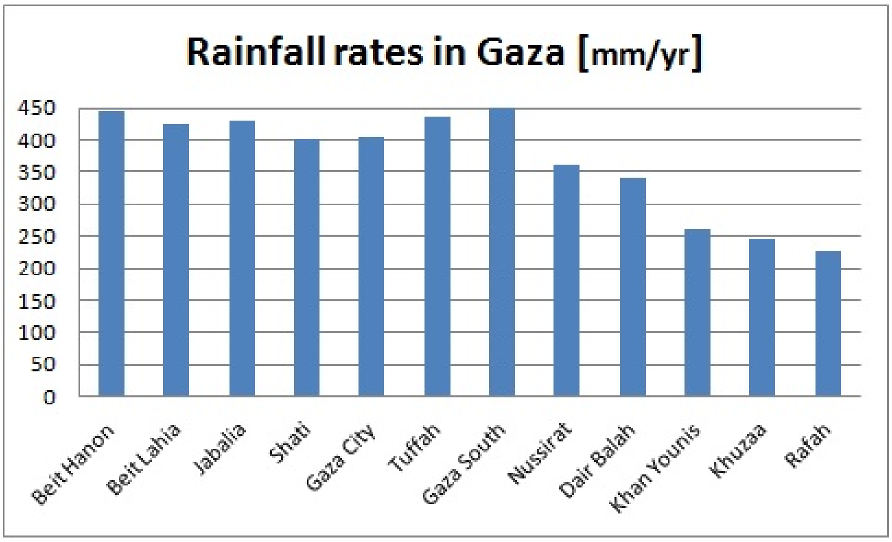

**Figure 2.2:** Mean yearly rainfall rates measured in the rainfall measurement stations in the Gaza Strip (mm/yr) (PCBS, 2008)

Annual average rainfall varies considerably across the Gaza Governorates, from about 400 mm/yr at the north-eastern border (Beit-Lahia) to around 220 mm/yr in Rafah at the south-western border with Egypt (figure 2.2). Moreover, for the same station there is very significant temporal variation from year to year: the annual rainfall shows a significant variation over the Gaza Strip climatic station for the period 1973 to 2010 (FAO, 2012 [15]). In the past, the porous soils of much of the Gaza region easily absorbed most of this rainfall and provided the primary source for recharging the groundwater aquifer of the region, especially along the coast where sand dunes are the main soil structure. However, most urban areas of the Gaza governorates do not have a natural drainage outlet because of their low lying topography. Heavy rainfall causes storm water to collect in low areas and flood streets and walkways. Rapid growth has decreased the open areas available for percolation of rainwater and has increased the runoff amount.

#### 2.1.1.3 *Evaporation and evapotranspiration*

The monthly average potential evaporation over 25 years in Gaza varies between a maximum of 174 mm in July and a minimum of 63 mm in January, with an annual average potential evaporation of 1,300 mm.

### 2.1.2 *Topography and soil*

Land surface elevation gradually slopes downwards from east to west, ranging from 105 m above the mean sea level (highest point Joz Abu 'Auda), to the mean sea level in the west. The terrain is flat or rolling, with dunes pushing in from the coast towards east, particularly in the southern part of the Gaza Strip. The soil in the GS is mainly composed by sand, clay and loess:

- the sand soil forms the majority of the area (around 80%) and it is located along the coastline from south to the northern border of the Strip; usually it is in the form of sand dunes;
- clay soil (dark brown or reddish brown types) is mainly located in the north-eastern part of the Gaza Strip;
- loess soil is found around Wadis [1], the largest surface water feature in Gaza.

### 2.1.3 *Land use*

The land use and land cover map of Gaza Strip in 2010 table 2.3 shows that the agricultural land occupies about 225km$^2$ (62%) and the urbanized area occupies about 90km$^2$ (25%). The urbanized are is expected to bigger than today, but documented estimations do not exist. Future expansion of the urbanized area are expected, with consequent increase of total amount of rainwater losses (surface run-off) and increase of pressure on groundwater resources.

## 2.2 WATER RESOURCES IN OCCUPIED PALESTINIAN TERRITORY

The occupied Palestinian territories host a considerable amount of fresh water resources in both the West Bank and Gaza Strip, found in the form of surface water and groundwater: the Jordan River and two majors aquifers, the Mountain Aquifer in the West Bank and the Coastal Aquifer in the Gaza Strip. These resources have been fully controlled by Israel since 1967: the water resources available for Palestinians are limited and insufficient for the essential needs. Because of this handling, the Palestinian water rights were denied as well as the need for a proper management that resolves the problem of water scarcity in the region: oPt water resources have been over-exploited, polluted, and not equally distributed among Israelis and Palestinians (PHG, 2008 [30]). The conflict over water is one of the most imperative problems in the Middle East: due to the the arid nature of the region, water problems constitute a challenge for future generations. In the following sections the available water resources and their current status is described (PHG, 2008 [30]).

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[1] A valley, gully, or streambed that remains dry except during the rainy season

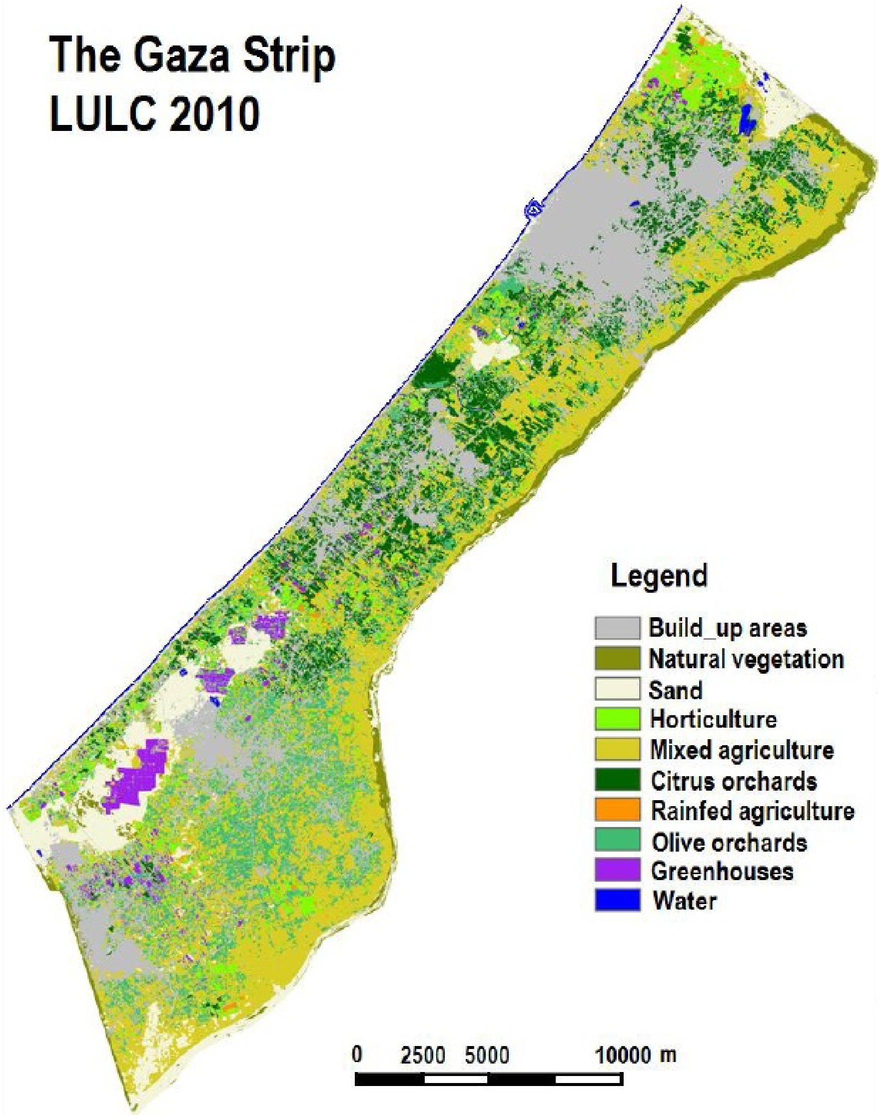


**Figure 2.3:** Land use and land cover map of Gaza Strip in 2010

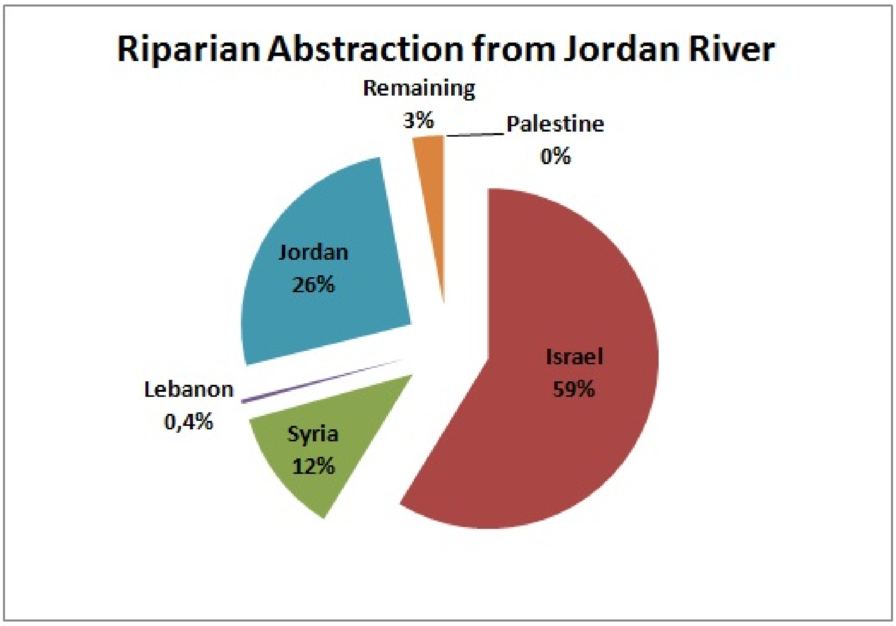


**Figure 2.4:** Riparian Abstraction from the Jordan River (PHG, 2008 [30]).

### 2.2.1 *Surface water: the Jordan River*

The Jordan River flows over 300 kilometers in the Middle East territories. A large web of tributaries from Lebanon and Syria constitute its southward flow, which emerges into Lake Hula (part of which was drained by Israel and used as agricultural land), Lake Tiberias and Finally the Death Sea. Today, the resources of Jordan River are overexploited: Israel, Jordan, Lebanon, Syria are responsible for the current water level decrease due to their abstraction and/or diversion of flows through the installation of dams and catchment reservoirs. However, the exploitation of Israel is the main cause of this depletion and pollution: its abstractions are around 58,33% of Jordan River water, while Jordan, Syria, Lebanon, and Palestine abstract 25,76%, 12,12%,0,38% and 0% respectively, as shown in figure 2.4 (PHG, 2008 [30]) . Since the Israeli occupation , Palestinians lost all the possibilities to access the Jordan River resources even though the whole of eastern aquifer flows within the borders of the West Bank: in effect, Palestinian agriculture relied on these water resources before this Isreali seizure. In the oPt, a variety of other forms of surface water can be found: wadis, seasonal lakes, and natural springs.

### 2.2.2 *The Mountain aquifer*

The Mountain Aquifer is the main supplier of groundwater in the oPt. It is divided into three sub-basins that are classified according to their flow directions: The Western Aquifer, the Eastern Aquifer, and the Northeastern Aquifer. Despite the fact that these three aquifer predominantly fall within the borders of West Bank, Israel controls them, granting a minimum allocation to the Palestinians, who can use only 5,5% of Western Aquifer, less than 20% of Northeastern Aquifer and about 30% Eastern Aquifer resources.

### 2.2.3 *The Gaza Coastal Aquifer*

The shallow Gaza Coastal Aquifer extends along the shores of the Mediterranean Sea. It is the unique source of water for the GS: the three Wadis have become dry because Israel has retained and changed the course. This aquifer is part of a regional groundwater system covering Israel and Egypt, and in the Gaza Strip it extends 40 km long. Concerning the hydraulic properties, from results of pump tests the transmissivity values range between 700 and 5000 $m^2/d$, the corresponding hydraulic conductivity (K) are mostly within 20-80 m/d. The flow is mainly perpendicular to coastline, with a general direction east toward west, where fresh groundwater discharge in the Mediterranean Sea. Locally the flow is strongly disturbed by overpumping: the presence of large cones of depression causes water levels below the mean sea level and produces an hydraulic gradient from the Mediterranean Sea towards the major pumping wells. Figure 2.5 shows flow fields between 1935 and 2010: these images highlight the general decrease of groundwater levels in time (Dentoni, 2012 [12]). Nowadays, the northern part of GS, water levels range from 10 (eastern border) to 0 (along the shore) meters above the mean sea level; in the southern part, the gradient is from 20 (eastern border) to 0 (along the shore) meters above the mean sea level. The constant drop of water level is estimated to be about 20-30 cm each year, due to overexploitation (Dentoni, 2012 [12]). Concerning water quality, the Gaza aquifer is considered generally poor: most of the wells located in the area are not anymore suitable for drinkable purposes, because the quality of the extracted water is very low, exceeding World Health Organization (WHO) standards both for chlorides (250 mg/l), due to pollution and salt water intrusion (SWI), and for nitrate (50 mg/l), caused exclusively by pollution. Due to over-exploitation, this aquifer is depleted: the replenishment rates cannot compensate the abstracted quantities and salt water intrusion occurs. This intrusion causes a further deterioration in water quality. In addition to the fact that the Gaza Coastal Aquifer does not receive sufficient rainwater quantities for recharge, Israeli water policies block the renewable

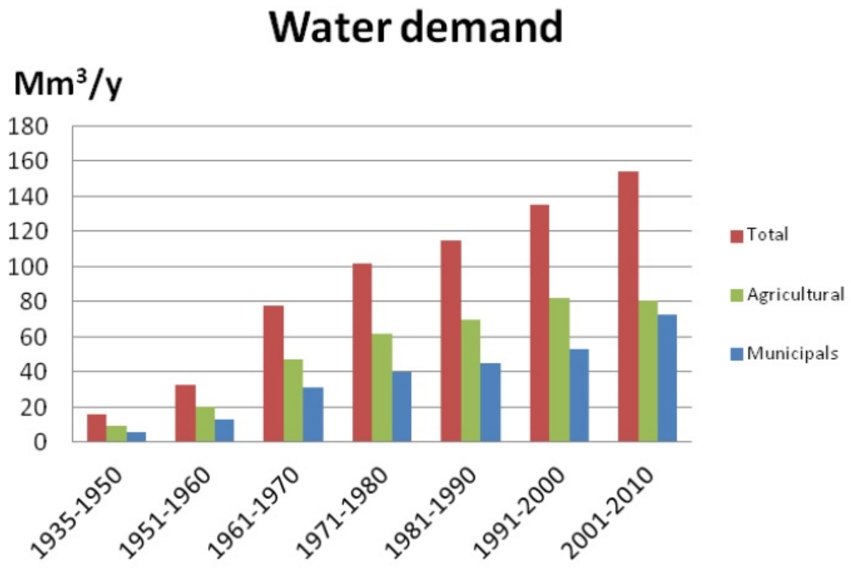


**Figure 2.5:** Representation of water demand and its contributions between 1935 and 2010 (Dentoni, 2012 [12]).

| **Fresh groundwater availability** | $60*10^6$ $m^3/yr$ |
|---|---|
| agricultural extraction | $80*10^6$ $m^3/yr$ |
| domestic extraction | $85*10^6$ $m^3/yr$ |
| **Total extraction** | $165*10^6$ $m^3/yr$ |
| **Annual deficit** | $105*10^6$ $m^3/yr$ |

**Table 2.2:** Annual groundwater balance of coastal aquifer (PWA, 2012 [32])

yield from the westwards surface and ground water flows. This water embargo was obtained by surrounding the border of Gaza Strip with a large number of deep wells and diversions [30]. Furthermore, the pumping rate of the Palestinian private wells is unregulated: the total annual abstraction is about $165*10^6$ $m^3/yr$ and the replenishment is $60*10^6$ $m^3/yr$, creating an average annual deficit of about $105*10^6$ $m^3/yr$. In particular, the groundwater balance reported by Palestinian Water Authority (PWA) during the Stockholm World Water Week 2012 (PWA) is shown in table 2.2.

Dentoni (2012) tried to estimate the different water balance contributions, taking into account the available amount of fresh groundwater and the different withdrawals. The obtained results are shown in table 2.3.

In recent years, the increasing abstraction both for agricultural and for private use (see figure 2.5) generates irreversible environmental

| | |
|---|---|
| rainfall recharge | $(40-45)*10^{6}m^{3}/yr$ |
| lateral inflow | $10-40*10^{6}\ m^{3}/yr$ |
| leakage lfrom water distribution system | $(10-15)*10^{6}\ m^{3}/yr$ |
| return flow agricultural | $20*10^{6}\ m^{3}/y]$ |
| return flow waste water | $10*10^{6}\ m^{3}/yr$ |
| loss of aquifer storage | $(2-3)*10^{6}\ m^{3}/yr$ |
| salt water intrusion | $(10-45)*10^{6}\ m^{3}/yr$ |
| **Fresh groundwater availability** | $(102-178)*10^{6}\ m^{3}/yr$ |
| agricultural extraction | $88*10^{6}\ m^{3}/yr$ |
| domestic extraction | $84*10^{6}\ m^{3}/yr$ |
| Mekorot | $4*10^{6}\ m^{3}/yr$ |
| discharge | $(10-50)*10^{6}\ m^{3}/yr$ |
| **Total extraction** | $(186-226)*10^{6}\ m^{3}/yr$ |
| **Annual deficit** | $(8-124)*10^{6}\ m^{3}/yr$ |

**Table 2.3:** Annual groundwater balance of coastal aquifer (Dentoni, 2012 [12]).

damages and, together with pollution problems, due to excessive use of pesticides and the spilling of wastewater from cesspit and septic tanks, is causing a complete depletion of the coastal aquifer: solutions to halt or at least reduce these problems are urgently needed in Gaza Strip.

### 2.2.4 *The current situation of water services*

*"‘Access to water is a persistent issue. Each Israeli settler uses five times as much water as a Palestinian neighbor, who must pay four times as much per gallon."’*[**Carter J., ’Palestine Peace Not Apartheid’, 1967**].

The problems related to water access are mainly related to the absence of transparency, a bad water governance and a lack of equality in provision of water and sanitation services: the current situation is due to the complete control of Israeli on water resources in oPt. Since the access to Zone C areas is forbidden due to military control: this means that each possible delivery of water and sanitation services was impeded. Furthermore, Israeli violations of the Oslo Agreement left Palestinians with a forced reliance on water purchased from the Israeli company "Mekorot", which sells almost 52% of Palestinian water consumptions and subjugates many Palestinian communities to severe water cuts (PHG, 2008 [30]).

The water network currently does not cover more than 65% of occupied Palestinian territories. In the West Bank (WB) the system lacks an equitable distribution among the different communities: the regions characterized by a less developed water network are rural areas with elevated exposure to Israeli military operations. In the GS, there is a better water network system than in WB because of its small area and high density population. These conditions lead GS to be highly dependent on Palestinians resources mainly supplied by the Coastal Municipalities Water Utility (CMWU). However, the Gaza Strip conditions are affected by Israeli siege, economic embargo and high loss rate (more than 40%) caused by illegal connections, utility dysfunction and worn out pipes. The WHO recommended standard for the average per capita consumption is 100 L/d per capita, but in Palestine this consumption does not exceed 66 L/c/d and in many cases its value is about 25 L/d per capita. Despite that, in 2007/2008 residents in GS paid 11.6% of their incomes on water, while in WB they paid 6.1%: these percentages of their household incomes on water and sanitation surpass the standards recommended by UNICEF and WHO (which is equal to 3.5%). This high expenditure is due to several water cuts by Mekorot and limited coverage of the water network: many Palestinian communities are forced to buy expensive water tankers. The cost of these tankers is 11 New Israeli Shenkel (NIS)/$m^3$ (1 NIS is equal to about 0.274 U.S. dollars). These underdevelopments of water and sanitation services in the oPt caused the spread of water related diseases, which produce prominent effects on the general health of the Palestinian population.

## 2.3 HISTORICAL EVENTS

In 1922, after the collapse of the Ottoman Empire that ruled Greater Syria for four centuries (from 1517 to 1917), the British Mandate for Palestine was established. Large-scale Jewish immigration from abroad, mainly from Eastern Europe took place during the British Mandate. The recent historical events of Palestine were hotly disputed between Arabs and Jews. In 1947, the total Jewish ownership of land in Palestine was 1.850 $km^2$, which is 7.04% of the total land of Palestine. Public property or "crown lands", the bulk of which was in the Negev, belonging to the government of Palestine may have made up as much as 70% of the total land. The 1947 United Nations Partition Plan proposed a division of Mandate Palestine between an Arab and a Jewish state, with Jerusalem and the surrounding area to be a 'corpus separatum' under a special international regime. The regions allotted to the proposed Arab state included what became the GS, and almost all of what became the WB, as well as other areas. The Partition Plan was passed by the UN General Assembly on November 1947. The Partition Plan was accepted by the Jewish leadership, but rejected by the Arab leaders. The Arab League threatened to take military measures to prevent the partition of Palestine and to ensure the national rights of the Palestinian Arab population. One day before the expiration of the British Mandate for Palestine, on 14 May 1948, Israel declared its independence within the borders of the Jewish State set out in the Partition Plan. US President Harry Truman recognized the State of Israel de facto the following day. The Arab countries declared war on the newly formed State of Israel heralding the start of the 1948 Arab-Israeli War. After the war, the 1949 Armistice Agreements established the separation lines between the combatants, leaving Israel in control of some of the areas designated for the Arab state under the Partition Plan, Transjordan in control of the WB and East Jerusalem, Egypt in control of the GS and Syria in control of the Himmah Area. In 1950, Jordan annexed the WB and East Jerusalem. Only the United Kingdom formally recognized the annexation of the WB, de facto in the case of East Jerusalem. In the GS the Arab League formed the All-Palestine Government, which operated under Egypt occupation. Article 24 of the Palestinian National Covenant of 1964, which established the Palestine Liberation Organization, stated: "This Organization does not exercise any territorial sovereignty over the WB in the Hashemite Kingdom of Jordan, on the GS or in the Himmah Area" (i.e. the areas of the former Mandate Palestine controlled by Jordan, Egypt and Syria, respectively). Israel captured both territories in the 1967 Six-Day War, as well as other territory belonging to Egypt and Syria. Since then, these territories have been designated Israeli-occupied territories. Immediately after the war, on June 19, 1967, the Israeli government offered to return the Golan Heights to Syria, the Sinai to Egypt and most of theWB to Jordan in exchange for peace. At the Khartoum Summit in September, the Arab parties responded to this overture by declaring "no peace with Israel, no recognition of Israel and no negotiations with Israel." UN Security Council Resolution 242 introduced the "Land for Peace" formula for normalizing relations between Israel and its neighbors. This formula was used when Israel returned the Sinai Peninsula to Egypt in 1979 in exchange for a peace treaty. While that treaty mentioned a "linkage" between Israeli-Egyptian peace and Palestinian autonomy, the formerly Egyptian-occupied territory in Gaza was excluded from the agreement, and remained under Israeli control. The Oslo Accords of the early 1990s between the Palestine Liberation Organization and Israel led to the creation of the Palestinian Authority. This was an interim organization created to administer a limited form of Palestinian self-governance in the territories for a period of five years during which final-status negotiations would take place. The Palestinian Authority carried civil responsibility in some rural areas, as well as security responsibility in the major cities of the WB and the GS. Although the five-year interim period expired in 1999, the final status agreement has yet to be concluded despite attempts such as the 2000 Camp David Summit, the Taba summit, and the unofficial Geneva Accords.

### 2.3.1 *History of water resources*

Since 1947, Jordan river basin is the object of the so called "'Arab-Israeli water conflict"'. After the 6 Days War in 1967, Israel started to abduct the bulk of water resources and still Israeli is maintaining its control over them: Israeli Military imposed severe and restricted water policies that facilitates the Israeli exploitation of groundwater aquifers.

From 1967 to 1968 Israeli gave new military orders in water management, which allowed Israel to attain a grip over all water resources, transactions and abstractions in the oPt. Furthermore, in recent years, especially during the summer season, the Palestinians have been exposed to this policy a great deal, compelling people to rely on pricey yet unhealthy tanker water

In 1995, OSLO II INTERIM AGREEMENT (Article 40) was aimed at transferring water responsibilities in the oPt from Israel to the Palestinian Autorithy, but in reality no "real authority" is granted, because every water and sanitation project has to be approved by the Joint Water Committee, which rarely approves one of these projects. Also after the treaty between Israeli and Jordan in 1995, Israel's domination over regional water was maintained.

The current water crisis is caused by Israeli reoccupation of Palestine during the second Intifada (2000-2005). Israel consumes water at a greater rate than any bordering Arab country and its policies are disapproved by several International Organisms.

These historical events created large disparities among the Palestinians and the Israelians in terms of abstraction, allocation and consumption of water: Israel currently abstracts 84% of groundwater and its average per capita consumption is 350 L/d per capita (higher than those in many European countries) compared to 76 L/d per capita in Palestine (PHG, 2008 [30]).

## 2.4 MILLENNIUM DEVELOPMENT GOALS: THE CRITICALITIES IN THE GAZA STRIP

In September 2000, leaders of 189 Countries met at the United Nations in New York and endorsed the Millennium Declaration, a commitment to work together to build a safer, more prosperous and equitable world (UN, 2000 [38]). The Declaration was translated into a road-map setting out eight time-bound and measurable goals to be reached by 2015, known as the MDGs, namely:

1. Eradicate extreme poverty and hunger

   - Reduce by half the proportion of people whose income is less than 1$ a day
   - Achieve full and productive employment and decent work for all, including women and young people
   - Reduce by half the proportion of people who suffer from hunger

2. Achieve universal primary education
   - Ensure that all boys and girls complete a full course of primary schooling
3. Promote gender equality and empower women
   - Eliminate gender disparity in primary and secondary education preferably by 2005, and in all levels of education no later than 2015
4. Reduce child mortality
   - Reduce by two thirds the mortality of children under five
5. Improve maternal health
   - Reduce maternal mortality by three quarters
   - Achieve universal access to reproductive health
6. Improve maternal health
   - Reduce maternal mortality by three quarters
   - Achieve universal access to reproductive health
7. Improve maternal health
   - Reduce maternal mortality by three quarters
   - Achieve universal access to reproductive health
8. Improve maternal health
   - Reduce maternal mortality by three quarters
   - Achieve universal access to reproductive health
9. Combat HIV/AIDS, malaria and other diseases
   - Halt and reverse the spread of HIV/AIDS
   - Achieve, by 2010, universal access to treatment for HIV/AIDS for all those who need it
   - Halt and reverse the incidence of malaria and other major diseases
10. Ensure environmental sustainability

**Figure 2.6:** The 8 Millennium Development Goals, to be achieved by 2015

- Integrate principles of sustainable development into country policies and programmes; reverse the loss of environmental resources
- Significantly reduce the rate of biodiversity loss by 2010
- Halve the proportion of people without access to safe drinking water and basic sanitation
- Improve the lives of at least 100 million slum dwellers by 2020

11. Develop a global partnership for development
    - Develop further an open, rule-based, predictable, non-discriminatory trading and financial system
    - Address special needs of the least developed countries, landlocked countries and small island developing States
    - Deal comprehensively with developing countries' debt
    - In cooperation with pharmaceutical companies, provide access to affordable essential drugs in developing countries
    - In cooperation with the private sector, make available the benefits of new technologies, especially information and communications technologies

### 2.4.1 *MDGs: criticalities in the oPt*

The occupied Palestinian territories are placed in the lower middle-income group of countries in terms of the Human Development Index. The ongoing social-economic and political crisis in the oPt in general, and the GS, in particular, are expected to cause a dramatic decrease in MDGs indicators, especially with respect to poverty and hunger, health, and education. In addition to the economic and social closure of the territory, the sharp increase in the prices of major production inputs and basic food supplies, together with the world financial crisis, has made the current national poverty reduction strategies insufficient and less than adequate to face the existing criticalities. The uncertainty in the political situation poses challenges in achieving progress until 2015, the cut-off date for most MDGs based national strategies (UNDP, 2011 [40]).

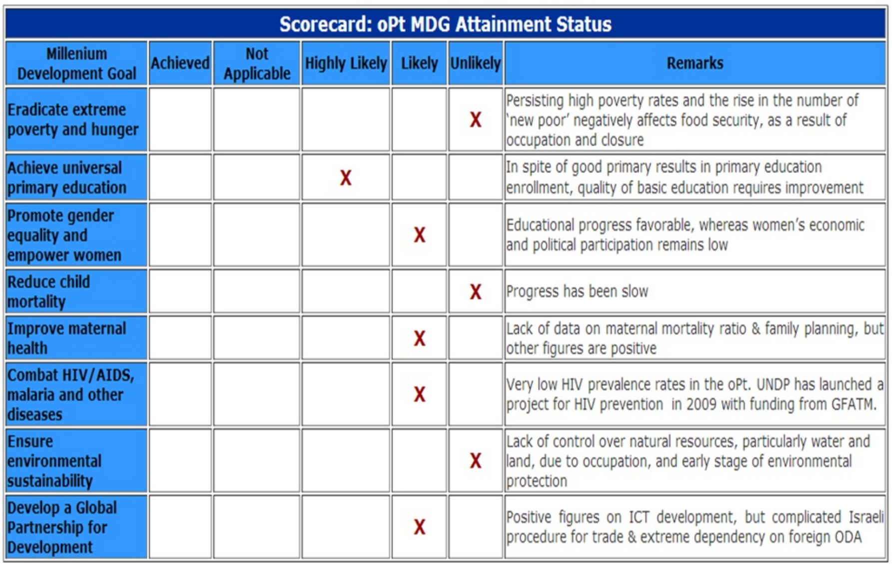
The MDGs priorities in oPt are:

1. MDGs integrated into national development planning and resources allocation processes to ensure, or at least improve, the sustainability of natural resource consumptions;
2. Sector specific programs and policies to advance MDGs (Goals and Targets);
3. Development and operationalization of the MDGs and poverty monitoring framework;
4. Develop and implement effective MDGs communications and advocacy strategies.

The poverty rate (based on consumption patterns) increased, between 1996 and 2010, from 23.6% to 25.7% (18.3% in the West Bank and 38% in the GS); 14.1% of this percentage suffered from extreme poverty (8.8% in the WB and 23% in the GS). The percentage of individuals whose income is below the national poverty line in the oPt increased to 48.6% (36.2% in the WB and 69.3% in the GS), including 37.6% whose income is below the extreme poverty line (24.6% in the WB and 59.2% in the GS).

#### 2.4.1.1 *Status of Food Security*

At first glance, the latest data on food security - released by the FAO, the World Food Program (WFP) and the UN Agency for Palestinian in July 2012 - seem to warrant optimism. The percentage of households lacking food security was 44% in the GS and 17% in the West Bank in 2011, making 2011 the second straight year in which the number of those living in food insecurity decreased in both the West Bank and GS. In the GS, the percentage dropped from 60% in 2009 to 44% in 2011, and in the West Bank, it decreased from 22% to 17%. However, upon a deeper examination, a more discouraging picture is revealed. First, these data are based on economic access to food, which is dependent upon having permanent job: many of those who are food secure are on the PNA payroll; since much of the PNA funding comes from foreign aid, these employed are left in unstable and unsustainable conditions due to volatility of these aids. Both in the WB and in the GS, the ability of Palestinians to access their land and waters is



Scorecard: oPt MDG Attainment Status

| Millenium Development Goal | Achieved | Not Applicable | Highly Likely | Likely | Unlikely | Remarks |
|---|---|---|---|---|---|---|
| Eradicate extreme poverty and hunger | | | | | X | Persisting high poverty rates and the rise in the number of 'new poor' negatively affects food security, as a result of occupation and closure |
| Achieve universal primary education | | | X | | | In spite of good primary results in primary education enrollment, quality of basic education requires improvement |
| Promote gender equality and empower women | | | | X | | Educational progress favorable, whereas women's economic and political participation remains low |
| Reduce child mortality | | | | | X | Progress has been slow |
| Improve maternal health | | | | X | | Lack of data on maternal mortality ratio & family planning, but other figures are positive |
| Combat HIV/AIDS, malaria and other diseases | | | | X | | Very low HIV prevalence rates in the oPt. UNDP has launched a project for HIV prevention in 2009 with funding from GFATM. |
| Ensure environmental sustainability | | | | | X | Lack of control over natural resources, particularly water and land, due to occupation, and early stage of environmental protection |
| Develop a Global Partnership for Development | | | | X | | Positive figures on ICT development, but complicated Israeli procedure for trade & extreme dependency on foreign ODA |

**Figure 2.7:** Scorecard: oPT MDGs attainment status (UNDP, 2011 [40])

severely curtailed by the occupying Israeli army. More than 35% of Gaza's farmlands and 85% of its fishing marine waters are totally or partially inaccessible due to Israeli imposed restrictions. Farmlands located within 500 meters from the perimeter fence are totally inaccessible, while access to areas up to 1500 meters is dangerous due to live fires from the Israeli army. Consequently, an estimated 75,000 metric tons of produce are lost every year. Since 2009, the Israeli naval forces have (illegally) prevented fishermen from accessing sea areas beyond three nautical miles from Gaza's coast, where the main sardine shoals are found. This has severely undermined the livelihoods of 35,000 people. In 2011, for example, Palestinian fishermen in Gaza were only able to catch approximately 383 tons of sardines, down from 645 tons in 2010, and down from 1,983 in 2008. While the Palestinian health ministry determined that Gazians needed daily an average of 2,279 calories each to avoid malnutrition -requiring 170 trucks a day - an average of only 67 trucks entered Gaza daily.

#### 2.4.1.2 *Ensure environmental protection and sustainability*

The seventh goal concerns environmental protection and sustainability and is broken down into three targets:

1. integration of sustainable development and reduction of biodiversity loss: given the lack of sovereignty and autonomy in the West Bank and Gaza, and given that the PNA has access to only 21 percent of its water resources, this first target becomes a relatively mute point;

2. halving the proportion of poor people without sustainable access to safe water and sanitation by 2015. This goal is mea-

sured with two indicators: proportion of population using an improved drinking water source and proportion of population using an improved sanitation facility; in the GS the majority of water is contaminated. In particular, more than 90% of the water from the Gaza aquifer is unsafe for human consumption without treatment. Only 10% of the aquifer water is drinkable; the aquifer water is likely to become unusable by 2016 and irreversibly damaged by 2020, while the demand for water is expected to increase 60% by 2020. Furthermore, water network connections are limited and not all the people can access it. The ability of Palestinians to reach sources of water is obstructed due to movement and access restrictions such as checkpoints, earth mounds, and the separation wall, imposed by the Israeli military. These increase significantly the costs of accessing water with some families having to pay as much as 40 percent of their monthly income for water (global accepted standard is 4 percent). All these conditions make the Palestinians deprived of the minimum accepted WHO water allotment (100 liters per capita per day). Regarding improved sewage facilities, there are conflicting data: data from PNA state that 55% of the homes in the oPt are linked to sewage network, however data from Emergency Water Sanitation-Hygiene Group (EWASH) state that only 31% of Palestinians linked to the sewage network and there is only one Waste Water Treatment Plant (WWTP) in operation. In the GS, import restrictions have impeded the expansion and upgrading of Gaza's sewage infrastructure. Nearly 90 million liters of untreated or partially treated sewage are discharged into the sea every day. The contamination of seawater poses a serious health hazard and serious investments in water and sanitation infrastructure are needed;

3. achieving a significant improvement in the lives of at least 100 million slum dwellers by 2015.

# 3

# THE CASE STUDY

## 3.1 OVERSEAS NGO AND LOCAL PARTNERS

The case study considered in this work was identified in collaboration with gazian agronomists, which work with Overseas NGO (`www.overseas-onlus.org`). This NGO works in the GS and WB territories since 2002 and its interventions mainly concern agriculture and rural development, and rainfall water management to agricultural purposes. Its activities focus on agricultural development since 1974 (in Sierra Leone). Its projects aim to promote domestic horticulture using biological techniques and drip irrigation systems, which permit to increase the production and food security, while minimizing water consumption. Overseas collaborates with local partners: Union of Agriculture Work Committees Association (UAWCA) is the partner in the GS. In 2011 they started a new project focused on integrated agriculture and aquaculture: in general, with the goals to rebuild some agricultural structures destroyed or damaged during the Gaza War between 2008 and 2009, and to increase the food security level for Gazians (52% of the population is food insecure and 17% risks to become food insecure, FAO, 2012 [15] ). To achieve these goals the following specific actions have been implemented:

- diversifying the sources of profit by rehabilitating the agricultural assets;
- distribution of courtyard animals;
- introduction of aquaculture in ponds;
- rehabilitation of wells and pools for rainfall collection.

The possibility to integrate aquaculture with agricultural practices is offered by water ponds existing in the area: the aquaculture is introduced to better exploit the existing water ponds used to collect rainfall water. The NGO provides both the fingerlings (the young fish to be grown) and the feed for farmers. The idea of the introduction of aquaculture is implemented to cope with:

- reduction in fish availability, due to the limitation on maritime miles, within the fishery is allowed, imposed by Israel;
- lack of proteins procurement;
- lack of diversification of agricultural activities and sources of profit;

Furthermore, different studies consider Integrated Agriculture and Aquaculture (IAA) advantageous in terms of environmental impacts analyzed with LCA: if aquaculture flows are completely integrated with agriculture ones (e.g. fishes eat livestock manure, fields are irrigated with water 'fertilized' by fishes, and terrestrial animals are fed with agricultural wastes), substances, like nutrients, can be better exploited, and this activity could help to diversify family-scale agricultural production in developing countries (Efole Ewoukem et al., 2012 [13] and Phong, De Boer, and Udo, 2011 [31]). Overseas NGO and its local partners in the GS are interested in the evaluation of benefits and disadvantages of the agricultural systems, they have implemented in the area, and in particular in the aquaculture activities. Agronomists working in the area provided us with the field data necessary to conduct our analysis.

## 3.2 AGRICULTURE IN THE GAZA STRIP

The agricultural sector plays an important role in the GS economy, indeed the main exported products come from agriculture: strawberries, flowers and peppers. According to its importance, the related water consumptions correspond to about the 50% of the total ones(Dentoni, 2012 [12] ). The cultivated area represent the 62% (about 225 $km^2$) of the Strip, but it is decreasing every year. More than 20,400 agricultural holdings are present in this territory (PCBS, 2010 [28]). The main characteristics of the agricultural sector are:

- an average farm area of 0.9 ha; since the average area referred to each holding family is about 0.5 ha, each farm involves about 2 families (about 18 peole);
- 91.4% of agricultural holdings are owned by the agricultural holders;
- about 65% of vegetable crops is uncovered and irrigated;
- sheep livestock presents the highest number of heads among ruminant animals and a high number of poultry birds is raised (about 110 thousand);
- about 80% of plant and mixed holdings use organic fertilizers, 74% use chemical ones, and 74% use agricultural pesticides;

Starting from these general characteristics and taking advantage from information provided by local agronomists, our analysis is focused on standard average sized farm in the GS.

## 3.3 THE CASE STUDY: A STANDARD FARM IN THE GAZA STRIP

Given the critical geographic and historical conditions and the acute way in achieving MDGs by 2015, the living conditions of the GS population need improvements, especially in terms of food security and environmental sustainability. This study provides a joint analysis of food production (focusing on proteins), and resource exploitation in a standard farm in the GS. Firstly, the water consumption associated to crops is estimated. Then, other environmental impacts are assessed in an LCA framework. In particular, we want to assess whether investing in aquaculture can be an effective mean to increase protein production. In fact, water ponds already exist in several farms with the function of collecting rainfall. The average farm in the GS is characterized by an extension of about 9000 $m^2$ (**PCSB:2013 PCSB:2013** [**PCSB:2013**]). It produces both animal and vegetable products: in particular, animal production consists in sheep meat, chicken meat and egg, and possibly fish from aquaculture. As for crop production, we consider different rotation systems, which are present in the GS. Each alternative is composed by animal production and one of the alternative agricultural fields proposed. Each element is described in the following paragraphs.

FISH POND Fish ponds existing in the farms assisted by Overseas NGO are characterized by an average area of 50 $m^2$ and a maximum volume of 100 $m^3$. Since the ponds are used as rainfall collection pools for irrigation, one pond serves about 3000 $m^2$ of agricultural field: following this rule, three ponds are considered in the analyzed farm. A project held by Overseas NGO, starting in April 2011, introduced aquaculture of Tilapia fish in these ponds. For the first years of test of this new investment, the NGO provides the fish feed (produced in Israel) for each farm. The only connection between aquaculture (pond) and agriculture (field) is the water flow from the pond to the field: for this reason, the integration between these two activities is not complete (it could be created a complete integration among the three main components: e.g. fishes eat livestock manure, fields are irrigated with water 'fertilized' by fishes, and terrestrial animals are fed with agricultural wastes)

OTHER ANIMALS: SHEEP AND CHICKEN Sheep and chicken are breeded almost exclusively for household consumption. These animals are left free in the courtyard of the farm. We considered an average of 7 sheep and 15 chicken per farm. Concerning the feed, the sheep are fed with fodder produced during the months with no cultivation in the field (usually January), and with grass growing in the courtyard during the rest of the year. In the farms located nearby the buffer zones [1] the animals graze in this area, where humans are not allowed. The product obtained from sheep is the meat. The 15 chicken are fed with a specific feed produced in Israel mainly composed by concentrates. The products obtained from chicken livestock are meat and egg. Since its products are consumed by household or local consumers, the terrestrial livestock system in the standard farm belongs to the grazing category and not to the industrial one: generally, the livestock systems belonging to the grazing category have lower environmental impacts than industrial ones (Mekonnen and Hoekstra, 2012 [24]).

AGRICULTURAL FIELD The average cultivated field has an extension of about 8500 $m^2$. Different rotation systems were proposed by Overseas agronomist: the first one, raising tomatoes and cucumbers, made under greenhouses and the other four in the open field. The starting point, corresponding to zero in the clock, is the month of September, which is the starting month of the agricultural season which follows the rainfall seasonality.

Two main categories of agricultural systems are analyzed:

1. greenhouse system: this is the case of alternative A (figure 3.1), in which tomatoes and cucumbers are cultivated under greenhouses;
2. open field: this is the case of other alternatives (B,C,D and E); alternative B (figure 3.2) is based on only two crops during a year (pea grown for 4 months (pea4) and eggplant grown for 5 months (eggplant5)), while the other three systems are based on three crops per year: in alternative C (figure 3.3), cabbage, pea grown for 3 months (pea3) and pepper grown for 4 months (pepper4) are cultivated; in system D (figure 3.4) cauliflower, pea3 and eggplant grown for 4 months (eggplant4) are cultivated; and finally in case E (figure 3.5) lentil, cabbage and pepper4 are cultivated.

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[1] The so-called buffer zone is a military no-go area that extends within the oPt along the entire GS's border with Israel as well as at sea.

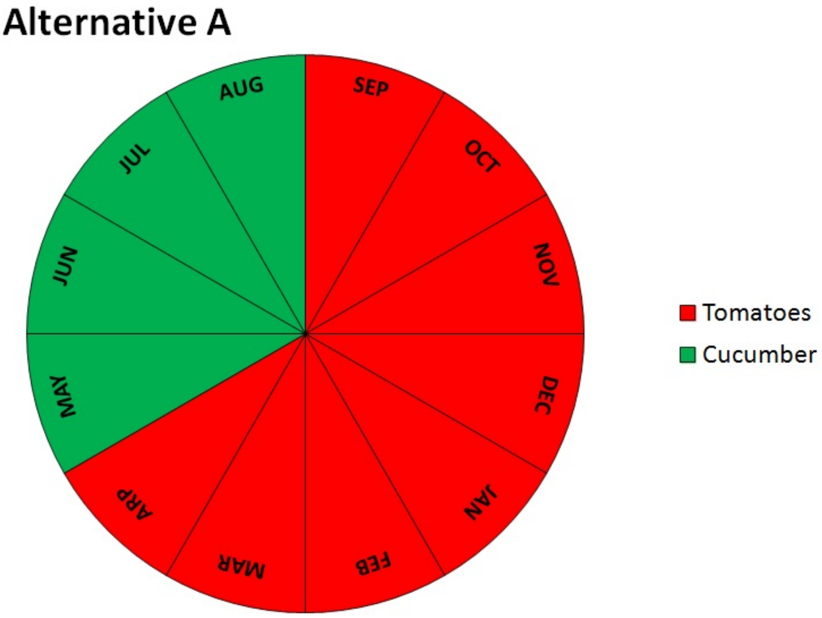

**Figure 3.1:** Alternative A: tomatoes and cucumbers are cultivated in greenhouses.

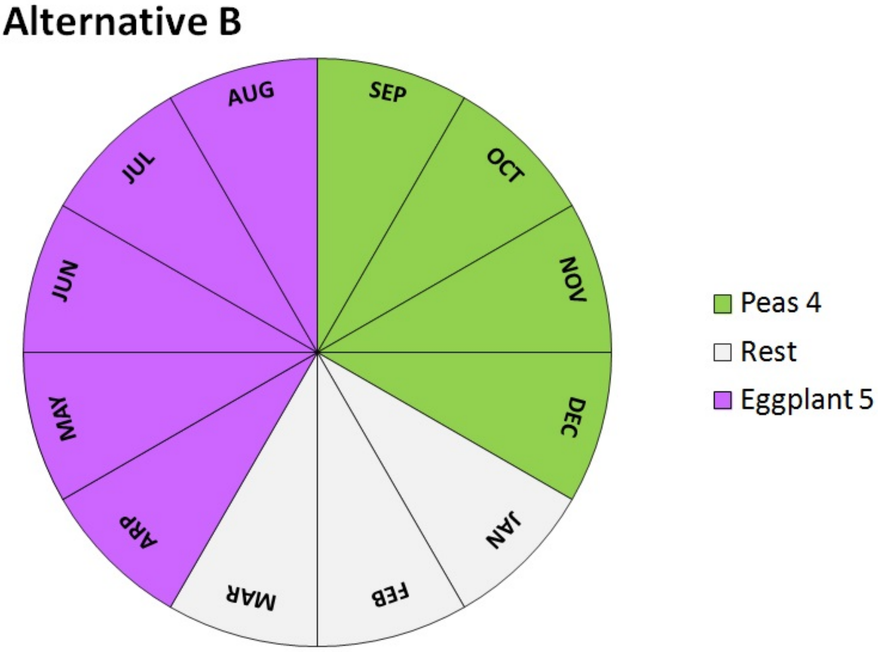

**Figure 3.2:** Alternative B: pea4 and eggplant5 are cultivated in open field.

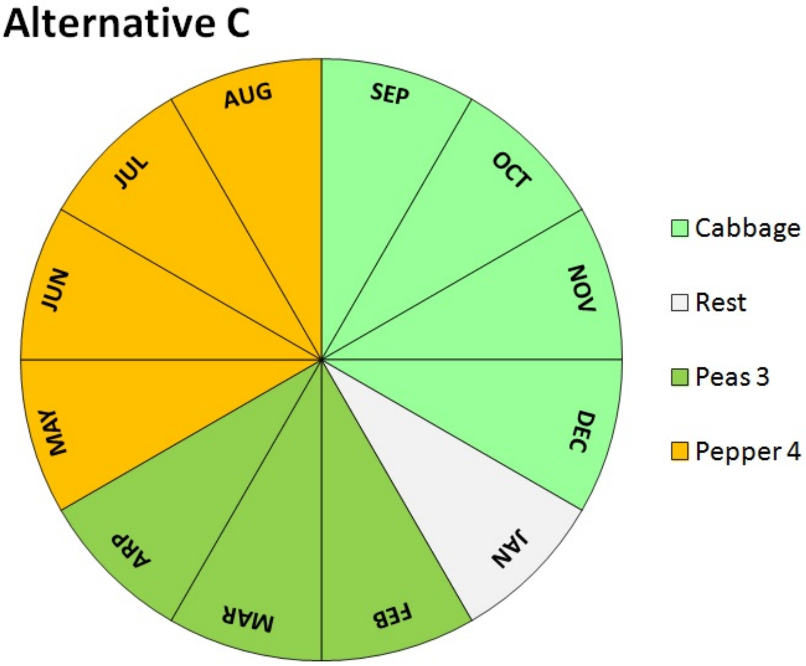

**Figure 3.3:** Alternative C: pea3, cabbage and pepper4 are cultivated in open field.

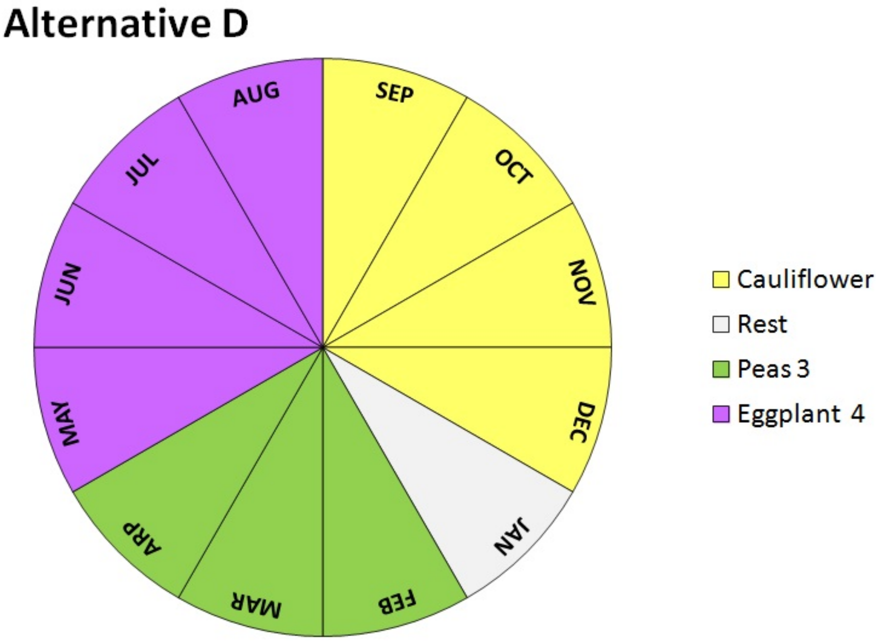

**Figure 3.4:** Alternative D: pea3, cauliflower and eggplant4 are cultivated in open field.

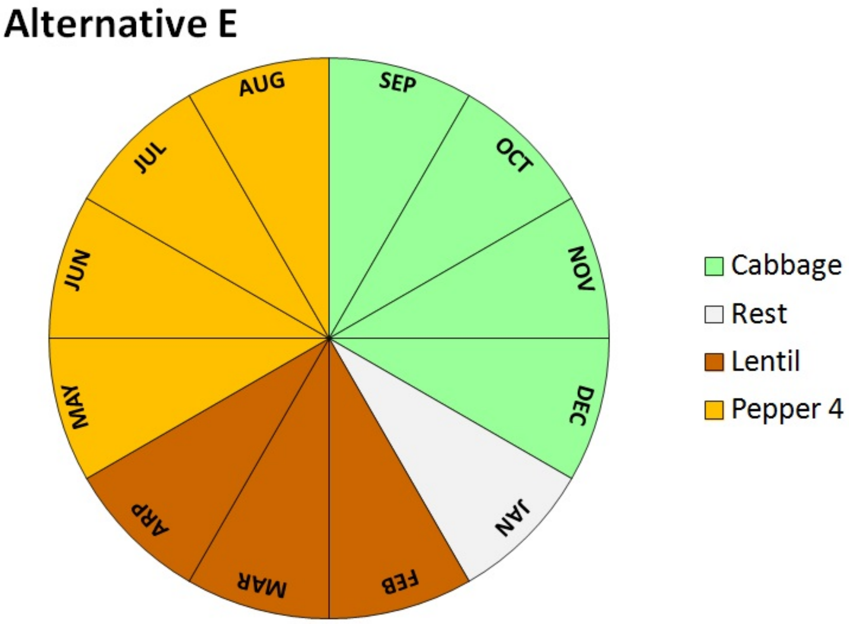

**Figure 3.5:** Alternative E: lentil, cabbage and pepper4 are cultivated in open field.

# 4

# METHODOLOGY: WATER FOOTPRINT AND LCA

The methodology adopted to achieve the goal proposed for this study integrates different existing methods. In particular, the WF assessment permit to quantify local impact related to water consumption of crops and animals raised in the analyzed agricultural systems in the GS; the impacts assessment is integrated and completed with the LCA: local, regional, and global impacts caused by the agricultural processes involved in our case study are estimated. From these two methodologies also an assessment of damages to human health, to ecosystem quality, and to resources can be obtained: the damages assessment integrated in LCA can be completed with the damages related to water consumption in the GS, localized using Water Stress Index (WSI), proposed by Pfister, Koehler, and Hellweg (2009 [29]). Referring the estimated impacts to protein production, the sustainability of food production system existing in the GS is assessed. Finally, we compare the WF with other indicator related to water use to verify if the results, in terms of sustainability and of alternatives rank, changes.

## 4.1 WATER FOOTPRINT

Water consumption and pollution occur due to different human activities: agriculture, industry, and domestic activities. The total volumes of consumed and polluted water are the sum of different direct and indirect contributions coming from activities belonging to the global economic system. For this reason, water is more and more considered as an international resource, characterized by growing international trade in water-intensive commodities: as a result, consumption of water resources has become spatially disconnected from the consumers. The evaluation of both direct and indirect WF, is essential to achieve a complete assessment of water consumption: in this study we assess the WF related to agricultural products, which could be locally or regionally consumed. The following chapter describes the methodology to assess Water Footprint and its phases as originally explained by Hoesktra, Chapagain, Aldaya and Mekonnen in [2].

### 4.1.1 *Water Footprint concept*

The 'Water Footprint' WF indicator was introduced by Hoekstra (2003 [21]) as a measure of every direct and indirect freshwater appropriation along the supply chain of a product or a production process. With this indicator, each contribution of water consumption is specified geographically and temporally and it shows water consumption volumes by source and polluted volumes by type of pollution. The WF differs from the classical measures of 'water withdrawal' (Gleick et al., 1993 [16] and Van Der Leeden, Troise, and Todd, 1990 [41]) in three aspects:

- It does not include in the calculation blue water use insofar as this water returns to the place where it came from.
- It is not restricted to direct water use, but also includes indirect water use.
- The total WF is the sum of three contributions, not only the blue water use: blue, green and grey WF.

Concerning the three different contributions, the blue and green ones refer to different water sources, from which the water is consumed, and the grey one refers to polluted water:

- The blue WF refers to consumption of blue water resources (surface and groundwater) along the supply chain of a product. 'Consumption' occurs when water evaporates, returns to another catchment area or the sea, or is incorporated into a product.
- The green WF refers to consumption of green water resources, i. e. rainwater without run-off contribution and groundwater recharge.
- The grey WF refers to the amount of consumed water due to pollution: it is defined as the volume of freshwater that is required to assimilate the load of pollutants given the natural background concentration and existing ambient water quality standards.

The WF with its components thus offers a complete description of the relation system between the different producers or consumers and the freshwater uses. On the other hand, it is a volumetric measure and does not measure the severity of local environmental impacts related to water consumption and pollution because they depends on the vulnerability of the local water system and on the intensity of consumption and pollution processes: WF accounts can be a good basis for local assessment of environmental, social and economic impacts.

### 4.1.2 *Water Footprint assessment*

The WF assessment involves all the activities made in order to quantify and even locate the WF of different processes, to asses the environmental, social and economic sustainability of the analyzed uses, and, finally, to formulate response strategies: the goal of WF assessment is to analyze how human activities affect water scarcity and pollution and their related impacts, and to work out solutions to make these activities more sustainable.

#### 4.1.2.1 *Goal*

Water footprint analysis may be characterized by different contexts and purposes and each of them requires different assumptions: it is important, as a first step, to specify which WF the study is going to deal with. The possible interests are:

- WF of a process step;
- WF of a product;
- WF of a consumer or a group of consumers (in a nation, in a municipality or province, in a catchment area or river basin);
- WF within a specific geographical area (within a nation, a municipality, a province, a catchment area or river basin);
- WF of a business;
- WF of humanity as a whole.

#### 4.1.2.2 *Scope of WF accounting*

The setting up of a WF account has to start with a clear definition of 'the inventory boundaries': they are a function of the purpose of the account and they determine which elements are included and which are not. Different elements have to be analyzed: the type of WF to include (blue, green, grey), the period of data, the level of spatio-temporal explication, consideration of direct and/or indirect WF and, finally, the definition of geographical boundaries.

#### 4.1.2.3 *Scope of sustainability assessment*

Concerning the phase of sustainability assessment, the primary question is which perspective will be chosen in the study: geographic, process, product, consumer or producer perspective. Then, a (some) hot-spot(s) is defined and analyzed. A hot-spot is the area where the WF is unsustainable during a period.

#### 4.1.2.4 *Scope of response formulation*

The scope of the response formulation phase depends on the sort of water footprint chosen as object of the study. While setting the scope for response formulation, it is important to clarify 'who' is/are the main actor/s in the action for reducing WF.

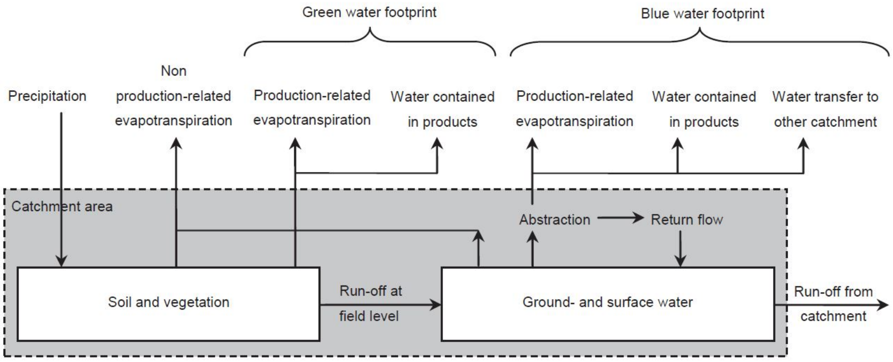

**Figure 4.1:** The green and blue water footprint in relation to the water balance of catchment area

### 4.1.3 *Water footprint accounting of crop growing processes*

Water is constantly moving on earth through the water cycle: the freshwater on land, which is the useful water for human activities, is continuously replenished, but its availability is limited. A balance between the annual replenishment rate and the amount of consumed water for domestic, agricultural and industrial activities should be maintained: the water consumption is expressed by the WF. Freshwater appropriation by humans concerns both the evaporative flow and the run-off. The evaporative flow is related to evapotranspiration processes in plants, soils and open-water surfaces caused by solar and wind energy. The run-off is due to water surplus on land ending up in the ocean and it is caused by precipitation, which exceeds evapotranspiration. The green WF refers to the human use of evaporative flow from the land surface, mostly for growing crops. The blue WF refers to the consumptive use of the run-off from catchment and does not include the return flow. This amount represents the use of run-off as source. The grey WF is defined as the volume of water required to assimilate waste, quantified as the volume of water needed to dilute pollutants to such an extent that the quality of the ambient water remains above agreed water quality standards [2]. This estimated amount of water represents the use of run-off as a sink.

The following subsections describe the three components of WF and their calculation referred to growing crop or tree processes. The total water footprint of the growing process of crop $\mathrm{WF_{proc}}$ is the sum of the green, blue and grey components [$\mathrm{m^3/year}$]:

$$\mathrm{WF_{proc}} = \mathrm{WF_{proc,green}} + \mathrm{WF_{proc,blue}} + \mathrm{WF_{proc,grey}} \tag{4.1}$$

Estimating the three contributions of WF of growing a crop requires a large number of data sources: in general, it is always preferable to find local data related to the crop field location, but if it is too laborious to collect them, it is possible to use data from nearby locations or regional or national averages.

Finally, with the following methodology the WF of the involved alternative agricultural systems and their products in Gaza Strip can be assessed.

#### 4.1.3.1 *Green WF*

Green water refers to the precipitation on land that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation and then evaporates or transpires through plants: this component can be made productive for crop growth. The green WF in a process is equal to $[m^3/year]$:

$$\text{WF}_{\text{green}} = \text{GreenWaterEvaporation} + \text{GreenWaterIncorporation} \quad (4.2)$$

In agriculture the green water consumption can be measured or estimated with empirical formulas or with crop models, which estimate evapotranspiration based on input data on climate, soil and crop characteristics.

Referring to a growing crop process, the green WF is calculated as the green component in crop water use ($CWU_{green}$, $[m^3/ha]$) divided by the crop yield (Y, [ton/ha]):

$$\text{WF}_{\text{proc, green}} = \frac{\text{CWU}_{\text{green}}}{\text{Y}} \quad (4.3)$$

In general, yields can be taken as given in the yield statistics, and CWU(green) can be calculated referring to the rainfall amount to the involved agricultural area. The 'green' Crop Water Use (CWU) represents the total rainwater evaporated from the field during the growing period.

#### 4.1.3.2 *Blue WF*

This indicator of consumptive water use refers to four cases:

- Water evaporates, which is the most significant case;
- Water is incorporated into the product;
- Water does not return to the same catchment area but to another catchment area or the sea;
- Water does not return in the same period (water scarce period and wet period): amounts of water can be consumed during scarce periods and can return during wet periods. This point underlines the importance of considering the temporal dimension in water-scarce areas.

Water is extracted from rivers and aquifers and it is used for irrigation, industrial or domestic purposes: the blue WF measures the amount of water available in a certain period that is consumed. The blue WF in a process [$m^3$/year] is inclues the following contributions:

$$WF_{\text{blue}} = EV_{\text{blue water}} + Inc_{\text{blue water}} + \text{LostRF} \tag{4.4}$$

- $EV_{\text{blue water}}$ is the evaporated blue water;
- $Inc_{\text{blue water}}$ is the incorporated blue water;
- LostRF is the lost return flow.

In assessing the blue WF different types of sources are distinguished: surface water, flowing (renewable) groundwater and fossil groundwater. In this study we used field data to assess the blue WF: Overseas provided us the amount of water consumed for irrigation and we excluded the fraction of groundwater recharge (22%). If no field data are available, referring to a growing crop process, the blue WF is calculated as the blue component in crop water use ($CWU_{\text{blue}}$, [$m^3/ha$]) divided by the crop yield (Y, [$ton/ha$]):

$$WF_{\text{proc, blue}} = \frac{CWU_{\text{blue}}}{Y} \tag{4.5}$$

In general, yields can be taken as given in the yield statistics (e.g. FAOSTAT). The $CWU_{\text{blue}}$ is calculated by accumulation of daily evapotranspiration ($ET$, [$mm/day$]) over the complete growing period (lgp: length of growing period in day), from the day of planting to tha day of harvesting:

$$CWU_{\text{blue}} = 10 \times \sum_{i=1}^{lgp} ET_{\text{blue}} \tag{4.6}$$

Since the differences in the length of growing period for different crop varieties are substantial, this factor can significantly influence the calculated CWU. Evapotranspiration is usually estimated using models, which use data on climate, soil properties and crop characteristics as inputs is more usual. One of the suitable models is the CROPWAT model developed by the Food Agriculture Organization of the United Nations [9], which is based on the method described in [3]. It offers two different options to calculate evapotranspiration: the 'crop water requirement option' (assuming optimal conditions) and the 'irrigation schedule option' (including the possibility to specify actual irrigation supply time). It is more advisable to use the second option because it is applicable for both optimal and non-optimal growing conditions, typical of the GS, and because it is more accurate, as the model includes a dynamic soil water balance. The required input data for CROPWAT model are:

- climate data from the nearest or the most representative meteorological station: precipitation (monthly data: mm), evaporation [mm/day], humidity [percentage], temperatures (minimum and maximum) [C], wind [km/day], sun [hours], solar radiation [MJ/$m^2$/day];
- crop parameters: Crop Coefficient (Kc) (explained in appendix B), crop yield and cropping pattern (planting and harvesting dates) can be taken from local data;
- soil maps;

Concerning the blue water incorporated into the harvested crop, it can be obtained simply by looking at the water fraction of the harvested crop. This value is typically in the order of 0.1 per cent of the evaporated water, up to 1 per cent at most.

#### 4.1.3.3 *Grey WF*

It is defined as the volume of freshwater that is required to assimilate the load of pollutants based on natural background concentrations and existing ambient water quality standards. This indicator concerns the degree of freshwater pollution and the approach taken in its accounting is the same as the so-called 'critical-load approach' [1]:

$$WF_{grey} = \frac{L}{c_{max} - c_{nat}} \tag{4.7}$$

where:

- L is the pollutant load $[m^3/year]$
- $c_{max}$ is the maximum acceptable concentration $[m^3/year]$
- $c_{nat}$ is the natural concentration in the receiving water body $[m^3/year]$

The natural concentration in a receiving water body is the concentration in the water body that would occur if there were no human disturbances in the catchment. For human-made substances that naturally do not occur in water, $c_{nat}$ =0. When natural concentrations are not known precisely but are estimated to be low, for simplicity one may assume $c_{nat}$ = 0. The natural concentration is used as reference because the grey WF is an indicator of the assimilation capacity, which depens on the difference between the maximum allowable and

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[1] In the critical-load approach the basic assumption is that the room for waste uptake of a water body is limited by the difference between the maximum and the natural concentration. This approach refers to the situation where the room for waste uptake has been fully consumed, and consequently, the grey WF will be equal to the available water flow.

natural concentration of a substance. If one would compare the maximum allowable concentration with the actual concentration of a substance, one would look at the remaining assimilation capacity, which is obviously changing all the time, as a function of the actual level of pollution at a certain time. Grey WF calculations are carried out using ambient water quality standards with respect to the maximum allowable concentrations for the receiving freshwater body. Both ambient quality standards and natural background concentrations vary for surface and groundwater bodies: thresholds in groundwater are often based on requirements for drinking water, while maximum acceptable concentrations in surface waters are typically determined by ecological considerations. The estimated values show the already consumed part of the assimilation capacity and they can result smaller, equal or higher than the existing water (river or groundwater) flow:

- when grey WF is smaller than the existing water flow, there is still sufficient water to dilute the pollutants to a concentration below the standards;
- when the two values are equal, the existing concentration is exactly equal to the ambient standard;
- when the grey WF exceeds the ambient flow, the pollution goes beyond the assimilation capacity of the receiving water body: this result is obtained due to the fact that grey WF is an indicator of the severity of water pollution expressed in terms of volume.

The type of source influences the calculation: in the case of diffuse source of water pollution, the pollutant load is the fraction of the total amount of chemical applied that reaches the groundwater or surface water. The amount of chemicals (e.g. fertilizers and pesticides) applied can be measured, but the fraction of chemicals that reaches the groundwater or surface water cannot be measured, since it enters the water in a diffuse way, so it is not clear when and where it should be measured. The simplest model is to assume that a certain fixed fraction of the applied chemicals reach the ground- or surface water.

Finally, when a waste flow concerns different forms of pollution and pollutants, the grey WF is determined by the most critical pollutant, which has the highest grey WF value. Furthermore, this indicator refers to the human-induced pollutant load, not to the load measured at some downstream point in the involved flow.

Referring to a growing crop process, the grey WF is calculated as the chemical application rate to the field per hectare (AR, $[kg/ha]$) times the leaching-run-off fraction ($\alpha$) divided by the maximum acceptable concentration ($c_{max}$, $[kg/m^3]$) minus the natural concentration for the pollutant considered ($c_{nat}$, $[kg/m^3]$) and then divided by the crop yield (Y, $[ton/ha]$), i.e.:

$$WF_{\text{proc, grey}} = \frac{[(AR \times \alpha)/(c_{max} - c_{nat})]}{Y} \tag{4.8}$$

The pollutant generally consist of fertilizers (N, P, etc.), pesticides and insecticides. The considered ’waste flow’ to freshwater bodies is a fraction of the total application of the substances quoted above: the pollutant taken into account is the one which has the highest grey WF.

#### 4.1.4 *WF of farm animal products*

Since the agricultural systems analyzed in this study livestock and aquaculture, a specific section is dedicated to the assessment of the water footprint farm animal products. Moreover, considering a global perspective, the importance of this assessment is due to the fact that the consumption of animal products is increasing, and consequently its pressure on fresh water resources.

Nearly one-third of the total water footprint of agriculture in the world is related to animal products. The water footprint of any animal product is larger than the water footprint of crop products with equivalent nutritional value.

Mekonnen and Hoekstra describes the methodology for calculating the WF of farm animal products. In this study the suggested methodology in [24] is followed. The calculation of total WF for an animal (a), in the country (c) in a production system (s) (industrial, mixed or grazing) is expressed as:

$$\mathrm{WF[a,c,s]} = \mathrm{WF_{feed}[a,c,s]} + \mathrm{WF_{drink}[a,c,s]} + \mathrm{WF_{serv}[a,c,s]} \tag{4.9}$$

The three components of the total WF are:

- $\mathrm{WF_{feed}}$ is the water consumed for the production of animal feed;
- $\mathrm{WF_{drink}}$ is water drunk by animals;
- $\mathrm{WF_{serv}}$ is the water consumed for different services like cleaning farmyard, washing the animals and carrying out the services necessary to maintain the environment.

##### 4.1.4.1 *WF of animal feed*

The WF of an animal related to the feed consumed consists in two parts: the WF of the various feed ingredients and the water that is used to mix the feed, as in equation (4.10).

$$\mathrm{WF_{feed}[a,c,s]} = \frac{\sum_{p=1}^{n} (\mathrm{Feed[a,c,s,p]} \times \mathrm{WF^{*}}_{\mathrm{prod}}\mathrm{[p]}) + \mathrm{WF_{mixing}[a,c,s]}}{\mathrm{Pop^{*}[a,c,s]}} \tag{4.10}$$

The terms involved in the equation are:

- Feed[a,c,s,p] is the annual amount of ingredient p $[ton/y]$;

- $WF^{*}_{prod}[p]$ is the water footprint of ingredient p $[m^3/ton]$;
- $WF_{mixing}[a,c,s]$ is the water consumed for mixing the different ingredients of the feed for an animal $[m^3/y/animal]$;
- $Pop^{*}[a,c,s]$ is the number of slaughtered animals per years or number of milk/egg producing animal in a year in country c from the production system s.

**WATER FOOTPRINT OF FEED INGREDIENTS** The animals feeds are mainly composed by three ingredients categories:

- Crops
- Roughages
- Crop-by-products

The WF is generally assessed following the methodology described in the previous section: blue and green WF are estimated using a crop water use model, and the grey one is estimated by looking at leaching and run-off of nitrogen-fertilizers only. As animal feed in a country originates from domestic production and imported products, a weighted average water footprint can be taken.

**VOLUME OF FEED** The total amount of feed consumed by animals is estimated as follows [20]:

$$\text{Feed}[a,c,s] = \text{FCE}[a,c,s] \times \text{P}[a,c,s] \tag{4.11}$$

- Feed[a,c,s] is the total amount of feed consumed by animal category a, in country c and in system production s [ton/y];
- FCE[a,c,s] is the feed conversion efficiency of an animal category a, in country c and in system production s [kg dry mass of feed/kg product] and it is estimated for each produced product;
- P[a,c,s] is the total amount of product (meat, milk, egg) produced [kg of product/y]

The Food Conversion Efficiency (FCE) is the amount of feed consumed per unit of produced animal product: low values of FCE mean efficient use of feed. The FCE for non-ruminants (pig and chicken) are adopted from [20], for ruminants (cattle, goats and sheep) these values are estimated as:

$$\text{FCE}[a,c,s] = \frac{\text{FI}[a,c,s]}{\text{PO}[a,c,s]} \tag{4.12}$$

- FI[a,c,s] is the feed intake per head by ruminant animal [kg dry mass/y/animal];

- PO[a,c,s] is the product output per head for ruminant animal [kg product/y/animal]

The product output is estimated as:

$$\text{PO[a,c,s]} = \frac{\text{P[a,c,s]}}{\text{Pop[a,c,s]}} \tag{4.13}$$

- P[a,c,s] is the total annual production of different products [kg/y];
- Pop[a,c,s] is the total population of different ruminants categories.

The estimation of the total amount of animal products (P) changes with the different products. The total amount of **meat** ($P_{meat}$) is estimated with the following equation:

$$\text{P}_{\text{meat}}\text{[a,c,s]} = \text{CY[a,c,s]} \times \text{SA[a,c,s]} \tag{4.14}$$

- CY[a,c,s] is the carcass yield [kg/animal] which is available on [5];
- SA[a,c,s] is the number of slaughtered animals per year, which results from multiplying the total population of each animal category ($Pop[a, c, s]$) and the yearly off-take rate (OR[a,c,s]):

  $$\text{SA[a,c,s]} = \text{Pop[a,c,s]} \times \text{OR[a,c,s]} \tag{4.15}$$

The total amount of milk ($P_{milk}[a, c, s]$) is estimated multiplying the milk yield per dairy cow (MY) [ton/dairy cow] and the number of dairy cows (DC):

$$\text{P}_{\text{milk}}\text{[a,c,s]} = \text{MY} \times \text{DC} \tag{4.16}$$

The total amount of produced eggs ($\text{P}_{\text{egg}}$[a,c,s]) is obtained multiplying the fraction of egg produced in country c with production system s ($\text{f}_{\text{egg}}$[a,c,s]) and the total amount of egg produced in country c ($\text{P}_{\text{egg}}$[a,c]) [ton/y]:

$$\text{P}_{\text{egg}}\text{[a,c,s]} = \text{f}_{\text{egg}}\text{[a,c,s]} \times \text{P}_{\text{egg}}\text{[a,c]} \tag{4.17}$$

In this study the total amount of consumed feed per animal is provided by Overseas, so the previous equations are not used.

FEED COMPOSITION The main ingredients of animal feeds are 'concentrates' and 'roughages'. The total volume of concentrates (Conc[a,c,s]) (t/yr)can be estimated multiplying the total amount of feed consumed by animal, category a in country c in production system s (Feed[a,c,s]) and the fraction of concentrates in the total feed ($\text{f}_{\text{c}}$[a,c,s]):

$$\text{Conc[a,c,s]} = \text{Feed[a,c,s]} \times \text{f}_{\text{c}}\text{[a,c,s]} \tag{4.18}$$

The values of $\text{f}_{\text{c}}$[a,c,s] can be retrieved from [20] and [7].

The global coverage on the composition of feed is not provided by any dataset, but the following sources include useful data:

- Hendy et al. (1995 [20]) provides the composition of pig and poultry feed;
- Wheeler (1985 [42]) provides feed composition in terms of major crop categories for different animal categories;
- AQUASTAT (2009 2009)provides the country average concentrate feed values for the period 1996-2003.

Finally, the roughages feed is divided into fodder, grass and crop residues using the data obtained from Bouwman et al., 2005 [7].

### 4.1.5 *Water Stress Indicators*

In arid regions like the GS, the water consumption in production processes (e.g. agricultural growing processes) may be crucial among the environmental impacts: a renationalized assessment is necessary to quantify its impacts in different locations creating regional differentiation of damage factors. For this reason in [29] a WSI is created. This index focuses on consumptive water use, that means water withdrawals which are evaporated, incorporated in products and waste. Water stress is commonly defined by the ratio of total annual freshwater withdrawals of different users ($WU_{ij}$, industry, agriculture, and household) to hydrological availability for a watershed i ($WA_i$):

$$WTA_i = \frac{\sum\limits_{j=1} WU_{ij}}{WA \quad i} \tag{4.19}$$

The variability of precipitation, both monthly and annual, may lead to increased water stress during specific periods. To correct for increased effective water stress, a variation factor (VF) is introduced to calculate a modified Withdrawals To Availability (WTA)$^*$, which differentiates watershed with Strongly Regulated Flows (SRF), which weaken the effect of variable precipitation significantly, but may cause evaporation. The Variation Factor (VF) is defined as the aggregate measure of dispersion of the multiplicative standard deviation of monthly ($s^*{}_{month}$) and annual ($s^*{}_{year}$) precipitation, assuming a log-normal distribution (resulted from Kolmogorov-Smirnov test):

$$VF = \exp(\sqrt{\ln(s^*_{month})^2 + \ln(s^*_{year})^2}) \tag{4.20}$$

This correction factor is applied differently to SRF and non-SRF to calculate a modified WTA (WTA$^*$):

$$WTA^*(SRF) = \sqrt{VF} \times WTA \tag{4.21}$$

$$WTA^*(non - SRF) = VF \times WTA \tag{4.22}$$

Finally, the WSI is adjusted to a logistic function to achieve continuous values between 0.01 and 1:

$$\mathrm{WSI} = \frac{1}{1 + (\exp(-6.4 \times \mathrm{WTA}^{*} \times ((\frac{1}{0.01}) - 1)))} \tag{4.23}$$

WSI has a minimal water stress of 0.01 as any water consumption has at least marginal local impact. The curve is tuned to result in a WSI of 0.5 for a WTA of 0.4, which is the threshold between moderate and severe water stress, when applying the median variation factor of all watersheds.

### 4.1.6 *Damage assessment*

The potential environmental damages of water use are assessed for three areas of protection: human health, ecosystem quality, and resources. This a crucial point in the GS, because the water scarcity seriously affect these three areas of protection

#### 4.1.6.1 *Damage on human health*

The phenomenon of water-scarcity causes generally two impact pathways for human health, which are mainly relevant in developing countries:

- lack of freshwater for hygiene and ingestion;
- water shortages for irrigation, resulting in malnutrition.

Pfister, Koehler, and Hellweg (2009 [29]) focuses on food production effects of water deprivation because competition in water scarce regions basically affects irrigation, and because hygiene conditions depend on local circumstances, and are therefore difficult to asses.

The cause-effect chain from water consumption to human health effects presents high complexity due to the numerous influencing factors: in addition to physical water scarcity, lack of wastewater-treatments and infrastructures and socio-economics factors. To cope with this high complexity, the chain is evaluated in three steps:

- quantifying the lack of freshwater for human needs;
- assessing vulnerability;
- estimating quantitative health damages related to water deficiency.

The damage ($\Delta\,\mathrm{HH}_{\mathrm{maln},i}$) induced by water consumption in a country i ($\mathrm{WU}_{\mathrm{cons},i}$, ($m^3$)), is measured in disability adjusted life years

(DALY), as the Eco-indicator-99 method (Goedkoop and Spriensma, 2001 [17]) for assessment of human health effects:

$$\Delta\ HH_{maln,i} = CF_{maln,i} \times WU_{cons,i} \tag{4.24}$$

- The first involved term ($CF_{maln,i}$) is the expected specific damage per unit of water consumed (DALY/$m^3$), and is obtained multiplying the water deprivation factor $WDF_i$ ($m^3{}_{deprived}/m^3{}_{consumed}$) and the effect factor $EF_i$, which quantifies the annual number of malnourished people per water quantity deprived (capita*yr/$m^3{}_{deprived}$).
  - $WDF_i$ is obtained multiplying the physical water stress index $WSI_i$ and the fraction of agricultural water use $WU_{\%,\ agr,i}$;
  - $EF_i$ is calculated multiplying the per-capita water requirements $WR_{maln}{}^{-1}$ to prevent malnutrition ($m^3$/(yr*capita)) and the human development factor $HDF_{maln,i}$, which relates to the human development index (HDI) to malnutrition vulnerability: $HDF_{maln}$ is derived from a polynomial fit of DALY values for malnutrition per 100000 people in 2002 ($DALY_{maln,rate}$) with corresponding HDI data:

$$HDF_{maln} = \begin{cases} 1 & \text{for} HDI < 30 \\ 2.03HDI^2 - 4.09HDI + 2.04 & \text{for} 0.30 \leqslant HDI \leqslant 0.88 \\ 0 & \text{for} HDI > 0.88 \end{cases} \tag{4.25}$$

- the second involved term is $WU_{cons,i}$ is the water consumption in a country ($m^3$), which causes the obtained damage.

The equation for damage on human health caused by water consumption can be rewritten in a complete way:

$$\Delta\ HH_{malnutrition,i} = \underbrace{\underbrace{WSI_i \times WU_{\%,\ agr,i}}_{WDF_i} \times \underbrace{HDF_{maln,i} \times WR_{maln}{}^{-1}}_{EF_i} \times DF_{maln}}_{CF_{maln,i}} \times WU_{cons,i} \tag{4.26}$$

### 4.1.6.2 *Damage on ecosystems quality*

The effects of freshwater consumption on terrestrial ecosystem quality (ΔEQ, ($m^2$*yr)) are assessed following the Eco-indicator-99-method [17], with units of Potentially Disappeared Fraction of species (PDF). PDF values are generally assessed as Vulnerability of vascular Plant species Biodiversity (VPBD) (Goedkoop and Spriensma 2001 [17]). Net

Primary Production (NPP) is considered a proxy of ecosystem quality by Pfister, Koehler, and Hellweg ( 2009 [29] ): the global relation between VPBD and NPP was tested, and a significant correlation was found. Nemani et al. (2003 [26]) developed indices from 0 to 1,which quantify the 'potential climatic constraints to plant growth' due to limited temperature, radiation, and water availability. The resulted fraction of NPP which is limited by water availability ($\text{NPP}_{\text{wat-lim}}$) represents the water-shortage vulnerability of an ecosystem, and is used as a proxy for PDF, due to the high correlation with VPBD. $\Delta$EQ is calculated multiplying $\text{NPP}_{\text{wat-lim}}$ and the ratio of $\text{WU}_{\text{consumptive}}$ and P (mean annual precipitation), which denotes the theoretical area-time equivalent which would be needed to recover the amount of consumed water by natural precipitation:

$$\Delta \text{EQ} = \text{NPP}_{\text{wat-lim}} \times \frac{\text{WU}_{\text{consumptive}}}{\text{P}} \tag{4.27}$$

#### 4.1.6.3 *Damage on resources*

The minimum time-step to evaluate water resource depletion is the year because in many locations precipitation has an annual cycle. Water stock exhaustion can be caused by the extraction of fossil groundwater or the overuse of other water bodies. The backup-technology concept [36] as used to assess abiotic resource depletion in EI99 [17], expressed in 'surplus energy' (MJ) to make the resource available in the future, is employed here for assessing the damage to freshwater resources ($\Delta$R), and for making water use comparable to other types of resource use. Desalination of seawater may be applied as a backup technology to compensate for water resource depletion [36]. The damage to freshwater resources is calculated with the following equation:

$$\Delta \text{R} = \text{E}_{\text{desalination}} \times \text{F}_{\text{depletion}} \times \text{WU}_{\text{consumptive}} \tag{4.28}$$

where $\text{E}_{\text{desalination}}$ is the energy required for seawater desalination$(\text{MJ}/m^3)$ and $\text{F}_{\text{depletion}}$ is the fraction of freshwater consumption that contributes to depletion. It derives from the WTA ratio as follows:

$$\text{F}_{\text{depletion}} = \begin{cases} \frac{WTA-1}{WTA} & for WTA > 1 \\ 0 & for WTA \leqslant 1 \end{cases} \tag{4.29}$$

### 4.1.7 *A unique water footprint value integrating consumptive and degradative water use*

A complete assessment of water use using a single score stand-alone water footprint, analogous to the carbon footprint, is required to better compare different results and to permit an immediate communicability. To facilitate single score reporting, the critical dilution volume approach, has been used to express a degradative emission in terms of a theoretical water volume (grey water), as explained in subsection 'Grey water footprint accounting'. This approach has not received widespread acceptance: Ridoutt and Pfister (2013 [34]) proposes a new approach taking advantage of the complex fate and effects models normally employed in LCA. The new method introduces the calculation of results for both Consumptive Water Use (CoWU) and Degradative Water Use (DWU) in the reference unit $H_2Oe$ (equivalent) [35], where 1 l $H_2Oe$ represents the burden on water system from 1 l consumptive freshwater use at the global average WSI. The use of the same referent unit enables summation and reporting as a single stand-alone score. Concerning CoWU, which is generally assessed by balancing water inputs and outputs, the characterization factor applied is the locally relevant WSI ($WSI_i$) divided by the global average WSI ($WSI_{global}$):

$$\mathrm{CoWU}(H_2Oe) = \frac{\mathrm{CoWU}_i \times \mathrm{WSI}_i}{\mathrm{WSI}_{global}} \tag{4.30}$$

Concerning DWU, each emission is modeled separately according to the relevant environmental mechanism using methods at endpoint level (e.g. EU-JRC 2011 relating to the human health area of protection)including:

- freshwater eutrophication
- freshwater eco-toxucity
- impacts relating to the human health area of protection

The individual endpoint results are calculated using ReCiPe impact assessment methodology [18], normalized with European factors, weighted using the Hierarchic cultural perspective and combined into a single value (ReCiPe points, global). This single value is converted into the units $H_2Oe$ by dividing by the global average consumption weighted value for 1 l of CoWU that is $1.86 * 10^6$ ReCiPe points [29]:

$$\mathrm{DWU}(H_2Oe) = \frac{\mathrm{RECIPE\ points\ (emission\ to\ waterfor\ product\ system)}}{\mathrm{RECIPE\ points(global\ average\ for\ 1\ l\ consumptive\ water\ use)}} \tag{4.31}$$

A single stand-alone water footprint result, expressed in the units $H_2Oe$, is calculated by adding the indicator results for CoWU and DWU:

$$\mathrm{WF}(H_2Oe) = \mathrm{CoWU}(H_2Oe) + \mathrm{DWU}(H_2Oe) \tag{4.32}$$

## 4.2 LIFE CYCLE ASSESSMENT

Life Cycle Assessment is a methodology insert in the context of ISO 14040:2006 and 14044:2006. It asses the environmental impacts of a product or a service during its Life cycle. First examples of LCA were implemented during the 1970s in the USA and in the UK, and this type of analysis was called REPA (Resource and Environmental Profile Analysis) [6]. At the beginning, the energetic flows were the main issue, and other aspects like waste production and recycling were not considered. In the '90s LCA became a widespread procedure within enterprises and research centers all over the world, and 1993 the most important study regarding LCA activities was published:'The LCA Sourcebook' [23]. Nowadays, the major industrial associations are publishing databases to share information about life cycle of their products and the related impacts assessed using LCA [6]. In Italy, synergic activities between industry and university are created to develop and share LCA: e.g. ENEA created 'Rete italiana LCA', which gathers experts to share works and information. The goal of LCA is a complete description of interactions between a product or service and the environment, quantifying the direct and indirect impacts on environment itself. The Society of Environmental Toxicology and Chemistry (SETAC) defines LCA as 'the evaluation of the complete life cycle of a product or activity, including extraction of raw materials, production, transport, distribution, use, reutilization and the final disposal' (SETAC, 1993): the product is analyzed 'from cradle to grave'. The analysis can also be partial, called 'from cradle to gate', which exclude the use phase, or 'from gate to gate', which analyze only the production phase. Finally, if the material is recycled, the analysis is called 'from cradle to cradle', to underline that the product returns resource.

### 4.2.1 *Methodology*

According to the ISO 14040 and 14044 standards, a LCA is carried out in four phases shown in figure 4.2:

1. goal and scope definition;
2. life cycle inventory (LCI);
3. life cycle impacts assessment;
4. interpretation.

In the following sections each phase is described.

#### 4.2.1.1 *Goal and scope*

In this first phase, the systems and its boundaries, the required data, and the functional unit to be used are determined. The functional unit

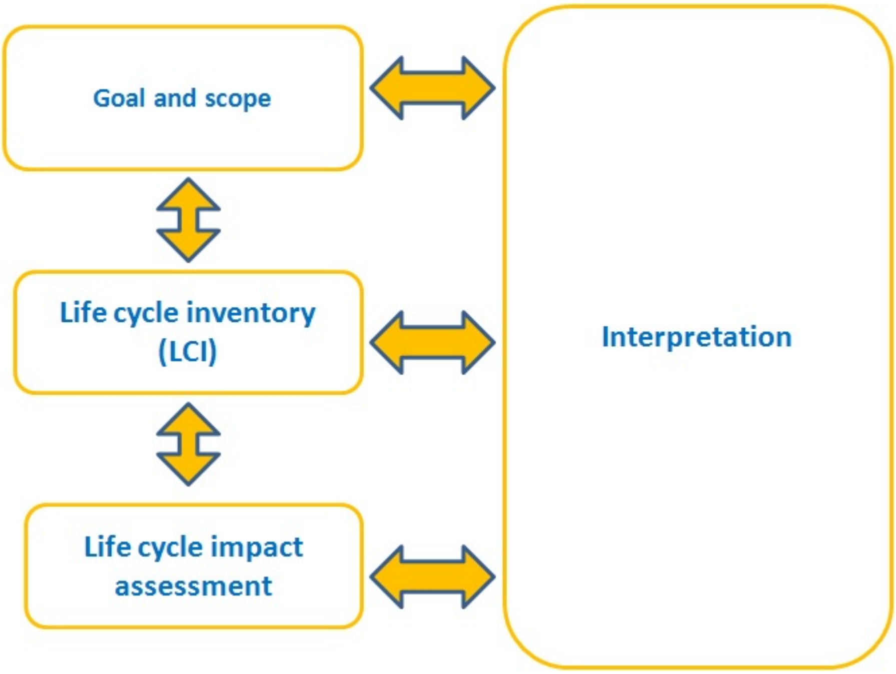

**Figure 4.2:** LCA is carried out in four interdependent phases: goal and scope definition, life cycle inventory (LCI), life cycle impacts assessment, and interpretation.

is the reference unit to which all the inputs and the outputs of the system will be referred: it is necessary in order ensure the possibility of comaprison between the results of LCA study of different systems. Moreover, the aim of the study and the future use of the results and the people to which the sudy is addressesd are defined.

#### 4.2.1.2 *Life cycle inventory*

This stage is a repeated procedure, during which every data which is eithr entering the system (e.g. raw materials, water, agents, fuels and other natural inputs) or is coming out to the environment (like products, air emissions, liquid effluents, by-products and wastes) is recorded and quantified. Data collection is the basis of the inventory analysis, and this procedure demands a detailed knowledge of each primitive process in order to describe, both quantitavely and qualitatively, all the related inputs and outputs referred to the functional unit. After data collection the calculation of inventory results is made: the mass balance linking all the subsystem (unit process) and the outputs of each subsystem and of the overall system are calcultated.

#### 4.2.1.3 *Life cycle impact assessment*

The impact assessment is a process to characterise and assess the effects and the impacts on the environment caused by the analyzed system and its recorded inputs and outputs. It is used for the identi-

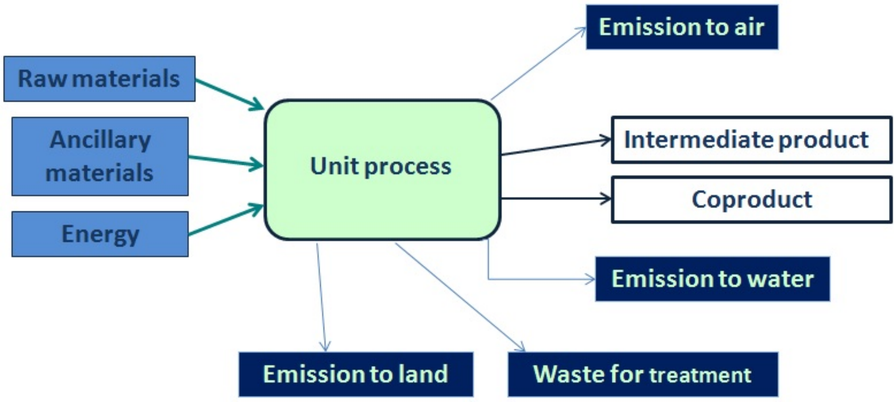

**Figure 4.3:** Example of unit process: on the right hand there are input flows (light blue boxes), the white boxes represent intermediate products, and the blue boxes are emission in the different environmental components and waste.

fication of improvement plans, for the comparison between different system based on selected indicators, for localisation of environmental issues, and for supporting decision makers. The compulsory steps involved in this phase are selection of impact categories, classification and characterization and the non-compulsory are normalization, grouping and weighing. The impact categories can be divided into two groups:

1. input categories are related to materials or resources consumption;
2. output categories are related to emission of different substances.

The main impact categories are:

- global warming ($CO_2$ equivalents);
- ozone depletion (trichlorofluoromethane (CFC-11) equivalents);
- acidification (hydrogen (H+) ion equivalent);
- photochemical smog (ethane ($C_2H_6$ equivalents);
- eutrophication (phosphate ($PO_4$) equivalents);
- terrestrial toxicity (converts $LC_{50}$ to equivalents; uses multimedia modeling exposure pathways);
- aquatic toxicity (converts $LC_{50}$ to equivalents; uses multimedia modeling exposure pathways);
- human health (converts $LC_{50}$ to equivalents; uses multimedia modeling exposure pathways);
- resource depletion (ratio of quantity of resources used versus quantity of resources left in reserve);

- land use (converts mass of solid waste into volume using estimated density);
- water use (ratio of quantity of water used versus quantity of resources left in reserve).

The impact categories are determined in two differente levels: midpoint and endpoint. The midpoint level categories are easily and precisely calculated, and they are characterized by low level of uncertainty. The endpoint level categories are more intuitive and clear because are related to final damages like human health, but they are characterized by an high uncertainty. With the classification the different inputs and outputs are classified within the the selected impact categories. Impact characterization uses science-based conversion factors, called characterization factors, to convert and combine the LCI results into representative indicators of impacts to human and ecological health. There exist different characterization methods: they are models which already include a set of impact categories, indicators, normalization and weighing factors. Normalization is an LCIA tool used to express impact indicator data in a way that can be compared among impact categories. This procedure normalizes the indicator results by dividing by a selected reference value. Grouping assigns impact categories into one or more sets to better facilitate the interpretation of the results into specific areas of concern. Typically, grouping involves sorting or ranking indicators. Finally, the weighting step (also referred to as valuation) of an LCIA assigns weights or relative values to the different impact categories based on their perceived importance or relevance. Weighting is important because the impact categories should also reflect study goals and stakeholder values. In this work the ReCiPe 2008 is chosen as characterization method. It is developped on the basis of Eco-indicator 99 and CML 2001. These methods convert emissions of pollutants and extraction of natural resources into indicators of midpoint level (CML 2001) or endpoint (Eco-indicator 99): with ReCipe 2008 is a method used to present the results of both the levels. It is dual approach, with 16 midpoint impact categories and 3 endpoint damage categories. According to Eco-indicator 99, ReCiPe 2008 presents three versions representing three different perspectives: individualist, hierarchist and egalitarian (Goedkoop et al., 2009, [18]). In table 4.1 and table **??** the impact categories with the relative characterization factors and the damage categories with relative indicators.

The ecoindicator connects the inventory results to midpoint categories. Subsequently, the endpoint categories are obtained from midpoint ones through characterization factors: in table 4.3 the hierarchist approach characterization factors are reported (water depletion and marine eutrophication are not correlated with damage categories, and '/' means that there exist different values of characterization factor).

| Impact category | Characterization factor | Unit |
|---|---|---|
| Climate change | Global Warming Potential | kg $CO_2$ eq |
| Ozone depletion | Ozone Depletion Potential | kg CFC-11 eq |
| Terrestrial acidification | Terrestrial Acidification Potential | kg $SO_2$ eq |
| Freshwater eutrophication | Freshwater Eutrophication Potential | kg P eq |
| Marine eutrophication | Marine Eutrophication Potential | kg N eq |
| Human toxicity | Human Toxicity Potential | kg 1.4-DB eq |
| Photochemical oxidant formation | Photochemical Oxidant Formation Potential | kg NMVOC |
| Particulate matter formation | Particulate Matter Formation Potential | kg PM10 eq |
| Terrestrial ecotoxicity | Terrestrial ecotoxicity Potential | kg 1.4-DB eq |
| Freshwater ecotoxicity | Freshwater ecotoxicity Potential | kg 1.4-DB eq |
| Marine ecotoxicity | Marine ecotoxicity Potential | kg 1.4-DB eq |
| Ionising radiation | Ionising radiation Potential | kg U235 eq |
| Agricultural land occupation | Agricultural Land Occupation Potential | $m^2/yr$ |
| Urban land occupation | Urban Land Occupation Potential | $m^2/yr$ |
| Natural land transformation | Natural Land Transformation Potential | $m^2$ |
| Water depletion | Water Depletion Potential | $m^3$ |
| Metal depletion | Metal Depletion Potential | kg Fe eq |
| Fossil depletion | Fossil Depletion Potential | kg oil eq |

**Table 4.1:** Impact categories and midpoint indicators in ReCiPe 2008

| Impact category | Indicators | Unit |
|---|---|---|
| Damage to human health | Disability-adjusted loss of life years | yr |
| Damage to ecosystem quality | Loss of species during a year | yr |
| Damage to resource availability | Increased cost | $ |

**Table 4.2:** Impact categories and endpoint indicators in ReCiPe 2008

| Impact category | Endpoint impact categories | | | |
|---|---|---|---|---|
| | **Unit** | **Human Health (DALY)** | **Ecosystem (species*yr)** | **Resources ($)** |
| Climate change | kg $CO_2$eq | $1.40 * 10^{(} - 6)$ | $7.39 * 10^{(} - 9)$ | - |
| Ozone depletion | kg CFC-11 eq | / | - | - |
| Terrestrial acidification | kg $SO_2$ eq | - | $5.80 * 10^{(} - 9)$ | - |
| Freshwater eutrophication | kg P eq | - | $4.44 * 10^{(} - 8)$ | - |
| Human toxicity | kg 1.4-DB | $7.00 * 10^{(} - 7)$ | - | - |
| Photochemical oxidant formation | kg NMVOC | $3.90 * 10^{(} - 8)$ | - | - |
| Particulate matter formation | kg PM10 eq | $2.60 * 10^{(} - 4)$ | - | - |
| Terrestrial ecotoxicity | kg 1.4-DB | - | $1.51 * 10^{(} - 7)$ | - |
| Freshwater ecotoxicity | kg 1.4-DB | - | $8.61 * 10^{(} - 10)$ | - |
| Marine ecotoxicity | kg 1.4-DB | - | $8.61 * 10^{(} - 10)$ | - |
| Ionising radiation | kg U235 eq | $1.64 * 10^{(} - 8)$ | - | - |
| Agricultural land occupation | $m^2/a$ | - | / | - |
| Urban land occupation | $m^2/a$ | - | / | - |
| Natural land transformation | $m^2$ | - | / | - |
| Metal depletion | kg Fe eq | - | - | $1.65 * 10^{(} - 1)$ |
| Fossil depletion | kg oil eq | - | - | $7.15 * 10^{(} - 2)$ |

**Table 4.3:** Midpoint to endpoint characterization factors

#### 4.2.1.4 *Interpretation*

In this phase the conclusion obtained from the previous phases are jointly considered and analyzed: its results should be robust referred to the goal previously defined. In this phase the complete work is examined to plan modifications to the analyzed system. Moreover, the interpretation makes the study clear and complete for the interested policy makers.

### 4.2.2 *SimaPro software*

The software used to conduct LCA is SimaPro. It is produced by the dutch company Pre Consultant and it is used by research centres, by companies, and consulting societies. It allows to build models of production processes or services and conduct LCA on them. The main applications are:

- carbon footprint calculation;
- ecodesign of products;
- Environmental Product Declaration (EDP);
- environmental impacts of products and services;
- environmental reports (e.g. GRI, Global Reporting Initiative).

International databases (e.g. Ecoinvent Processes, DK Input Output Database 99, and IDEMAT 2001 . . . ) are integrated in this software: these databases give information also on unknown or non achievable data regarding the analyzed process, and allows also comparisons among data belowing to different databases. Ecoinvent database is used in this work.

# Part II

# PRACTICE

# 5

# DATA

## 5.1 WATER FOOTPRINT

### 5.1.1 *Goal*

The goal of WF assessment in this study concerns a gazian average-sized farm. Different alternative production systems are considered, as explained in chapter 3: thus the WF assessment is addressed to evaluate different products, and then to the total WF of the entire farm production over a year, resulting from summing up all the WF values of products.

The main purpose of this assessment is to raise the awareness of companies and organizations (e.g. NGOs and local organizations) operating in the territory of the GS and helping them in optimizing investments in new solutions or activities to improve life quality of local people, especially in terms of food security, and avoiding the depletion of the already scarce natural resources in the area (especially water). Therefore this study aim to account WF of activities of the agricultural sector to assess the current conditions in terms of water consumption and to evaluate solutions, which are implemented to increase food production in the GS: since the rapid increase of the population and the consequent increase in water and food demand, the intervention on this sector is fundamental to reduce pressure on hydrological resources.

The main scope of interest concerns both direct and indirect WF: the direct one is related to the water consumptions from the coastal aquifer located in the GS and the indirect one derives from imported products (fertilizers, pesticides, etc.), especially from Israel. Finally, all the three components of WF are involved: green and blue are directly estimated from rainfall data and data from Overseas, and the grey one is assessed using data supplied by Overseas and WHO.

### 5.1.2 *Inventory boundaries*

The inventory boundaries define, the elements included in the analysis. This definition includes the following aspect:

- consideration of blue, green and/or grey WF: the water availability represents one of the best criticisms in the GS, especially concerning blue WF, so that may be the reason to focus on accounting the blue WF only, also because it has higher opportunity costs than the green water. However, in this study both blue and green WF are included, because the green can be substituted by the blue and in agriculture the other way around as well, and also because the green water resources are scarce, too. Given the water pollution problems in the area, also the calculation of grey WF is included: the hydrological resources are highly polluted and damaged by SWI. Therefore, groundwater quality in the Gaza aquifer is considered generally poor due to the fact that the most part of the extracted water is not suitable for drinkable purpose because it exceeds WHO standards both for chlorides (250 mg/l) and for nitrate (50 mg/l) [12].

- consideration of direct and indirect WF: concerning direct and indirect WF, as said above, they are both included. Since all the products (fertilizers, pesticides, feed, etc.) used in the analyzed processes are imported, especially from Israel, the indirect WF is estimated for these products: this contribution refers to an international scale of impacts. The direct WF refers especially to irrigation processes and fertilizers and pesticides application, and thus to local impacts.

### 5.1.3 *Scope*

Concerning the scope, the WF sustainability assessment is focused on food production processes, especially proteins, in a specific scarce water area, as the GS is. In particular, with the estimation of WF of existent alternative agricultural system, their contribution to the non sustainable water consumption in the GS is quantified. Generally, in WF sustainability assessment a/some hot spots are defined and analyzed. The hot spot is the area within the WF is unsustainable during a period. It can be identified by comparing green and blue WF to green and blue water availability, and comparing grey WF to available assimilation capacity: in this case is the whole GS is considered a hot spot, because in the whole area the water consumption is unsustainable if compared to the available hydrological resources.

### 5.1.4 *Scope of response formulation*

In this study, the task of reducing WF in order to increase sustainability in the GS area is addressed to farmers and to local and/or international organizations operating in the area. With this first assessment the current water consumption are quantified and compared to the actual water availability in the area. Furthermore, aquaculture in ponds, which was recently introduced, is evaluated in terms of WF, environmental impacts and protein supply. From the obtained results the different operators will decide if the investments in this new activity are favorable and sustainable. If they are not, the organization would try to improve these solution or find other suitable interventions.

### 5.1.5 *Water footprint of crops*

#### 5.1.5.1 *Green Water Footprint*

The values of green WF of different crops directly depend on precipitation and evaporation during the growing periods of different crops, and on the groundwater recharge rate (we use an average value). Data of rainfall (10-year average) (Al-Najar, 2011 [1]) and evaporation data (25-year average) (Ismail, 2003 [22]) for the GS are shown in figure 5.1 and in figure 5.2, respectively. The green WF is calculated referring to the cultivated area (8500 $m^2$) and the ponds (150 $m^2$), diversifying between greenhouse and open field cases. The adopted average groundwater recharge rate is 22% (Dentoni, 2012 [12]) and the evaporation occurring in the ponds are not taken into account in the final values following Aldaya et al. (2012 [2]).

As said above, the calculation is performed in a different way for crops grown in the greenhouse and in the open field:

1. Greenhouse (tomatoes and cucumbers): green WF is calculated as the amount of rain that falls on water ponds; no groundwater recharge is considered, because ponds are waterproofed;
2. Open field (peas, eggplants, peppers, cauliflowers, cabbages, lentils): green WF is calculated as the sum of the net rainfall on fields (i.e. total rainfall minus the water contributing to groundwater recharge) and the water available from ponds.

Blue water consumption from the fish pond is considered only during the months without aquaculture activities (January - March), because in the other months (April - December) it is already accounted in the value of WF of fish. On the other hand, the green water coming from the pond is assigned to crops. Water contribution to recharge is not accounted for the green WF, because it is not directly exploited by the crops during the growing period. The fraction of rainfall draining to the aquifer is about 20%.

#### 5.1.5.2 *Blue WF*

In this case study the "‘blue" water only concerns the groundwater because there is no surface water source in the Gaza Strip. The whole amount of water used for irrigation purpose is pumped from the coastal aquifer. Table 5.2 shows the volume of water per tonne of produced crop pumped for irrigation:

To calculate the blue WF, the water which returns to the same catchment is not included. This amount is 22% of the pumped water (Dentoni, 2012 [12]).

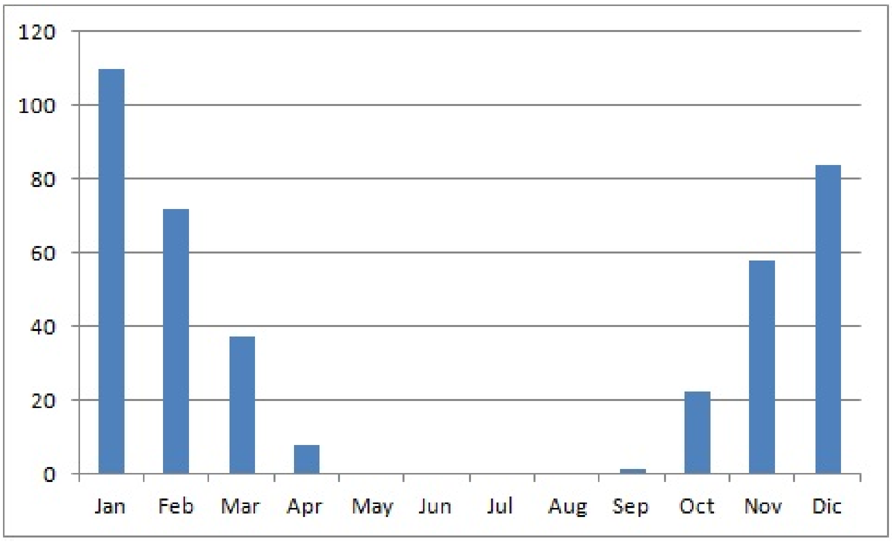

**Figure 5.1:** 10-year average rainfall data in the whole the Gaza Strip (mm/-month) (Al-Najar, 2011 [1])

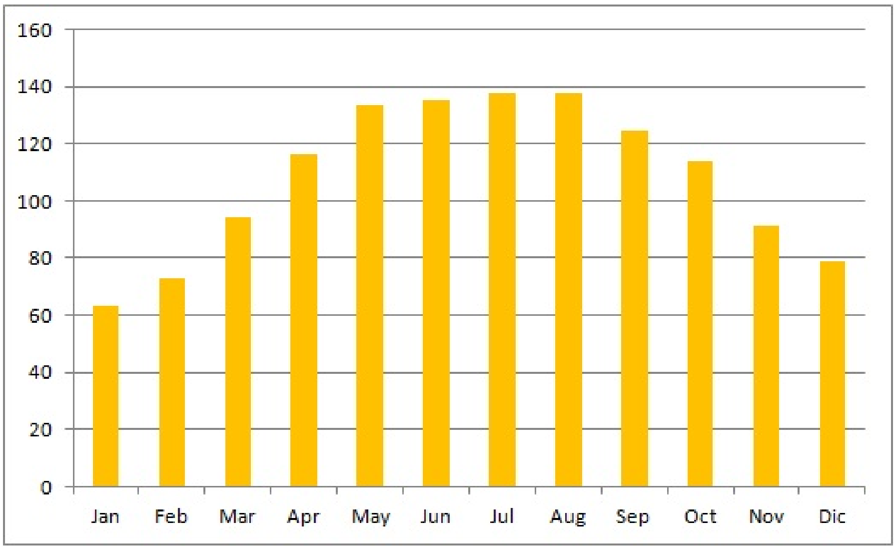

**Figure 5.2:** 25-year average evaporation in the whole the Gaza Strip (mm/-month) (Ismail, 2003 [22])

| **Crop type** | **Irrigation** ($m^3/t$) |
|---|---|
| cabbage | 80 |
| cauliflower | 192 |
| cucumber | 66.7 |
| eggplant4 | 200 |
| eggplant5 | 133.3 |
| lentil | 800 |
| pea3 | 714.3 |
| pea4 | 500 |
| pepper4 | 350 |
| pepper grown for 5 months (pepper5) | 280 |
| tomato | 66.7 |

**Table 5.1:** Water pumped for the irrigation of each crop (cubic meters per tonne of product) (field data, Overseas, 2012)

Since Al-Najar, 2011 affirms that the farmer irrigation practice in the GS exceeding the irrigation water requirement by 30%, we want to compare the obtained blue WF estimates with field data with the Crop Water Requirement (CWR) estimated by the FAO model CROPWAT to verify Al-Najar's thesis; climatic data, growing periods of different crops and crop parameters required to fill in this software are shown in appendix B. The obtained irrigation amounts from CROPWAT, needed for each crop are:

#### 5.1.5.3 *Grey WF*

The grey WF is defined as the volume of freshwater that is required to assimilate the load of pollutants based on natural background concentrations and existing ambient water quality standards, and it concerns the degree of freshwater pollution and its assimilation capacity (chapter 4). The estimation of the grey WF follows the method supplied by Aldaya et al.(2012)[2]. Its calculations are carried out using ambient water quality standards with respect to maximum allowable concentration in the receiving freshwater body. The ambient water quality standards may vary from place to place and so does the grey WF, because it depends on the difference between the maximum allowable and the natural concentration. For this reason the grey WF, as the other WF components, shows a high variability and the calculation needs specific data at the catchment scale, which are not simple to obtain because the water ambient quality standards do not exist for all substances and all places: some hypothesis are assumed as

| Crop type | Irrigation from CROPWAT ($m^3/t$) |
|---|---|
| cabbage | 51.6 |
| cauliflower | 92.9 |
| cucumber | 55.9 |
| eggplant4 | 135.6 |
| eggplant5 | 109 |
| lentil | 835 |
| pea3 | 215 |
| pea4 | 189 |
| pepper4 | 272 |
| pepper5 | 260 |
| tomato | 26 |

**Table 5.2:** Water pumped for the irrigation of each crop as estimated with CROPWAT (cubic meters per tonne of product)

suggested in Aldaya et al.(2012)[2] and as reported in chapter 5. The equation used for its calculation is equation (4.8). The first element required is the average AR of fertilizers (kg/ha). These on-field data were supplied by Overseas (see table 6.4).

As not all the data required to apply equation equation (4.8) were available, we made the following assumptions (as recommended in Aldaya et al., 2012 [2]):

- the leaching-run-off fraction, $\alpha$, is assumed equal to 10% (, [37]);
- the natural concentration for the different considered pollutants, $c_{nat}$, is assumed equal to zero because it is the concentration that would occur if there were no human disturbances in the catchment.

Since the analysis concerns only groundwater, we adopted the standards for the drinking water (as suggested in Aldaya et al., 2012 [2]). The maximum acceptable concentration of each fertilizer used in the farm is supplied by WHO:

- $c_{max}$ for N is 50 mg/l (for most crops the most critical pollutants are nitrate);
- $c_{max}$ for K is 10 mg/l (only for peas the most critical pollutants are substances containing on potassium);

| Crop type | AR (kg/ha) | | | |
|---|---|---|---|---|
| | N | K | P | Mg |
| cabbage | 150 | 120 | 120 | 0 |
| cauliflower | 150 | 120 | 120 | 0 |
| cucumber | 700 | 450 | 0 | 450 |
| eggplant4 | 860 | 250 | 600 | 0 |
| eggplant5 | 860 | 250 | 600 | 0 |
| lentil | 0 | 0 | 0 | 0 |
| pea3 | 25 | 500 | 50 | 0 |
| pea4 | 25 | 500 | 50 | 0 |
| pepper4 | 580 | 260 | 240 | 0 |
| pepper5 | 580 | 260 | 240 | 0 |
| tomato | 1000 | 230 | 125 | 0 |

**Table 5.3:** Average AR for different types of fertilizers and for different crops in kg/ha (Overseas, field data)

- $c_{max}$ for P is 5 mg/l;
- $c_{max}$ for Mg is 150 mg/l (applied on the field only fro growing cucumbers).

### 5.1.6 *Water footprint of animal products*

Referring to equation (4.9), in the case of GS only the consumption of water for food and drinking are considered. As explained in chapter **??**, the animals raised in our reference farm are sheep, chicken and fish. Most of the equations regarding animal feed consumption presented in chapter 4 are not used in this study, because most, such as the amount of feed consumed, were directly provided by Overseas.

#### 5.1.6.1 *WF of fish*

The investment in aquaculture seems to be convenient both in terms of enhanced protein production and in terms of reduced consumption of resources. Water consumption for aquaculture is due to both feed production and the maintenance of a minimum water level in ponds so as to permit fish survival. The feed is provided by the NGO and is produced in Israel, and the calculation of WF is based on WF data from Mekonnen and Hoekstra, 2010. The feed ingredients are shown in table 5.4. Concerning the maintenance of the minimum water level to for aquaculture, given the fact that fish are raised from

| Ingredient | % |
|---|---|
| yellow corn | 15 |
| fishmeal | 10 |
| soy bean meal | 50 |
| corn oil | 20 |
| premix | 5 |

**Table 5.4:** Fish feed composition:ingredients (%) produced in Israel (Aquamax, 2008 [4]

April to December, a certain amount of water has to be pumped from the aquifer to balance out evaporation, because during the dry season (from May to September) evaporation exceeds the rainfall. The minimum volume of water required depends on the final amount of fish (1 $m^3$ of water for each kg of fish produced). In this case study, each pond is considered to produce 80 kg of fish per year and, consequently, the required volume of water is 80 $m^3$. Given a pond area of 50 $m^2$, the minimum level required is 1600 mm.

To evaluate the blue WF of the pond, we calculated the water balance between rainfall and evaporation in each month, and then summed up the overall water demand from April to December. To this we added the amount of water needed to fill the pond at the beginning of April. On other hand, the green WF is not taken into account in calculating the WF related to fish, because it is attributed to crops.

#### 5.1.6.2 *WF of sheep meat*

The number of sheep raised in the reference farm is small (7), because the produced meat will be consumed by household. For this reason, concentrate feed is not used, and the related water consumption is not accounted for. The animals are fed only with:

- the fodder (whose annual total consumption is 1050 kg) growing in the field during the period of rest (January) with no irrigation: the only water consumed comes from rain (excluding the groundwater recharge, the water 'consumed' is about 108 mm in January) falling on the agricultural field (8500 $m^2$);
- the forage growing during the whole year on the pasture land (excluding the groundwater recharge, the water 'consumed' is assumed to be 200 $m^2$) which is rain-fed (305.76 mm in a year, without groundwater recharge amount); the total annual consumption is 1400 kg of grass.

Therefore, most of the water consumed by sheep is considered to be green water incorporated into forage. The only blue water we consider is that used for drinking. Following Mekonnen and Hoekstra, 2012 [24], we consider its contribution ranges between 1% and 2% of the total WF related to the sheep.

#### 5.1.6.3 *WF of chicken: meat and eggs*

The products obtained from chicken are eggs and meat, so allocation factors are needed to weigh these two products in terms of WF and environmental impacts.Based on total produced quantities, we use an allocation factor equal to 91.5% for eggs (162 kg/yr) and 8.5% (15 kg/yr) for chicken meat. The total amount of feed consumed is 547.5 kg (100g/day/animal). The feed composition was obtained using the ingredients provided by Daghir, 2008 [11]. Their values of WF were provided by Mekonnen and Hoekstra, 2010 [25] referring to Israel, the country of production:

| **Ingredient** | **%** |
|---|---|
| cereals (barley) and roughages | 76 |
| oilmeal (sunflower) | 15 |
| other concentrates (sesame meal) | 9 |

**Table 5.5:** chicken feed composition:ingredients (%) produced in Israel (Daghir, 2008 [11])

The WF for drinking was assumed to range between 1% and 2% of the total WF related to the chicken, as for sheep.

## 5.2 WATER STRESS INDICATORS

Following Pfister, Koehler, and Hellweg (2009 [29]), the first indicator of water stress is the WTA, which is the ratio of total annual freshwater withdrawals of different users ($WU_{ij}$, industry, agriculture, and household) to hydrological availability for the analyzed watershed (WA). For the GS the required data have been gathered from two different sources, and present different values (see chapter 2). PWA (2012 [10]) reports the following values:

- WA is equal to 60 millions of $m^3$;
- $WU_{agriculture}$ is equal to 80 millions of $m^3$;
- $WU_{domestic}$ is equal to 85 millions of $m^3$.

Dentoni (2012 [12]) reports the following ranges:

- WA between 102 and 178 $m^3$;
- $WU_{total}$ 186 and 226 $m^3$;

To obtain the WSI the VF is necessary. To calculate it we use the Climate Research Unit (CRU) data (CRU, 2010 [10]) on rainfall.

## 5.3 DAMAGE ASSESSMENT

### 5.3.1 *Damage on human health*

The calculation of $\Delta$ $HH_{maln,i}$ is obtained using equation (4.26). The required data are shown in table 5.6.

| Data | Value | Unit | Source |
|---|---|---|---|
| $WSI_i$ | 1 | adimensional | chapter 6 |
| $WU_{\%,agri,i}$ | 48.5 | % | [32] |
| WR | 1350 | $m^3/(yr{*}capita)$ | [29] |
| HDI | 0.670 | adimensional | [39] |
| HDF | 0.211 | adimensional | equation (4.25) |
| DF | 0.0185 | DALY/(yr*capita) | [29] |

**Table 5.6:** Data for Damage on Human Health

The different $WU_{consumptive}$ refer to the blue WF values of alternative agricultural systems, which will be calculated in chapter 6, and shown in table 6.11.

### 5.3.2 *Damage on ecosystem quality*

The required data for equation equation (4.27) are:

1. $NPP_{wat\text{-}lim}$ is calculated by Pfister, Koehler, and Hellweg (2009 [29]) for all countries, and the value obtained for the Gaza Strip is 0.5;
2. the mean annual precipitation, which in the GS is equal to 392,1 mm/yr [1]

The different $WU_{consumptive}$ refer to the blue WF values of alternative agricultural systems, which will be calculated in chapter 6, and shown in table 6.11.

### 5.3.3 *Damage on resources*

Concerning the damage on water resources, the Gaza Strip presents a critical situation, with a WTA>1, which means that the amount of consumed water is bigger than the available one. Specifically, it ranges between 1.04 and 2.22 (Dentoni, 2012 [12] and PWA, 2012 [32]). Consequently, also $F_{depletion}$ assumes different values ($F_{depl}1$, $F_{depl}$ 2, $F_{depl}$ 3, and $F_{depl}$ 4), which are reported in table 5.7). The derived average value of $F_{depletion}$ is equal to 0.314. The energy required for seawater desalination $E_{desalination}$ is set to 11 MJ/m$^3$ based on the-state-of-the-art. [1] The different $WU_{consumptive}$ refer to the blue WF values of alternative agricultural systems, which will be calculated in chapter 6, and shown in table 6.11..

| Name | WTA | $F_{depletion}$ |
|---|---|---|
| $F_{depl}1$ | 1.04 | 0.0430 |
| $F_{depl}$ 2 | 1.26 | 0.212 |
| $F_{depl}$ 3 | 1.82 | 0.452 |
| $F_{depl}$ 4 | 2.22 | 0.549 |

**Table 5.7:** $F_{depletion}$ values for different WTA

## 5.4 A UNIQUE WATER FOOTPRINT VALUE INTEGRATING CONSUMPTIVE AND DEGRADATIVE WATER USE

Referring to equation (4.30) and equation (4.31), the required data are:

- $WSI_i$, whose volume for the GS is 1 (see chapter 6);
- $WSI_{global}$, whose value is estimated by Ridoutt and Pfister (2010) and equal to 0.602;
- ReCiPe H/H points (global average for 1 l consumptive water use) estimated by Pfister, Koehler, and Hellweg and is equal to 1.86*10$^6$ ReCiPe points.
- the single values of RECIPE points for each fertilizer and pesticide: we consider the fraction of the fertilizers applied on the field emitted into water and soil, and then we calculate the ReCiPe H/H single scores; this method only considers four impact categories: freshwater eutrophication, human toxicity, freshwater ecotoxicity and marine ecotoxicity . Overall values for each crop are reported in table 5.8.

---

[1] The value of 11 MJ/m$^3$ matches the lower energy demand of operating desalination plants at 11-72 MJ/m$^3$ (Pfister, Koehler, and Hellweg, 2009 [29])

| Crop type | ReCiPe H/H points/(yr) |
|---|---|
| cabbage | 78 |
| cauliflower | 78 |
| cucumber | 0 |
| eggplant | 312 |
| pea | 39 |
| pepper | 156 |
| tomato | 93.6 |

**Table 5.8:** ReCiPe points of each crop caused by the application of fertilizers

## 5.5 PROTEIN PRODUCTION

This study analyses both on food production and natural resource consumption. The food issue focuses on protein production, so each farm product is considered in terms of proteins production. In table 5.9 the protein content provided by FAO (1953 [14]) of each product is illustrated. The reported values are referred to the fresh vegetables produced. Only the protein content of lentils is referred the dried product.

## 5.6 LCA

This system represents a sample farm in the Gaza Strip, as said in the previous chapter. To built this system different sources of information were required and consulted: Palestinian Central Bureau of Statistics (PCBS) and report written by Overseas NGO. The numerical values related to this system are insert in SimaPRO software. The farm occupy an area of 9 dunum (0.9 ha) and is made up of three parts: an agricultural field of 8.5 dunum (equivalent to 0.85 ha), 3 water ponds for aquaculture (1 pond every 3 dunum) and some space for livestock of terrestrial animals (e.g. goats, sheep, chicken . . . ). These statements correspond to 2-3 families as beneficiaries (overseas). Inputs and outputs are calculated over a year. The sample farm and its household represent the Functional Unit (FU) of LCA. In the following part the calculation of energy consumption and data of input- and output flows of materials of each component of the sample farm provided by Overseas are presented.

| **Product** | **Protein Content** (%) |
|---|---|
| fish | 20 |
| sheep meat | 12 |
| chicken meat | 12 |
| chicken egg | 11.2 |
| cabbage | 1.1 |
| cauliflower | 1.3 |
| cucumber | 0.6 |
| eggplant4 | 1.1 |
| eggplant5 | 1.1 |
| lentil | 26 |
| pea3 | 14.7 |
| pea4 | 14.7 |
| pepper4 | 1.2 |
| pepper5 | 1.2 |
| tomato | 1.1 |

**Table 5.9:** Protein contents of different crops (FAO 1953 [14]). They are referred to the fresh vegetables produced. Only the protein content of lentils is referred the dried product.

### 5.6.1 *Electricity consumption*

The whole amount of blue water is pumped from the coastal aquifer: this means that a certain amount of electricity is consumed. To quantify it equation (5.1) is used, where:

- El is the electricity consumed [kWh];
- V is the pumped volume [$m^3$], and it is different for each involved crop;
- H is the hydraulic head [m]: the adopted value is the average value for the GS and it is equal to 60 meter above the sae level [12];
- v is the pump efficiency; the adopted use id 75%.

$$El = \frac{(0.00273 \times V \times H)}{v} \tag{5.1}$$

### 5.6.2 *Input- and output flows*

In table 5.10 and in table 5.11 the input and output data of materials and energy for three fish ponds and their sources are illustrated. The annual fish production, equal to 80 $kg_{pond}$, the final weight of each fish, which is assumed to be 200 g per fish, and the mortality rate (10%) are provided by Overseas. From this data the final number of fish (1200 fish) and the initial number of fingerlings (1320 fingerlings) are obtained.

| Input | Value | Unit | Source |
|---|---|---|---|
| n°of fingerlings | 1320 | / | Overseas |
| weight of fingerlings | 2.2 | kg | Overseas |
| fodder | 540 | kg | Overseas |
| blue water | 373,6 | $m^3$ | elaboration |
| electricity | 81.5 | kWh | elaboration |
| fodder transportation | 200 | km | Overseas |

**Table 5.10:** Yearly material and energetic input flows related to aquaculture for a sample farm and their sources

| Output | Value | Unit | Source |
|---|---|---|---|
| final n°of fish | 1200 | / | Overseas |
| fish produced | 240 | kg | Overseas |

**Table 5.11:** Yearly material and energetic output flows related to aquaculture for a sample farm and their sources

In table 5.12 and in table 5.13 the input and output data of materials and energy for seven sheep and their sources are illustrated. The annual production of meat is obtained following different steps:

- the final animal weight is 32 kg/animal;
- the obtained carcass yield for Middle east countries is 20kg/animal ;
- the total meat production from 7 sheep is obtained multiplying the carcass yield and the number of animals (140 $kg_{meat}$/animal).

In table 5.14 and in table 5.15 the input and output data of materials and energy for fifteen chicken and their sources are illustrated. From these animals two products are obtained: egg and meat. Respecting the produced mass, two allocation factors are appointed to these products:

| Input | Value | Unit | Source |
|---|---|---|---|
| fodder | 1050 | kg | Overseas |
| grass | 1400 | kg | Overseas |
| blue water | 1.2 | $m^3$ | elaboration |
| electricity | 0.3 | kWh | elaboration |

**Table 5.12:** Yearly material and energetic input flows related to sheep livestock for a sample farm and their sources

| Output | Value | Unit | Source |
|---|---|---|---|
| final sheep weight | 224 | / | Overseas |
| meat production | 140 | kg | Overseas |

**Table 5.13:** Yearly material and energetic output flows related to sheep livestock for a sample farm and their sources

- 91.5% to egg (162 $kg_{egg}$/year are produced);
- 8.5% to meat (only 15 $kg_{meat}$/year are produced).

The annual production of meat is obtained following different steps:

- the final animal weight is 1.9 kg/animal;
- the obtained carcass yield for Middle east countries is 1kg/animal (FAOSTAT);
- the total meat production from 15 sheep is obtained multiplying the carcass yield and the number of animals (15 $kg_{meat}$/animal).

The annual production of egg is obtained following different steps:

- the egg weight is 60 g;
- the yearly number of egg obtained from each animal for Middle east countries is 180 egg/yr/chicken (FAOSTAT);
- the yearly production of eggs from fifteen chicken is 2700 eggs (162 $kg_{egg}$/year are produced).

In table 5.16 input- and output flows of different crops are presented. The components involved are:

- seed;
- water, but only the blue component;

| Input | Value | Unit | Source |
|---|---|---|---|
| feed | 547.5 | kg | Overseas |
| blue water | 28.7 | $m^3$ | elaboration |
| electricity | 36.6 | kWh | elaboration |

**Table 5.14:** Yearly material and energetic input flows related to chicken livestock for a sample farm and their sources

| Output | Value | Unit | Source |
|---|---|---|---|
| egg production | 162 | kg | Overseas |
| meat production | 15 | kg | Overseas |

**Table 5.15:** Yearly material and energetic output flows related to chicken livestock for a sample farm, and their sources

- occupied soil,which depends on the months involved in the growing period;
- electricity, consumed to pump the water needed for irrigation from the aquifer (it is calculated as explained before);
- fertilizers, in particular, $P_2O_5$, $K_2O$, N, and Mg.
- pesticides;
- transport of seed, pesticides and fertilizers; the km covered are 10-30 km, 85 km and 50 km, respectively;
- the output is the produced crop;
- waste are agricultural waste.

| **Crop Type** | **Unit** | cabbage | cauliflower | cucumber | eggplant4 | eggplant5 | lentil | pea3 | pea4 | pepper4 | pepper5 | tomato | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| seed | kg | 0.595 | 0.51 | 2.125 | 0.255 | 0.255 | 85 | 68 | 68 | 0.64 | 0.64 | 0.13 | Overseas |
| water (blue) | $m^3$ | 3060 | 4080 | 5100 | 6800 | 6800 | 1700 | 4250 | 4250 | 5950 | 5950 | 8500 | Overseas |
| occupied soil | $m^2/yr$ | 2833 | 2833 | 2833 | 2833 | 3541 | 775 | 775 | 2833 | 2833 | 3541 | 1856 | elaboration |
| electricity | kWh | 668 | 891 | 1113 | 1485 | 1485 | 371 | 928 | 928 | 1299 | 1299 |  | elaboration |
| $P_2O_5$ | kg | 102 | 102 | / | 510 | 510 | / | 42.5 | 42.5 | 204 | 204 | 106.25 | Overseas |
| $K_2O$ | kg | 102 | 102 | 382.5 | 212.5 | 212.5 | / | 21.25 | 21.25 | 221 | 221 | 195.5 | Overseas |
| N | kg | 127.5 | 127.5 | 595 | 731 | 731 | / | 425 | 425 | 493 | 493 | 850 | Overseas |
| Mg | kg | / | / | 382.5 | / | / | / | / | / | / | / | / | Overseas |
| organic | kg | 25500 | 25500 | 25500 | 25500 | 25500 | / | 25500 | 25500 | 25500 | 25500 | 25500 | Overseas |
| pesticide | kg | 17 | 17 | 17 | 17 | 17 | / | 17 | 17 | 17 | 17 | 27.2 | Overseas |
| transp. seed | kgkm | 5.95 | 5.1 | 21.25 | 2.55 | 2.55 | 850 | 680 | 680 | 3.4 | 3.4 | 3.8 | Overseas |
| transp. pesticide | kgkm | 1445 | 1445 | 1445 | 1445 | 1445 | / | 1445 | 1445 | 1445 | 1445 | 2312 |  |
| transp. $P_2O_5$ | kgkm | 5100 | 5100 | / | 25500 | 25500 | / | 2125 | 2125 | 10200 | 10200 | 5312 | Overseas |
| transp. $K_2O$ | kgkm | 5100 | 5100 | 19125 | 10625 | 10625 | / | 1062.5 | 1062.5 | 11050 | 11050 | 9775 | Overseas |
| transp. N | kgkm | 6375 | 6375 | 29750 | 36550 | 36550 | / | 21250 | 21250 | 24650 | 24650 | 42500 | Overseas |
| transp. Mg | kgkm | / | / | 19125 | / | / | / | / | / | / | / | / | Overseas |
| output | kg | 38250 | 21250 | 76500 | 34000 | 51000 | 1530 | 5950 | 8500 | 17000 | 21250 | 127500 | Overseas |
| waste | kg | 1275 | 1275 | 1700 | 1275 | 1275 | 1275 | / | / | 1275 | 1275 | 4250 | Overseas |

**Table 5.16:** Yearly material and energetic input- and output flows related to chicken livestock for a sample farm and their sources

# 6

# RESULTS

In this chapter the necessary analysis to answer to the goals of this work are implemented using the data presented in chapter 5: The main step are:

- WF assessment of single farm products and of involved agricultural systems;
- LCA of analyzed agricultural system;
- jointly analysis between food production, especially proteins, and water and land consumption to verify if the involved food production systems are sustainable;
- calculation of indicators related to WF;

## 6.1 WATER FOOTPRINT IN THE GAZA STRIP

Starting from data supplied by Overseas NGO and its agronomists and following the method explained in the WF assessment manual Aldaya et al. (2012) [2], the actual WF values of different alternative suitable agricultural systems in the GS, which involve crops and livestock activities, are assessed.

### 6.1.1 *Direct and indirect WF of different farm products*

The WF is accounted for each component involved in the different analyzed agricultural systems: for the different crops and animal products. Data used in this estimation were provided partly by Oversear and partly by Aldaya et al. 2012 [2] and Mekonnen and Hoekstra 2012 [24]. Furthermore, the production processes analyzed in this study use products imported from other countries, in particular from Israel, like fertilizers, pesticides and animal feeds. For this reason, the total WF related to the production can be split into two components: the direct WF, which directly affects gazian freshwater resources and causes local impacts, and the indirect one, which is related to the water resources in other countries (in this case Israel's ones) and causes impacts at regional scale.

The indirect WF value is obtained from SimaPRO software, and it involves the following contribution:

- lake water consumption;

- river water consumption;
- salt water from ocean;
- unspecified natural origin;
- water pumped from well (in ground);

This values are obtained assuming general production processes for fertilizers, pesticides and seeds: to obtain the specific and exact values of water consumption, the real production processes of fertilizers, pesticides and animal feeds used in the GS would be known, but this information is not available.

#### 6.1.1.1 *Green water footprint of crops*

The green WF of the different crops considered in the analysis is shown in table 6.1 and figure 6.1.

| **Crop type** | **Green** WF ($m^3/t$) | **Green WF farm** ($m^3$) |
|---|---:|---:|
| cabbage | 28.7 | 1096.35 |
| cauliflower | 51.6 | 1096.35 |
| cucumber | 0 | 0 |
| eggplant4 | 0 | 0 |
| eggplant5 | 1 | 51.4 |
| lentil | 507 | 775.7 |
| pea3 | 130.4 | 775.7 |
| pea4 | 129 | 1096.35 |
| pepper4 | 0 | 0 |
| pepper5 | 2.4 | 51.4 |
| tomato | 0.1 | 7.7 |

**Table 6.1:** Green WF values per tonne of crop ($m^3/t$) and for the annual farm production ($m^3$)

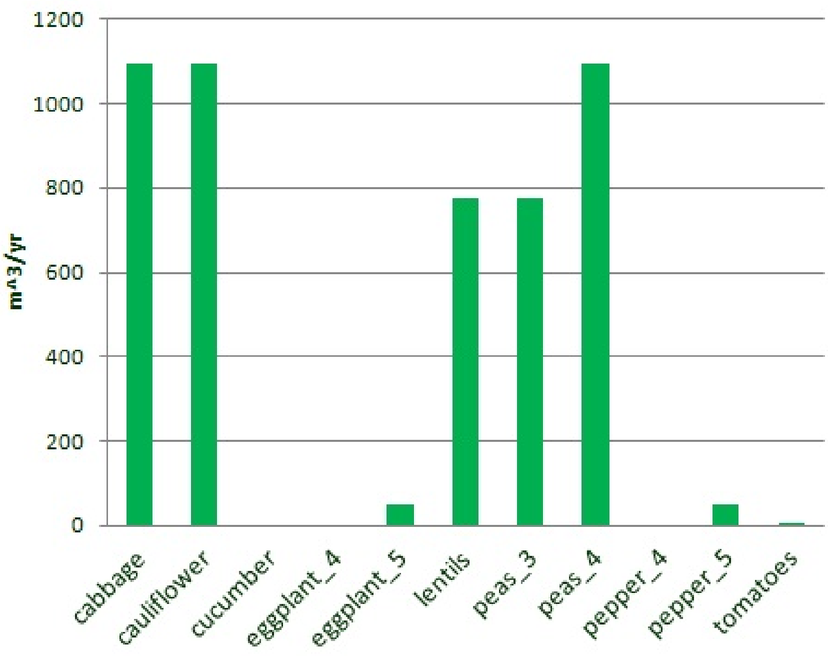

**Figure 6.1:** Annual green WF of the different crops

Cabbage, cauliflower, lentil and pea4 show the highest green WF values, because they are raised during the first part of the wet season. On the other hand, eggplant4 and pepper4 and cucumber are characterized by null green WF values, because they are cultivated during the dry summer. Finally, tomato has a low green WF value because it is raised in greenhouse.

#### 6.1.1.2 *Blue water footprint of crops*

Referring to the amount of water pumped for irrigation, the obtained values of blue WF of each tonne of crop produced and of the annual crop production in the farm are shown in table 6.2 and in figure 6.2.

| **Crop type** | **Blue** WF ($m^3/t$) | Blue WF farm ($m^3$) |
|---|---:|---:|
| cabbage | 62.4 | 2385.8 |
| cauliflower | 149.8 | 3182.4 |
| cucumber | 52 | 3978 |
| eggplant4 | 156 | 5304 |
| eggplant5 | 104 | 5304 |
| lentil | 866.7 | 1530 |
| pea3 | 557.1 | 3315 |
| pea4 | 390 | 3315 |
| pepper4 | 273 | 4641 |
| pepper5 | 218.4 | 4641 |
| tomato | 52 | 6630 |

**Table 6.2:** Blue WF values per tonne of crop in ($m^3/t$) and for the annual farm production in $m^3$

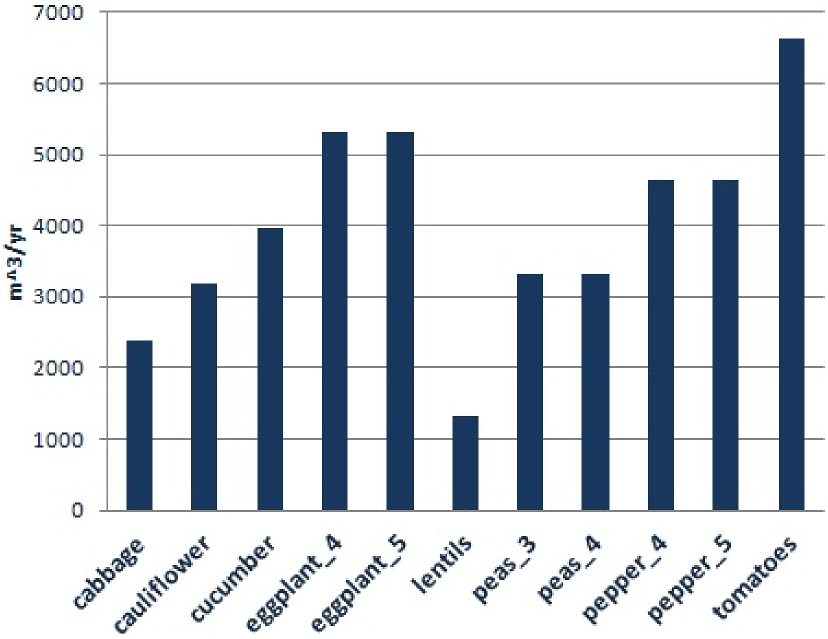

**Figure 6.2:** Annual blue WF of different crops

Tomato is the crop with the highest blue water requirements, but it has an high production rate, 150 t/ha, and for this reason the value of blue WF per tonne does not result the highest (see table 6.5). On the other hand, lentil presents the lowest blue WF value, but the production rate is very low if compared to other crops: it is only 1.8 ton/ha, and it caused a high blue WF value per tonne produced (see table

6.5).The data of production rate (kg/ha) for lentils refers to the dry matter, while for other vegetables it is referred to the fresh products: since the fresh vegetable are heavier than the dried ones, their related produced amounts per unit area are higher. Also eggplant and pepper present high blue WF values because they are mainly cultivated during the dry season. Our estimates of blue WF for each crop are compared with the relevant CWR obtained with CROPWAT (CROPWAT, 2010 [9]) . This comparison is made to verify if the farmers in GS are using more water necessary, as Al-Najar ( 2011 [1]) suggests in his work . Results are shown in table 6.3 and the surplus is calculated.

| Crop type | CWR | Blue WF (from CWR) | real Blue WF | wasted water |
|---|---|---|---|---|
| | $(m^3/t)$ | $(m^3/t)$ | $(m^3/t)$ | $(m^3/t)$ |
| cabbage | 1973.2 | 1539.49 | 2386.8 | 847.31 |
| cauliflower | 1973.2 | 1539.49 | 3182.4 | 1642.9 |
| cucumber | 4279.75 | 3328.21 | 3978 | 639.91 |
| eggplant4 | 4610.4 | 3596.11 | 5304 | 1707.89 |
| eggplant5 | 5554.75 | 4332.71 | 5304 | 971.3 |
| lentil | 1278 | 996.84 | 1326 | 329.16 |
| pea3 | 1278 | 996.84 | 3315 | 2318.16 |
| pea4 | 1603.95 | 1251.08 | 3315 | 2063.92 |
| pepper4 | 4618.9 | 3602.74 | 4641 | 1038.26 |
| pepper5 | 5524.15 | 4308.84 | 4641 | 332.16 |
| tomato | 3316.7 | 2578.03 | 6630 | 4042.97 |

**Table 6.3:** Crop water requirement and blue water footprint of different crops estimated with CROPWAT compared with blue water footprint estimates based on field data. The amount of wasted water is calculated as the difference between the two estimations.

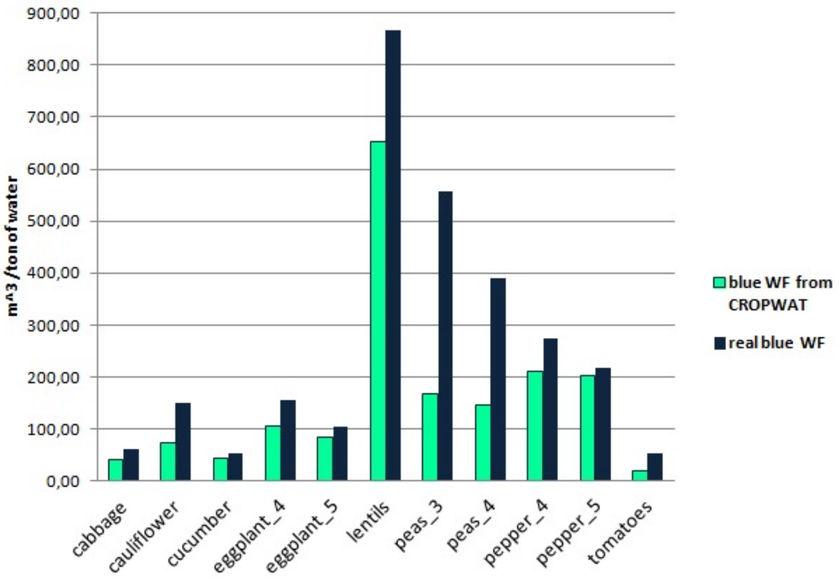

**Figure 6.3:** Comparison between real blue water footprint and blue WF calculated with CROPWAT (values calculated per each produced tonne of crop).

Observing figure 6.3, Al-Najar's (Al-Najar, 2011 [1]) thesis seems to be verified, because for all the cultivated crops the blue WF estimates on field data than the estimates with CROPWAT.

#### 6.1.1.3 *Grey water footprint of crops*

The obtained values of grey WF per produced tonne of different considered crops are shown in table 6.4. Aldaya et al. (2012) [2] suggests to calculate grey WF just for the most critical pollutant. In this case N is the most critical pollutant for the majority of crops, but values of grey WF related to other pollutants are not negligible, as it is shown in table 6.4. For this reason, a total grey WF is derived as the sum of the contributes of each fertilizer (it is shown in the last column of table 6.4). [1]

---

[1] The complete calculation is shown in the appendix A

| Crop type | Grey WF ($m^3/t$) | | | | |
|---|---|---|---|---|---|
| | NGrey WF | KGrey WF | PGrey WF | MgGrey WF | totGrey WF |
| cabbage | 6.67 | 26.67 | 53.33 | 0 | 3315 |
| cauliflower | 12 | 48 | 96 | 0 | 3315 |
| cucumber | 15.6 | 50 | 0 | 3.33 | 5270 |
| eggplant4 | 43 | 62.5 | 300 | 0 | 13787 |
| eggplant5 | 28.67 | 41.67 | 200 | 0 | 13787 |
| lentil | 0 | 0 | 0 | 0 | 0 |
| pea3 | 7.143 | 714, 29 | 142.86 | 0 | 5143 |
| pea4 | 5 | 500 | 100 | 0 | 5143 |
| pepper4 | 58 | 130 | 240 | 0 | 7276 |
| pepper5 | 46.4 | 104 | 192 | 0 | 7276 |
| tomato | 13.33 | 15.33 | 16.67 | 0 | 5780 |

**Table 6.4:** Annual grey WF per produced tonne of different crops: the total grey WF shown in the last column is derived as the sum of the the different contributes of each fertilizer shown in the first four columns.

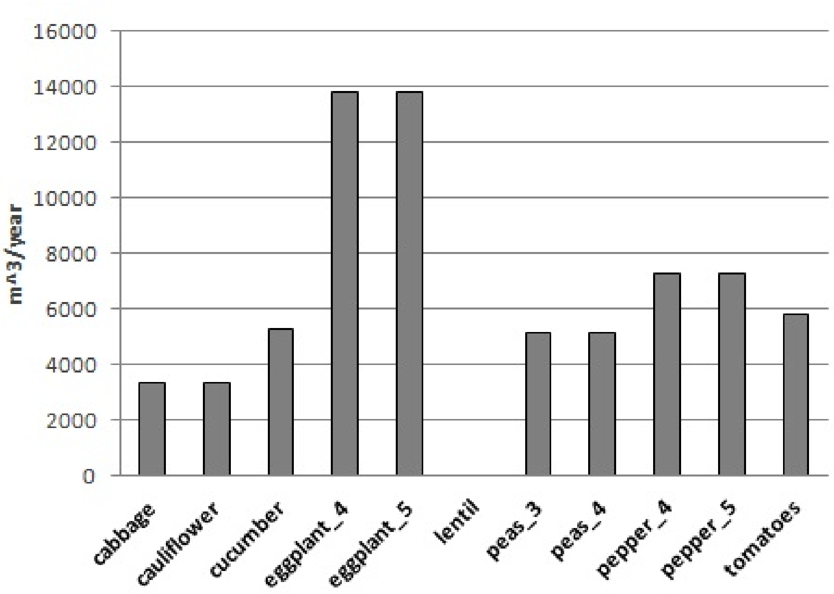

**Figure 6.4:** Annual value of grey WF for the different crops

Eggplant is the crop with the highest grey WF value, because it requires large amounts of nitrogen. On the contrary, lentil does not need fertilizers in this type of agricultural system (this could cause the low production rate), and consequently its related grey WF is equal to zero.

Table 6.5 resumes the WF estimates of crops (both direct and indirect contributions).

| Crop type | WF | $m^3/t$ direct | indirect |
|---|---|---|---|
| cabbage | Green | 28.7 | / |
| | Blue | 62.4 | 2.9 |
| | Grey | 86.7 | / |
| cauliflower | Green | 51.6 | / |
| | Blue | 149.7 | 6.11 |
| | Grey | 156 | / |
| cucumber | Green | 0 | / |
| | Blue | 52 | 2.32 |
| | Grey | 68.9 | / |
| eggplant | Green | 0.55 | / |
| | Blue | 130 | 4.95 |
| | Grey | 378 | / |
| lentil | Green | 507 | / |
| | Blue | 866.7 | 22 |
| | Grey | 0 | / |
| pea | Green | 129.7 | / |
| | Blue | 473.6 | 16.8 |
| | Grey | 734.65 | / |
| pepper | Green | 1.25 | / |
| | Blue | 245.7 | 8.7 |
| | Grey | 385.2 | / |
| tomato | Green | 0.06 | / |
| | Blue | 52 | 2.14 |
| | Grey | 45.3 | / |

**Table 6.5:** Direct and indirect WF of crops

#### 6.1.1.4 *WF of fish*

As explained in chapter 5, the WF of aquaculture activities take into account two components:

1. the first one is due to fish feed production; this feed is produced in Israel and its WF is considered as an indirect WF for the GS, because it does not directly exploits the gazian coastal aquifer water;
2. the second one concerns the necessity of pumping water from the aquifer to the pond to maintain a minimum water level for aquaculture; the water balance of the pond is affected by a high evaporation rate, especially during the dry season (from May to September).

The calculation of fish feed WF is obtained by summing up the WF of different ingredients. The specific WF for each ingredient referred to Israel are provided by Mekonnen and Hoekstra (2010) [25]. The WF estimates of ingredient and fish feed are shown in table 6.6 .

| Ingredient | **yellow corn** | **fishmeal** | **soy meal** | **corn oil** | **feedWF** | **feedWF$_{farm}$** |
|---|---|---|---|---|---|---|
| | $m^3/t_{ingr}$ | $m^3/t_{ingr}$ | $m^3/t_{ingr}$ | $m^3/t_{ingr}$ | $m^3/t_{feed}$ | $m^3/yr$ |
| green WF | 88 | 0 | 388 | 181 | 244 | 131 |
| blue WF | 455 | 0.374 | 1825 | 939 | 1169 | 631 |
| grey WF | 163 | 0 | 434 | 336 | 308 | 167 |

**Table 6.6:** WFof main fish feed ingredients ($m^3/t_{ingredient}$) produced in Israel, of tonne of fish feed produced ($m^3/t_{feed}$), and of the 540 kg yearly consumed in the standard farm ($m^3/yr$)

The second contribution to water consumption, concerning the maintenance of a minimum level of water in the pond, is obtained through a water balance. As explained in chapter 5, the minimum level in the pond ($min_{lev}$) is equal to 1600 mm (corresponding to a water volume of 80 $m^3$). Two terms contribute to the overall water requirement:

1. the first one considers the fact that the pond is empty at the beginning of April (it is due to the fact that during March the evaporation is higher than the rainfall) and it is necessary to fill it: 1600 mm of water are needed;
2. the second one depends on the difference between rainfall and evaporation during the aquaculture season (from April to December).

The total amount of water pumped from the aquifer is 373.6 $m^3/yr$, and the monthly amounts are shown in Figure 6.5.

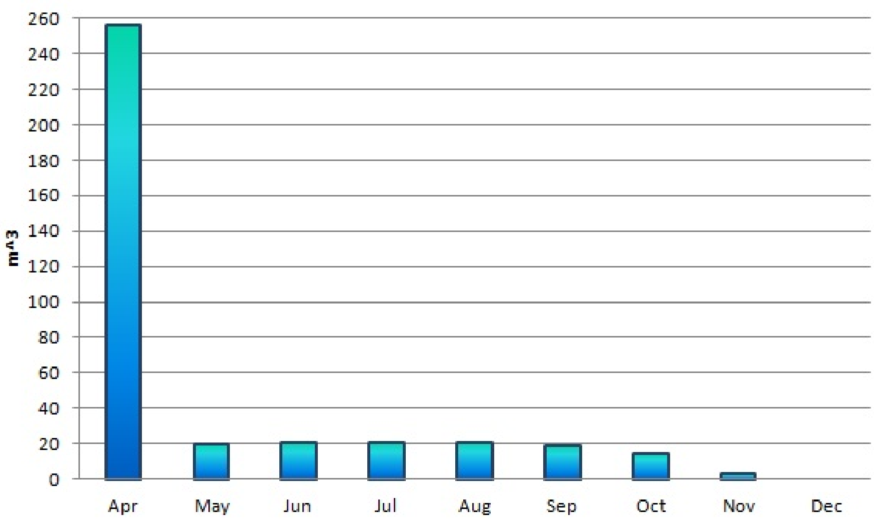

**Figure 6.5:** Amount of water pumped from aquifer to maintain the minimum level of water in pond to permit aquaculture, in $m^3$

### 6.1.1.5 *WFof sheep meat*

As explained in chapter 5, the sheep raised in the analyzed farm are fed only with grass and rain fed forage: for this reason the relevant WF is composed only by green water is equal to 923 $m^3/yr$. The blue WF only concerns the drinking water and is considered equal to the 2% of the total WF: the corresponding value is 18.8 $m^3/yr$.

### 6.1.1.6 *WF of chicken: meat and eggs*

As explained in chapter 5, the WF of chicken livestock take into account two components:

1. water consumption due to chicken feed production; this feed is produced in Israel and its WF is considered as 'indirect' WF because it does not directly exploits the coastal aquifer;
2. drinking water.

The calculation of chicken feed WF is obtained by summing up the different WF of ingredients. The necessary values of WF of ingredient referred to Israel are provided by Mekonnen and Hoekstra (2010) [25]. The WF estimates of ingredients and chicken feed are shown in table 6.7.

| Ingredient | **barley+roughages** | **oilmeal** | **sesame meal** | **feedWF** | **feedWF$_{farm}$** |
|---|---|---|---|---|---|
| | $m^3/t_{ingr}$ | $m^3/t_{ingr}$ | $m^3/t_{ingr}$ | $m^3/t_{feed}$ | $m^3/yr$ |
| green WF | 3033 | 1160 | 473 | 2521 | 1380 |
| blue WF | 0 | 6563 | 1374 | 1108 | 606 |
| grey WF | 685 | 534 | 107 | 610 | 334 |

**Table 6.7:** WFof main chicken feed ingredients ($m^3/t_{ingredient}$) produced in Israel, of tonne of fish feed produced ($m^3/t_{feed}$), and of the 547.5 kg yearly consumed in the standard farm ($m^3/yr$)

Drinking water is assumed to be about the 2% of the total blue WF and is equal to 12.3 $m^3/yr$ of water pumped from the aquifer. Table 6.8 resumes the WF estimates of animal products (both direct and indirect contributions)

| product | $m^3/t$ | | |
|---|---|---|---|
| | **WF** | **direct** | **indirect** |
| fish | Green | 0 | 243.6 |
| | Blue | 1556.7 | 1169 |
| | Grey | 0 | 308.4 |
| sheep meat | Green | 6593.2 | 0 |
| | Blue | 134.5 | 0 |
| | Grey | 0 | 0 |
| chicken meat | Green | 0 | 214.3 |
| | Blue | 1.9 | 94.2 |
| | Grey | 0 | 52.9 |
| egg | Green | 0 | 2395.6 |
| | Blue | 21.5 | 1052.7 |
| | Grey | 0 | 579.8 |

**Table 6.8:** Direct and indirect WF of animal products

### 6.1.2 *Comparison with data from the literature*

Mekonnen and Hoekstra (2010) [25] provide blue, green and grey WF of growing processes of crops in different countries. These include blue and green WF for the GS crops. Therefore, we compare our estimates with those reported by Mekonnen and Hoekstra (2010) for the GS, the surrounding countries and the world. Concerning the crops, the grey WF estimates related to the GS are not provided. The database regarding the animal products does not include data related to the GS. In table 6.9 and in table 6.10 the different WF values of crops and animals products in the GS are compared with the values of Lebanon, Israel and with a global average.

| Crop type | our estimates |  | Mekonnen and Hoekstra, 2010 |  |  |  |
|---|---|---|---|---|---|---|
|  | WF | GS | $\text{GS}_{\text{Mekonnen}}$ | **Lebanon** | **Israel** | **Global av.** |
| cabbage | Green | 28.7 | 20 | 38 | 46 | 181 |
|  | Blue | 62.4 | 83 | 104 | 118 | 26 |
|  | Grey | 86.7 | / | 137 | 98 | 73 |
| cauliflower | Green | 51.6 | 11 | 76 | 28 | 189 |
|  | Blue | 149.7 | 105 | 15 | 109 | 21 |
|  | Grey | 156 | / | 223 | 242 | 75 |
| cucumber | Green | 0 | 20 | 29 | 20 | 206 |
|  | Blue | 52 | 42 | 73 | 38 | 42 |
|  | Grey | 68.9 | / | 119 | 44 | 105 |
| eggplant | Green | 0.55 | 9 | 96 | 15 | 234 |
|  | Blue | 130 | 68 | 67 | 64 | 33 |
|  | Grey | 378 | / | 227 | 42 | 95 |
| lentil | Green | 507 | 1893 | 993 | 3548 | 4324 |
|  | Blue | 866.7 | / | 0 | 19852 | 489 |
|  | Grey | 0 | / | 0 | 0 | 1060 |
| pea | Green | 129.7 | 412 | 584 | 1251 | 1453 |
|  | Blue | 473.6 | / | 0 | 3563 | 33 |
|  | Grey | 734.65 | / | 0 | 0 | 493 |
| pepper | Green | 1.25 | 43 | 108 | 51 | 240 |
|  | Blue | 245.7 | 24 | 10 | 10 | 42 |
|  | Grey | 385.2 | / | 288 | 62 | 97 |
| tomato | Green | 0.06 | 25 | 43 | 25 | 108 |
|  | Blue | 52 | 46 | 46 | 26 | 63 |
|  | Grey | 45.3 | / | 109 | 33 | 43 |

**Table 6.9:** Comparison between our WF estimates related to crops and those reported by Mekonnen and Hoekstra (2010) for different countries

In general, the values obtained for WF are similar to the ones provided by Mekonnen and Hoekstra (2010) [25] for the GS. Note that the differences in growing periods may influence the values of green WF and consequently the blue water requirement. Moreover, since GS, Lebanon and Israel are located in the Middle East, which is a dry area characterized by low precipitations, the global average WF has an higher green WF values because it includes the WF of the countries with wetter climates and higher precipitation rates.

| Product | | $m^3/ton$ | | | |
|---|---|---|---|---|---|
| | **WF** | **GS** | **Lebanon** | **Israel** | **Global av.** |
| $\text{meat}_{\text{sheep}}$ | Green | 6593 | 6270 | 8343 | 9.8 |
| | Blue | 133 | 290 | 260 | 522 |
| | Grey | 0 | 48 | 42 | 76 |
| $\text{meat}_{\text{chicken}}$ | Green | 214 | 3067 | 1338 | 3.55 |
| | Blue | 96 | 1278 | 76 | 313 |
| | Grey | 52 | 329 | 138 | 467 |
| egg | Green | 2396 | 3010 | 3580 | 2.6 |
| | Blue | 1074 | 1264 | 197 | 244 |
| | Grey | 580 | 327 | 375 | 429 |

**Table 6.10:** Comparison between our WF estimates related to animal products and those reported by Mekonnen and Hoekstra (2010) for different countries

For fishes, values of WF are not provided by Mekonnen and Hoekstra (2010). Concerning the sheep meat, the value of WF estimated in this study is not completely representative because it involves only an extensive grazing system, and for this reason the blue WF is characterized by a lower value than other countries. Concerning chicken, meat hats lower WF than eggs, due to the fact that the main product if chicken are eggs and, consequently, most of resources are consumed by the animals to produce them.. In general, for eggs GS is characterized by values similar to Lebanon, which has similar climatic conditions and blue water availability. On the other hand, Israel has in general higher green WF, probably because the grazing systems are the most diffused in the country: Mekonnen and Hoekstra (2010) affirm that, generally, the grazing systems has a higher green WF than the industrial ones; on the other hand, the industrialized systems are characterized by a higher blue WF, mainly caused by concentrate feeds.

Finally, the WF values calculated for this case study are based on field data (e.g. irrigation) and for this work they should be more precise than the CROPWAT model estimation.

### 6.1.3 *Water footprint of alternative agricultural systems*

As explained in chapter 3, we consider five alternative crop rotation systems. The relevant WF values are by obtained summing up the different components of WF for each farm product. The results are shown in table 6.11.

| System | $m^3/yr$ | | | |
|---|---|---|---|---|
| | Green WF | Blue WF | Grey WF | Total WF |
| A | 1191 | 11012 | 11047 | 23250 |
| B | 2336 | 9024 | 18928 | 30287 |
| C | 3057 | 10747 | 15734 | 29537 |
| D | 3055 | 12206 | 22245 | 37506 |
| E | 3057 | 8759 | 10591 | 22406 |

**Table 6.11:** WF values for the different alternative agricultural systems held in the sample farm

The alternative E has the lowest blue, grey and total WF values; D has the highest values for the same components.

#### 6.1.3.1 *Water footprint vs protein production: comparison among the alternative systems*

Since one of the goals of our work was to asses food security, in particular the ability to satisfy an adequate protein supply, we analyze our results about the WF of different farming alternatives also in terms of protein production. Results are summarized in table 6.12 and present that alternative A is the most performing one in terms of WF per tonne of protein produced.

| **System** | WF ($m^3$) | Proteins (kg/yr) | ($m^3/kg_{protein}$) |
|---|---:|---:|---:|
| A | 23250 | 1946 | 11.9 |
| B | 30287 | 1895.1 | 16 |
| C | 29537 | 1583 | 18.6 |
| D | 37506 | 1609.5 | 23.3 |
| E | 22406 | 1277.1 | 17.5 |

**Table 6.12:** WF, protein content and WF per kg of protein produced by different crop rotation alternatives

Summarizing:

- the alternative A (animals,tomato and cucumber in greenhouse) is characterized by the lowest green WF, because the cultivations are covered by greenhouses and the total value of WF results only higher than alternative E (animals, lentil, three crops, lentil, cabbage and aggplant, in open field); on the other hand the blue WF is one of the highest, only lower than alternative D (animals, three crops, pea, caulifloer and eggplant, in openfield); the alternative E presents the lowest value of WF, especially of blue and grey WF, because lentil cultivation methods used in this system do not need neither an high amount of water (only 2000 $m^3/ha$) nor the application of fertilizers;
- the proteins production results the highest due to the high yield of involved crops (even though tomato and cucumber have a low protein contents).

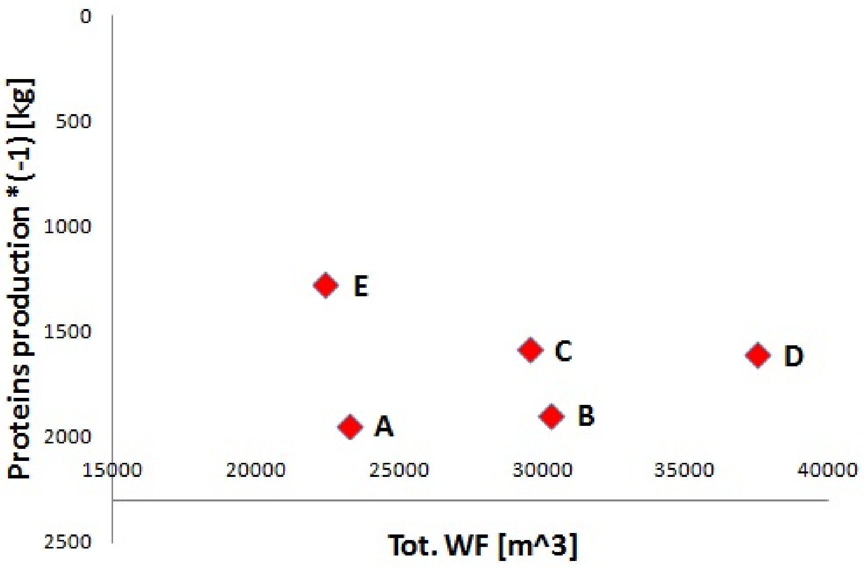

**Figure 6.6:** Pareto Front: comparison between water consumption and proteins production

Figure 6.6 shows the comparison among alternatives.

## 6.2 LCA OF AGRICULTURAL SYSTEM IN THE GAZA STRIP

In this study the LCA has the goal to compare the different alternative agricultural systems in terms of environmental impacts: both local and global impacts are considered with LCA. As said in chapter 2, the environmental sustainability is one of the most serious problems in the GS, together with food security and child mortality. In the previous analysis the only environmental aspects analyzed were water and land consumption. LCA allows to enlarge and complete the environmental analysis with other impacts categories: the alternative agricultural systems will be compared and ranked according to the different environmental indicator values. The characterization method used in this study is ReCiPe H in the two level Midpoint and Endpoint.

Observing the impact categories at the midpoint level (see figure 6.8), it emerges that alternative A (animals,tomato and cucumber in greenhouse) results has the highest impact values for the majority of the selected impact categories: it is mainly due to the high total fertilizers and pesticides application rates of tomatoes and cucumbers. Only for two categories alternative A does not present the highest impacts:

- for particulate matter formation: alternative D (animals, three crops, pea, caulifloer and eggplant, in openfield) is characterized by the highest impact due to high electricity consumed to pump water from aquifer needed by eggplants;

- ionizing radiation: the impact related to alternative C (animals, three crops, pea, cabbage and pepper, in openfield) results the highest due to peppers production,especially caused by fertilizers application.

In general impacts related to alternative B (two crops, pea and eggplant, in open field) result the lowest: it is mainly due to the facts that in this system is less intensive than the others because only two crops are raised during an agricultural year and there is a three-months period of rest for the agricultural soil. Moreover, the peas cultivated in this system does not need intense fertilization. The we redefine the impact category called 'water depletion', to make the results robust with those obtained with WF analysis: in figure 6.7 we only consider the blue WF of different alternative systems (this choice respect the ReCiPe methods, which only include the surface or groundwater consumed), while figure 6.8 we consider the total WF.

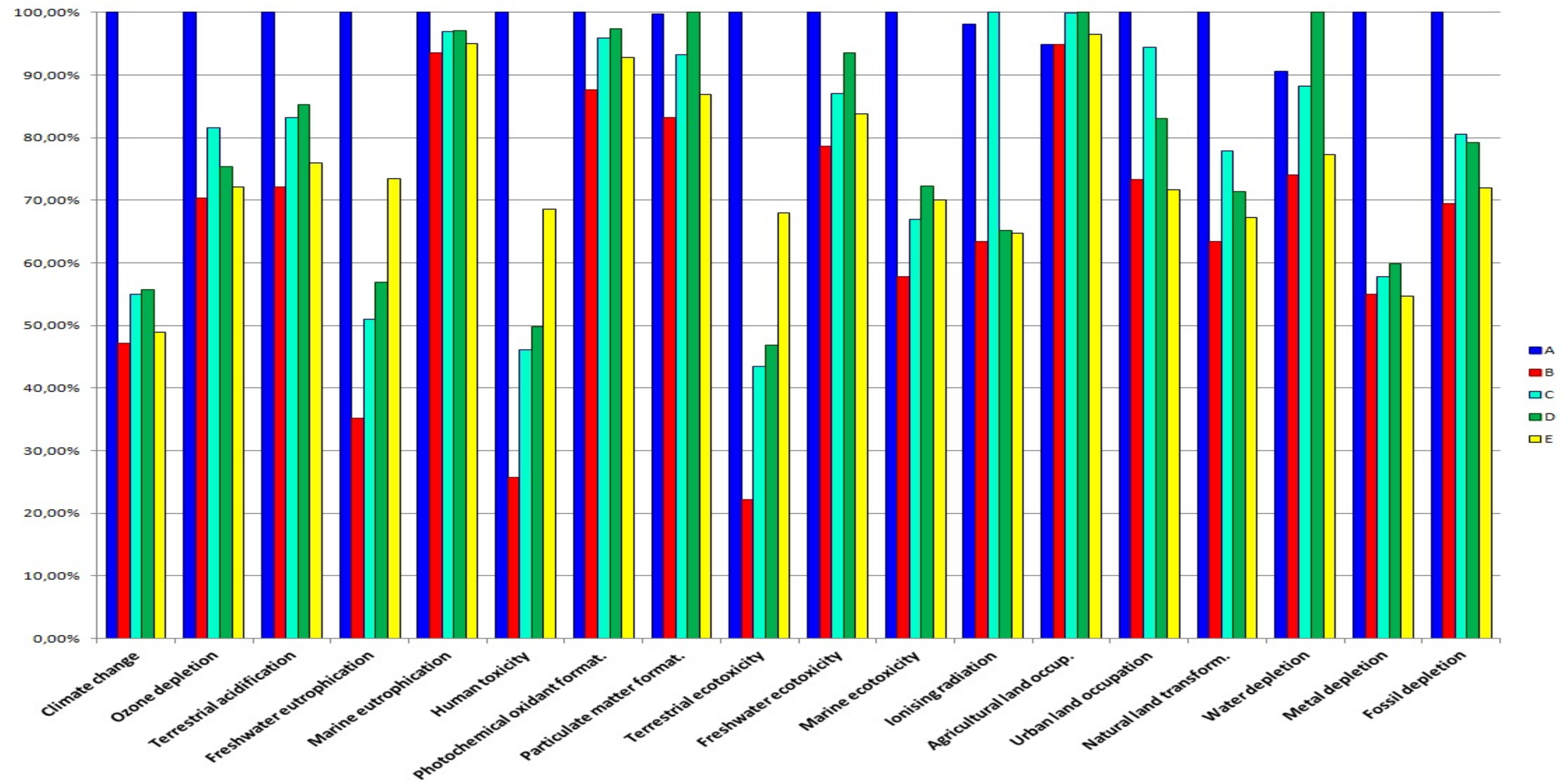

**Figure 6.7:** Comparison among different alternative systems using ReCiPe Midpoint H impact indicators. For the impact category 'water depletion', we consider only the blue WF

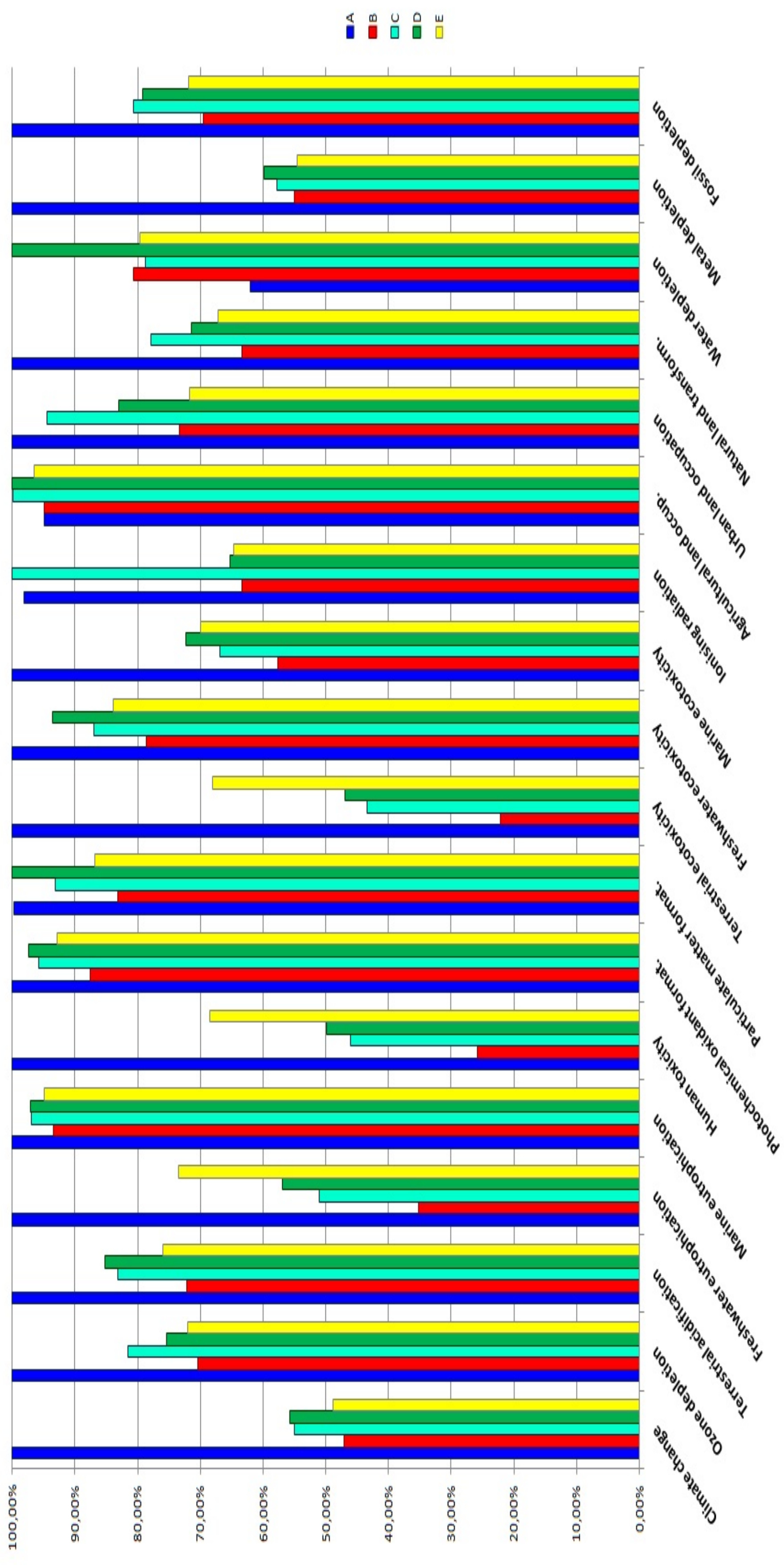

**Figure 6.8:** Comparison among different alternative systems using ReCiPe Midpoint H impact indicators. For the impact category ‘water depletion’, we consider the total WF.

Through characterization factors, the endpoints indicators are obtained from the midpoint ones.

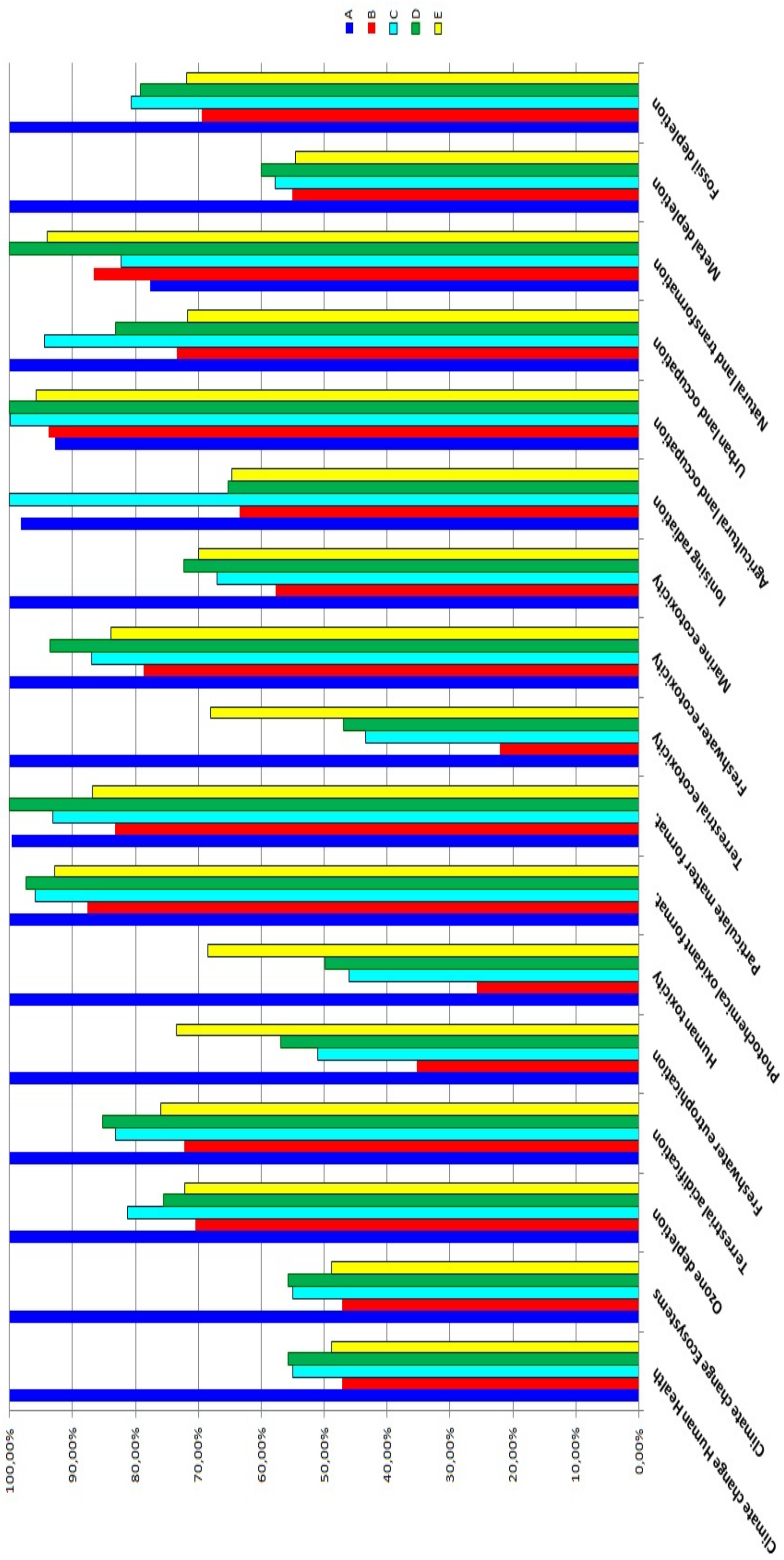

**Figure 6.9:** Comparison among different alternative systems using ReCiPe Endpoint H impact indicators.

Observing the results of endpoint level, only one indicator change from the midpoint level: it concerns the natural land transformation.

Finally, using World ReCiPe H/H weights, the single scores are obtained (see figure 6.10).

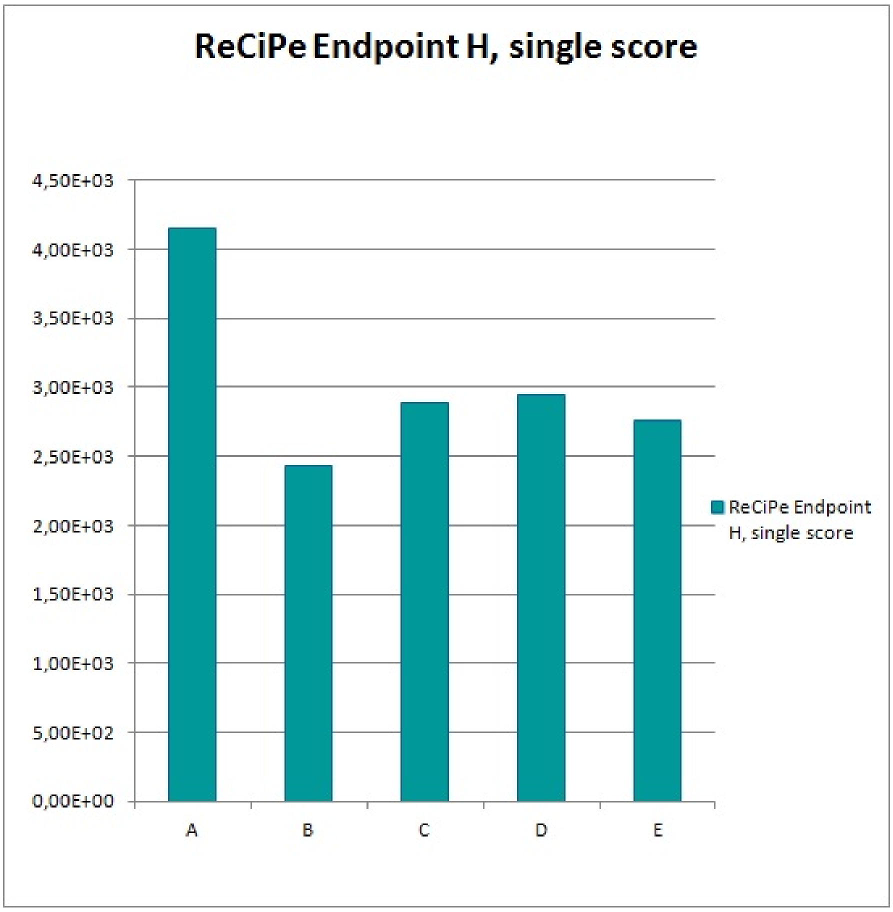

**Figure 6.10:** Comparison among different alternative systems using ReCiPe Endpoint H single scores.

The obtained single scores (figure 6.11) are half influenced by human health component and the rest is mainly influenced by resources consumption. The damages on ecosystem quality only represent the 5% of each single scores: this is the first difference between ReCiPe H single scores and the ones due to water consumption, by which the damages on ecosystem quality represents the 99% of each total score.

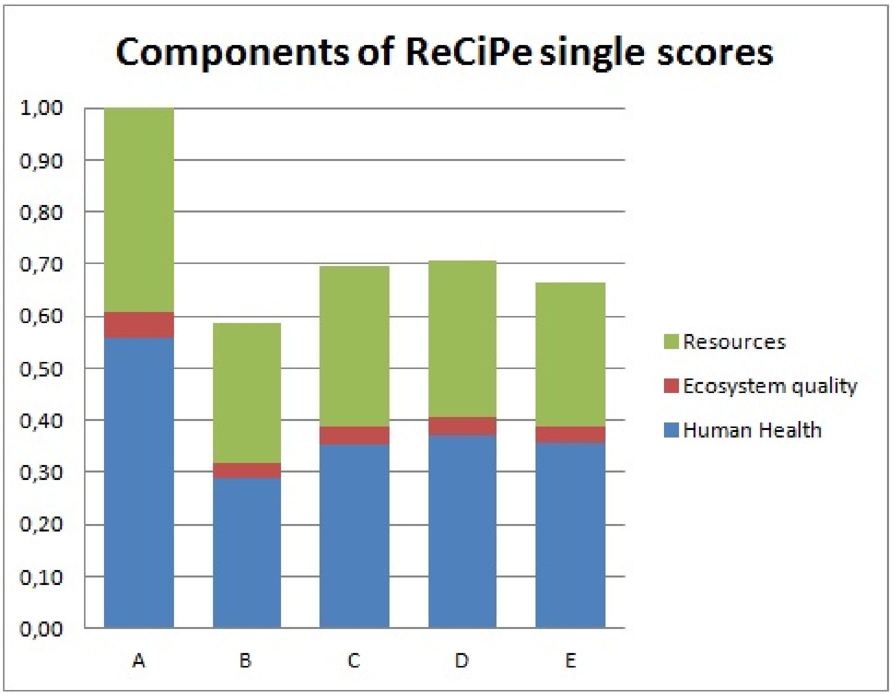

**Figure 6.11:** Percentages contribution of the three types of damage to ReCiPe Endpoint H single scores.

If we compare the single scores obtained from ReCiPe Endpoint H and the single scores due to water consumption in the GS (table 6.13), it emerges that the first ones are lower than the second (three order of magnitude), and the ranking of the different systems changes from the first to the second: alternative D is the worst in terms of damages caused by water consumption, and alternative E is the best; while alternative A is the worst for the damages obtained from ReCiPe method, and alternative B results the best. Moreover, the relative proportions among the different alternatives change from the first type of single scores to the second as shown in figure 6.12.

| system | Single scores | |
|---|---|---|
| | **Water Consumption** | **ReCiPe H** |
| Alternative A | $6.12 * 10^6$ | $4.16 * 10^3$ |
| Alternative B | $5.02 * 10^6$ | $2.43 * 10^3$ |
| Alternative C | $5.97 * 10^6$ | $2.89 * 10^3$ |
| Alternative D | $6.78 * 10^6$ | $2.94 * 10^3$ |
| Alternative E | $4.87 * 10^6$ | $2.76 * 10^3$ |

**Table 6.13:** Comparison between damage single scores obtained from ReCiPe Endpoint H and water consumption in the GS.

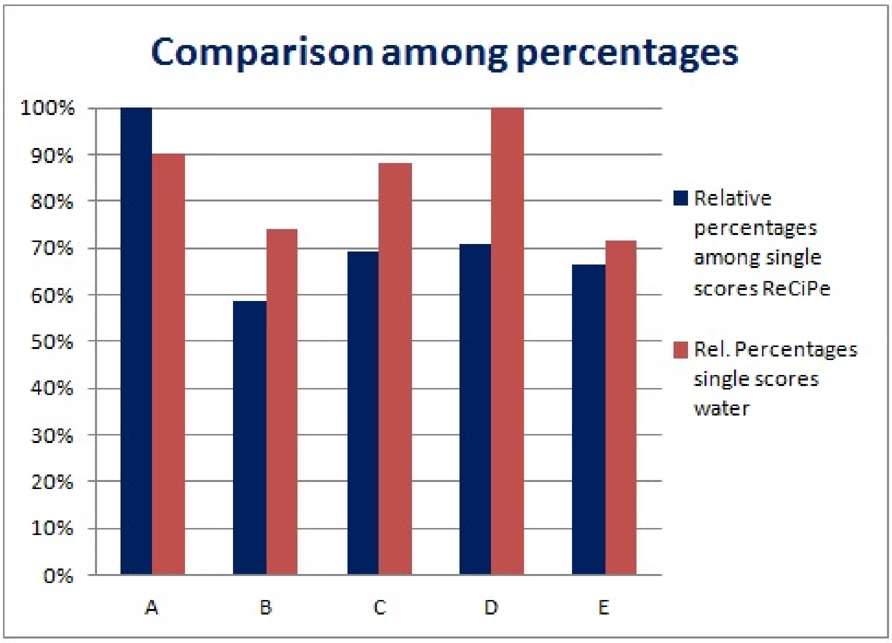

**Figure 6.12:** Comparison among different alternative systems using relative percentages.

The differences between these two methods suggest to implement both these two methods for damage calculation in cases like the GS, which are characterized by an arid climate and water scarcity.

## 6.3 ACHIEVING FOOD SECURITY IN THE GAZA STRIP: A PROTEIN BALANCE AT REGIONAL SCALE

In this section, we perform a regional-based balance of food production and resources exploitation, to test if food security a jointly analysis of the sustainability of resources exploitation and food production in the GS could be achieved by implementing the farming alternatives assessed in the previous sections to the whole agricultural land of the GS. Different simple scenarios are considered:

- BAU (without import-export); two period of time are analyzed: the actual situation and the future one (in 2020);
- protein requirement for the whole gazian population is achieved with one single product;
- Import-export scenario, built basing on required protein in the GS, to assess whether the food procurement changes and the water issue could improve with virtual water trade;

These preliminary scenarios are obviously strong semplifications and further analysis would be implemented.

### 6.3.1 *Business As Usual scenario*

#### 6.3.1.1 *BAU today*

As said in the presentation of the case study in chapter 3, the sample farm has an extension equal to about 9000 $m^2$, which is the average area of a farm in the Gaza Strip (PCBS, 2010). The whole agricultural area occupies the 62% of the whole GS and is equal to 225 $km^2$ (Dentoni, 2012 [12]), and can be occupied by 25000 'sample farms' (each having an area of 9000 $m^2$). To verify if these sample farms would be able to produce the entire amount of proteins required by the gazian population, respecting the average protein intake recommended by FAO, 20.5 kg/yr/person, and given the population in the Gaza Strip, 1763387 people, the total amount of protein required is $3.62*10^7$ $kg_{protein}/yr$. It is necessary to underline, that this analysis is made only for protein production, but a diet requires also other nutritional components like carbohydrates, fats and so on: that means that other natural resources are needed to produce an equilibrate diet in the GS. We followed this procedure:

- for each alternative, we estimate the total amount of proteins (taking into account the specif protein content of each crop and animal product) that would be produced if that alternative were implemented across the whole agricultural area of the GS;
- we compared results with the total amount of proteins that would be necessary to satisfy the protein intake recommended by FAO and calculated the corresponding protein surplus/deficit for each alternative; in case of deficit, the additional area that would be necessary to produce the missing amount of proteins is calculated (and compared with the area of the GS, es-

timating the equivalent Gaza Strips necessary to produce the required proteins amount);

- the total consumption of water required by each alternative system is assessed and compared with the annual groundwater availability, estimating the fraction of coastal aquifer which would be required to satisfy the water demand for protein production
- the same calculations are used to forecast the protein and water balance in 2020, assuming an increase in population (CIA, 2013 [8] and PCBS, 2010 [28] and a corresponding decrease in the availability of agricultural area; .

The total protein production of each alternative is shown in table 6.14.

| System | $kg_{protein}/yr$ | | |
|---|---|---|---|
| | 1 farm | 25000 farms | surplus/deficit |
| alternative A | 1946.1 | $4.87 * 10^7$ | $+1.24 * 10^7$ |
| alternative B | 1895.1 | $4.74 * 10^7$ | $+1.12 * 10^7$ |
| alternative C | 1584 | $3.96 * 10^7$ | $+3.4 * 10^6$ |
| alternative D | 1609.5 | $4.02 * 10^7$ | $+4.03 * 10^6$ |
| alternative E | 1277.13 | $3.19 * 10^7$ | $-4.28 * 10^6$ |

**Table 6.14:** Protein production in kg/yr: of a single farm and of the whole agricultural area for the different alternative systems; the third column show the deficit (negative numbers) or surplus (positive numbers) caused by the different scenarios for the total agricultural area in the GS and whether compared to FAO recommendations (20.5 $kg_{proteins}/yr$ per person)

The first four alternative systems would, in principle, satisfy the required protein production: the first one mainly produces tomatoes and cucumber, which have an high production rate per unit of area but a very low protein content. However, this would imply that each person should eat about 5 kg/day of tomatoes every day to achieve the recommended protein intake (table 6.15), which obviously does not make sense. Moreover, applying this type of system to the whole agricultural area in the GS would require to cover 225 $km^2$ with greenhouses, and consequently reduce the groundwater recharge due to infiltration of rainfall water. For the other alternatives, the cultivation of peas (B, C, and D) permits the achievement of 'food security' (pea provides more than 60% of annual protein) conditions in terms of proteins thanks to the relatively high protein content and the high production rate per unit area. However, also these alternatives imply that each person should eat more than 8 kg/day of vegetables (about 16 times more than the recommended intake (FAO) of about 0.4 kg/-day per person).

| Food | kg/pers/day | kg/pers/yr | Italy(kg/pers/yr) |
|---|---:|---:|---:|
| fish | 0.0093 | 3.4 | 25 |
| sheep meat | 0.0054 | 2 | 2 |
| chicken meat | 0.0006 | 0.2 | 18 |
| egg | 0.0063 | 2.3 | 13 |
| cucumber | 2.97 | 1084.6 | / |
| tomato | 4.95 | 1807.6 | / |

**Table 6.15:** Yearly and daily diet derived from alternative A (tomato and cucumber are cultivated in greenhouse) for each people in the GS to achieve the recommended protein intake by FAO. The values related to Italy are reported to have a criterion for comparison (for vegetables the overall value is about 70 kg/yr/person).

For the last alternative, which does not satisfy the protein demand due to the low production rate per unit of area of lentils, much area would be occupied and consequently more agricultural fields would be needed: about 300 $km^2$ of agricultural field are needed, which correspond to more than 80% of the whole territory of the GS. This increment of agricultural area means that some urbanized area would be occupied by farms ( from 62% to 82% of the total GS area), and the corresponding farms are 28,348: the displacement of about 200,000 people from these areas to remaining urban areas would increase urban density, which is already one of the highest in the world.

Table 6.16 shows the total WF that would correspond to each alternative and the relevant fraction of the Gaza coastal aquifer that would be necessary to satisfy the corresponding water demand. Note that only the freshwater is considered, not the fossil aquifer, and it is equal to 60 millions $m^3$/year of freshwater.

| System | farm WF | Gaza WF | aquifer fraction |
|---|---|---|---|
| | $m^3/yr$ | $m^3/yr$ | % |
| alternative A | 23411 | $5.85 * 10^8$ | 975 |
| alternative B | 30448 | $7.61 * 10^8$ | 1370 |
| alternative C | 29698 | $7.42 * 10^8$ | 1240 |
| alternative D | 37667 | $9.42 * 10^8$ | 1570 |
| alternative E | 22567 | $5.64 * 10^8$ | 940 |

**Table 6.16:** Water consumption of BAU scenario: total WF and equivalent freshwater aquifers

The obtained values show that none of the agricultural systems considered would be sustainable in terms of water consumption: the hydrological resources, consisting in the coastal aquifer, are not sufficient to achieve food security and they would be depleted within a short period of time. The same assessment is performed only considering blue WF, instead of total WF, and the results show (see table 6.17) that, neither in this case, the water consumption of considered agricultural systems would not be sustainable.

| System | farm blue WF | Gaza blue WF | equivalent aquifer |
|---|---|---|---|
| alternative A | 11012 | $2.75 * 10^8$ | 4.59 |
| alternative B | 9024 | $2.26 * 10^8$ | 3.76 |
| alternative C | 10747 | $2.69 * 10^8$ | 4.48 |
| alternative D | 12206 | $3.05 * 10^8$ | 5.09 |
| alternative E | 8759 | $2.19 * 10^8$ | 3.65 |

**Table 6.17:** Blue water consumption of BAU scenario: blue WF and equivalent freshwater aquifers

From this first step on the whole territory of the GS it can be concluded that:

- applying the alternative sample farms on the whole agricultural land in the GS, the yearly required amount of proteins for the Gazians could not provide the required amount of proteins: the derived diet for local people is not realistic, because it presents a excessive portion of vegetables (16 times bigger than the vegetable portion recommended by FAO);
- in general, the natural resources in the GS cannot be used in a sustainable way in order to provide the necessary proteins for

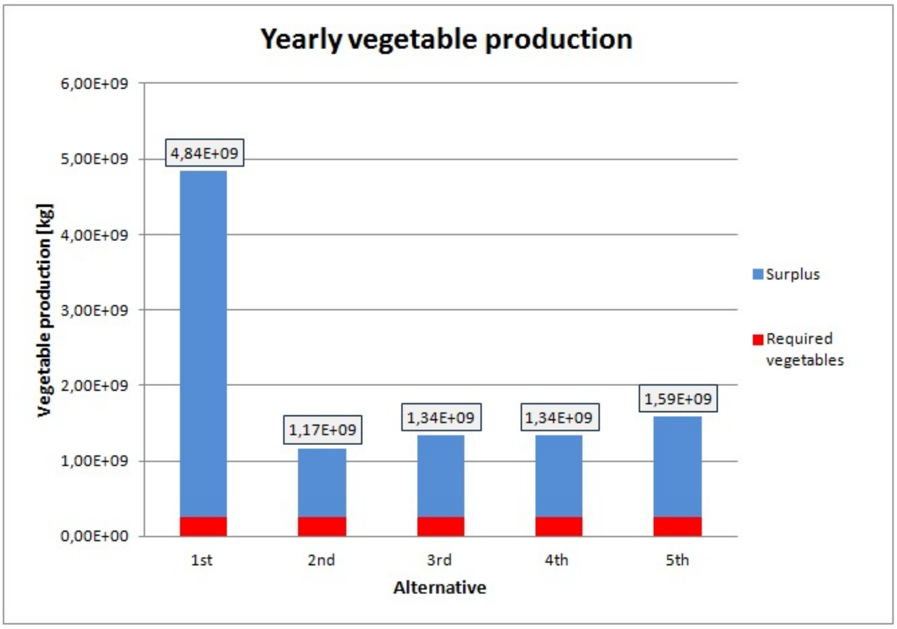

**Figure 6.13:** Yearly vegetables production in kg/year: the red part is the yearly vegetables requirement for the whole population of the Gaza Strip; The blue part is the annual surplus od vegetables and the whole bar (red and blue) represents the effective annual production of vegetables of the different alternative systems (the total amount is shown by labels)

its population: since the estimations on freshwater availability affirm that the annual freshwater recharge is between 60 and about 180 $m^3$ millions of water per year, the water available for all the necessities (from domestic use to food production) per gazian goes from 34 to 100 $m^3$ per capita per year; the analyzed systems present water consumptions included between about 250 and 480 $m^3$ per fed person just for producing proteins,which is higher than the estimated per capita availability;

Other nutrients are simply considered. In particular, all the analyzed agricultural systems can achieve the recommended yearly vegetable intake for the whole gazian population: FAO recommends a portion of 400 g of vegetable per day. In figure 6.13 the different yearly crop productions in theGS are plotted, and all the alternative systems can provide more than the required amount of vegetables for the population in the GS.

Furthermore, a simple consideration about carbohydrates is made: FAO affirms that 60% of daily kcal should come from carbohydrates: Assuming an average daily kcal requirements of 2200 kcal, 1320 kcal should come from carbohydrates. Two of the major crops raised in the GS are wheat and barley. Given the energetic contents of 3400 kcal/kg and 3380 kcal/kg and the yields (FAOSTAT, 2011) of 1621.5 kg/ha and 1391 kg/ha, respectively for wheat and barley, the needed areas for producing required carbohydrates for gazian population are 1541 ha (4.2 equivalent GS) and 1807 ha (5 equivalent GS) respectively. In general, it could be concluded that the natural resources of the GS (in particular water and land) are not sufficient for the procurement of the necessary nutrients for a balanced diet for its population: this is only a first supposition, and further more detailed analysis are required.

### 6.3.1.2 *BAU in 2020*

Given a rate of urbanization of 3.3% (CIA, 2013 [8]), the future situation will be more critical than the actual one. In 2008, the urban population was about 72% (CIA, 2013 [8]) and each year it will increase by 3.3%: that means that in 2020 the population will be more than 2.10 million and 77% of it will live in urbanized area. This will cause an increment of proteins requirement from 36 million kg/yr to more than 43 million kg/yr and the portion of land dedicated to agricultural activities and the number of farms will be reduced ( 196 $km^2$, corresponding to the 54% of the GS area, and 21750 farms) and replaced by urban areas: the urbanized areas will more than double (+107.5%, Hamad et al., 2012 [19]), and due to this land use change also the available water resources will be reduced (Hamad et al., 2012 [19]). All these changes will influence the protein balance in the GS as shown in table 6.18. Only alternatives C and D can satisfy the proteins demand thanks to the high production per unit of area and to the high protein content of peas.

| System | kg/yr | | |
|---|---|---|---|
| | 1 farm | 21750 farms | surplus/deficit |
| alternative A | 1946.1 | $4.23 * 10^7$ | $-8.31 * 10^5$ |
| alternative B | 1895.1 | $4.12 * 10^7$ | $-1.94 * 10^6$ |
| alternative C | 1584 | $3.45 * 10^7$ | $-8.71 * 10^6$ |
| alternative D | 1069.5 | $3.50 * 10^7$ | $-8.15 * 10^6$ |
| alternative E | 1277.1 | $2.78 * 10^7$ | $-1.54 * 10^7$ |

**Table 6.18:** Protein production in kg/yr in 2020: of a single farm and of the whole agricultural area for the different alternative systems

Due to the deficit of proteins production, for all the alternatives much area would be needed to achieve the required amount of proteins as shown in table 6.19.

| **System** | area required[kmq] | % of GS area |
|---|---|---|
| alternative A | 199.6 | 55 |
| alternative B | 205 | 56 |
| alternative C | 245.2 | 67 |
| alternative D | 241.3 | 66 |
| alternative E | 304.1 | 83 |

**Table 6.19:** Area required to achieve the recommended amount of proteins for all the alternatives, and the relative portion of the Gaza Strip territory (in 2020 the agricultural area is assumed to be about 196 $km^2$, corresponding to the 54% of the total GS area)

Concerning water consumption, the situation cannot be quantified because precise estimations of water availability in 2020 do not exist, but it would be worse than today because, even though the water consumption for food production will decrease due to the reduction of agricultural area, the freshwater availability will be less than actual one. Generally, in the future natural resources the GS would become scarcer than today: even the agricultural land would be not sufficient to produce the necessary proteins for the Gaza population.

### 6.3.2 *One-product protein procurement*

This analysis is made on each single product of the sample farm in order to verify if a/some product can provide the required proteins without depleting the freshwater resources: the proteins production is fixed and it is equal to the recommended protein intake for the whole population of the GS (36 millions $kg_{proteins}$) and this amount will be produced with each one of the analyzed farm products. For each product land and water consumption needed for the whole protein production are estimated to compare the different products. Table 6.20 shows the needed area [ha] to produce the required proteins amount, the corresponding equivalent GS and the production of proteins per unit of area [kg/ha], which quantify the efficiency in protein production in terms of land use. For terrestrial animals the land occupation for each head is provided by FAO and it is respectively 2.5 $m^2$/ewe for sheep and 0.34 $m^2$/chick for chicken.

| System | needed area | equivalent GS | Protein per unit of area |
|---|---|---|---|
| | [ha] | n° | [kg/ha] |
| fish | 11314 | 0.31 | 3200 |
| $\text{meat}_{\text{sheep}}$ | 3771 | 0.1 | 9600 |
| $\text{meat}_{\text{chicken}}$ | 10528 | 0.28 | 3529 |
| egg | 1027 | 0.03 | 35259 |
| cabbage | 73140 | 2 | 495 |
| cauliflower | 111399 | 3.05 | 325 |
| cucumber | 67045 | 1.84 | 540 |
| eggplant4 | 82283 | 2.25 | 440 |
| eggplant5 | 54844 | 1.50 | 660 |
| lentil | 77360 | 2.12 | 468 |
| pea3 | 35184 | 0.96 | 1029 |
| pea4 | 24628 | 0.67 | 1470 |
| pepper4 | 150852 | 4.13 | 240 |
| pepper5 | 120682 | 3.31 | 300 |
| tomato | 21942 | 0.6 | 1650 |

**Table 6.20:** Land consumption for production of required proteins amount from each farm product; in particular, the shown elements are: the total needed area to produce the total amount of required proteins [$m^3$/yr], the corresponding equivalent GS, and the amount of proteins produced in a unit of area [kg/ha]

Concerning land consumption, from the results shown in table 6.20 fishes from aquaculture result less efficient (lowest proteins production per unit of area) than other animal products. Even if the required area for each fish is lower then the one for sheep and chicken, due to the lower weight of fish, the proteins production per ha results the lowest. Moreover, extending aquaculture means waterproofing the soil and reducing the groundwater recharge from rainfall. The best product are the chicken egg thanks to the high production rate. Concerning vegetables, the best crop results pea4: fresh pea in general presents an high protein content (14.7%, lower only than the one of lentil) and also a good production rate (5 - 8 times higher than lentil). Tomatoes are ranked as third because they have the highest production rate; but due to their low protein content, it is necessary eating more than 6 kg of tomatoes per day to achieve the recommended proteins intake.

Table 6.21 shows the needed volume of water ($m^3$/yr) to produce the required proteins amount, the corresponding equivalent coastal aquifers, the $m^3$ consumed per each kg of proteins produced, and the production of proteins per $m^3$ consumed ($kg/m^3$), which quantify the efficiency in protein production in terms of water consumption.

| System | WF | equivalent aquifers | water consumed/kg | Proteins per $m^3$ |
|---|---|---|---|---|
| | $[m^3/yr]$ | n° | $[m^3/kg/yr]$ | $[kg/m^3]$ |
| fish | $2.82 * 10^8$ | 4.7 | 7.8 | 0.13 |
| $\text{meat}_{\text{sheep}}$ | $2.59 * 10^6$ | 0.68 | 1.1 | 0.89 |
| $\text{meat}_{\text{chicken}}$ | $2.11 * 10^7$ | 0.4 | 0.6 | 1.71 |
| egg | $2.28 * 10^7$ | 0.4 | 0.6 | 1.59 |
| cabbage | $2.05 * 10^8$ | 3.4 | 5.7 | 0.18 |
| cauliflower | $4.17 * 10^8$ | 7 | 11.5 | 0.09 |
| cucumber | $3.14 * 10^8$ | 5.2 | 8.7 | 0.12 |
| eggplant4 | $5.13 * 10^8$ | 8.6 | 14.2 | 0.07 |
| eggplant5 | $3.42 * 10^8$ | 5.7 | 9.5 | 0.11 |
| lentil | $1.21 * 10^8$ | 2 | 3.3 | 0.3 |
| pea3 | $6.42 * 10^7$ | 2.29 | 3.3 | 0.3 |
| pea4 | $9.17 * 10^7$ | 1.6 | 3.8 | 0.26 |
| pepper4 | $8.24 * 10^8$ | 13.7 | 22.8 | 0.04 |
| pepper5 | $6.59 * 10^8$ | 11 | 18.2 | 0.05 |
| tomato | $1.71 * 10^8$ | 2.9 | 4.7 | 0.21 |

**Table 6.21:** Water consumption for production of required proteins amount from each farm product; in particular, the shown elements are: the total yearly water volume consumed to produce the total amount of required proteins $[m^3/yr]$, the corresponding equivalent coastal aquifer, the water consumed for producing each kg of proteins $[m^3/kg/yr]$, and the amount of proteins produced with a $m^3$ of water consumed $[kg/m^3]$

In this analysis only blue water consumption in considered. From the values shown in table 6.21, aquaculture is characterized by the least efficient proteins production per $m^3$ of blue water consumed (only 0.13 $kg/m^3$) among animals products. Chicken meat results the most efficient, due to the fact that a small allocation factor based on produced amount is applied to this product: 91.5% of water consumed to raise chicken is allocated to egg, only 8.5% to meat. Concerning the crops, the pea3 are characterized by the best production of proteins per $m^3$ of consumed blue water. Apart from pulses (peas and lentils), tomato and cucumber present are relatively high protein production rate due to their high yields.

From this analysis on single products general conclusions can be deduced:

1. aquaculture does not seem to be a good investment both for natural resources consumption (land and water) and for protein production;
2. among the crops, peas are characterized by the highest efficiency in natural resource consumption for producing proteins;
3. terrestrial livestock could result a sustainable solution in producing proteins in the GS; it is necessary to remind that the analyzed livestock systems are not intensive but grazing ones, and the increment of production would need and industrialization of processes with consequent increase of water use.

### 6.3.3 *Trading based on protein demand*

Given the surplus of produced vegetables shown in figure 6.13, a scenario import-export system is introduced: it is assumed that the whole amount of animal products and the recommended portion of vegetables (0.4 kg/person/day) are consumed by Gazians, and the surplus of vegetables is exported. The total protein obtained from animal products 2114550 $kg_{proteins}/yr$, which corresponds to the 6% of the total proteins requirement. The total annual amount of vegetables for Gazians is $2.57 * 10^8$ $kg_{vegetables}/yr$, and the proteins obtained are shown in table 6.22. The vegetable proteins come from tomatoes for alternative A, peas and eggplants for system B, peas and peppers for system C, peas and cauliflowers for system D and lentils and eggplants for system E (the choice is made selecting vegetables with higher protein contents).

| System | kg/yr | | |
|---|---|---|---|
| | **Proteins from VEG** | **TOT proteins (veg+anim)** | **deficit** |
| alternative A | $2.83 * 10^6$ | $4.95 * 10^6$ | $-3.12 * 10^7$ |
| alternative B | $2.31 * 10^7$ | $2.52 * 10^7$ | $-1.1 * 10^7$ |
| alternative C | $2.32 * 10^7$ | $2.53 * 10^7$ | $-1.09 * 10^7$ |
| alternative D | $2.33 * 10^7$ | $2.54 * 10^7$ | $-1.08 * 10^7$ |
| alternative E | $1.24 * 10^7$ | $1.45 * 10^7$ | $-2.17 * 10^7$ |

**Table 6.22:** Blue water consumption of BAU scenario: blue WF and equivalent freshwater aquifers

We can observe that the alternative A has the highest protein deficit, because tomato and cucumber has a low protein content, while the alternative producing pea has the lowest deficit.

To analyze the farm products in an economic perspective, we need the crop prices: they are shown in table 6.23 (PCBS, 2010 [28].

| Crop type | Price ($/kg) |
|---|---|
| cabbage | 0.67 |
| cauliflower | 0.71 |
| cucumber | 0.62 |
| eggplant4 | 0.69 |
| eggplant5 | 0.69 |
| pea3 | 1.78 |
| pea4 | 1.78 |
| pepper4 | 1.38 |
| pepper5 | 1.38 |
| tomato | 0.84 |

**Table 6.23:** Prices of different crops ($)

With the sell of the surplus of vegetables a certain profit is earned (see Table 6.24).

| system | crop | sold amount | profit |
|---|---|---|---|
| | | [kg] | [$] |
| Alternative A | Cucumber | $1.91 * 10^{9}$ | $1.19 * 10^{9}$ |
| | Tomato | $2.93 * 10^{9}$ | $2.46 * 10^{9}$ |
| | eggplant4 | $1.23 * 10^{9}$ | $8.53 * 10^{8}$ |
| Alternative B | Cabbage | $9.56 * 10^{8}$ | $6.37 * 10^{8}$ |
| Alternative C | pepper4 | $3.16 * 10^{8}$ | $4.37 * 10^{8}$ |
| Alternative D | Cauliflower | $4.23 * 10^{8}$ | $3.01 * 10^{8}$ |
| | eggplant4 | $8.50 * 10^{8}$ | $5.89 * 10^{8}$ |
| Alternative E | Cabbage | $9.56 * 10^{8}$ | $6.37 * 10^{8}$ |
| | eggplant4 | $6.31 * 10^{8}$ | $4.37 * 10^{8}$ |

**Table 6.24:** Amount of vegetables sold (kg/year) in the different alternatives and the earned profit ($)

Basing on proteins import demand, this scenario is characterized by the purchase of the amount of proteins needed to achieve the annual recommended proteins intake. These imported proteins are provided half by beef and half by wheat flour: they are chosen because, in the Business As Usual (BAU) scenario, no cereals are cultivated and because the meat portion per person provided with the analyzed agricultural systems is not sufficient (the recommended annual intake is about 130 kg per person, and the BAU scenario only provides about 2 $kg_{meat}$). Table 6.25 shows price (PCBS, 2010 [28]), protein content (FAO, 1953 [14]) and recommended portion of beef and flour (FAO, 1953 [14]).

| characteritic | Unit | Beef | Flour |
|---|---|---|---|
| Price | $/kg | 13.3 | 0.6 |
| Protein content | % | 15 | 12 |
| Recommended portion | kg/week/person | 0.35 | 1.35 |

**Table 6.25:** Flour and beef: price ($/kg), protein content (%) and recommended portion (kg/week/person)

Since the protein deficit is fixed, and the 50% is provided by beef and 50% by flour, we calculated the deriving amount of beef and flour, and their consequent weekly portions (see table 6.26).

| system | beef | wheat flour | beef | wheat flour |
|---|---|---|---|---|
| Alternative A | $1.04 * 10^8$ | $1.30 * 10^8$ | 1.13 | 1.42 |
| Alternative B | $7.68 * 10^6$ | $9.60 * 10^6$ | 0.08 | 0.10 |
| Alternative C | $3.62 * 10^7$ | $4.53 * 10^7$ | 0.39 | 0.49 |
| Alternative D | $3.59 * 10^7$ | $4.48 * 10^7$ | 0.39 | 0.49 |
| Alternative E | $7.23 * 10^7$ | $9.03 * 10^7$ | 0.79 | 0.99 |

**Table 6.26:** Amount of beef meat and wheat flour imported in the fourth scenario based on protein import demand (kg/yr), and obtained weekly portions of imported products (kg/pers/week).

Observing the deriving portions, for the beef, the portions obtained with alternatives C and D are similar to the recommended one; alternatives A and E provide exceeding the 0.35 kg/week per person, while alternative B provide a low portion of beef. Concerning the flour, only alternative A provides a portion similar to the recommended one, while the portions obtained from all other alternatives are lower than the recommended 1.35 kg/week per person. Consequently we assess the necessary amount of money to buy the needed amounts of beef and flour. The results are shown in table 6.27.

| **system** | **Purchase [$]** |
|---|---|
| Alternative A | $1.49 * 10^9$ |
| Alternative B | $1.08 * 10^8$ |
| Alternative C | $5.09 * 10^8$ |
| Alternative D | $5.04 * 10^8$ |
| Alternative E | $1.02 * 10^9$ |

**Table 6.27:** Money ($) spent to buy beef meat and wheat flour obtained in the fourth scenario of purchase of both beef and flour.

Since the necessary money are lower than those earned with the surplus of vegetable of BAU scenario , a new production system is obtained (see table 6.28): it is characterized by a reduction of exported crop amounts.

| system | crop | inner consumption | export | total production |
|---|---|---|---|---|
| | | [kg] | [kg] | [kg] |
| Alternative A | Cucumber | 0 | $2.99 * 10^8$ | $2.99 * 10^8$ |
| | Tomato | $2.57 * 10^8$ | $8.25 * 10^8$ | $1.08 * 10^9$ |
| Alternative B | pea4 | $2.13 * 10^8$ | 0 | $2.13 * 10^8$ |
| | eggplant5 | $4.5 * 10^7$ | $7.48 * 10^7$ | $1.20 * 10^8$ |
| Alternative C | Cabbage | 0 | $2.01 * 10^8$ | $2.01 * 10^8$ |
| | pepper4 | $1.09 * 10^8$ | $2.86 * 10^8$ | $3.95 * 10^8$ |
| | peas3 | $1.49 * 10^8$ | 0 | $1.49 * 10^8$ |
| Alternative D | Cauliflower | $1.09 * 10^8$ | $1.21 * 10^8$ | $2.30 * 10^8$ |
| | eggplant4 | 0 | $2.31 * 10^8$ | $2.31 * 10^8$ |
| | peas3 | $1.49 * 10^8$ | 0 | $1.49 * 10^8$ |
| Alternative E | Cabbage | 0 | $4.01 * 10^8$ | $4.01 * 10^8$ |
| | eggplant4 | $2.19 * 10^8$ | $2.87 * 10^8$ | $5.06 * 10^8$ |
| | lentil | $3.83 * 10^7$ | 0 | $3.83 * 10^7$ |

**Table 6.28:** New production system based on proteins demand

Focusing on protein procurement and its impacts, we want to assess whether the reduced crop production in the GS and the consequent reduction in water consumption could make the different agricultural systems scenarios sustainable in terms of water consumption. Given the values of different components of WF for the different farm products in $m^3/ton$, the different values of total WF and its components for different alternative systems in the new production scenario are assessed. The proteins procurement of alternative A is the most influenced by importation, because it has the lowest inner proteins production (due to the low proteins contents of cucumber and tomatoes): the reduction in exportation highly affect the water consumption of this type of system, because it is characterized by an high crop production and reduction rate is higher than other alternatives. For these reasons the WF of alternative A result the lowest.

Assuming that the annual fresh groundwater recharge is equal to $60 * 10^6\ m^3/year$ (PWA, 2012 PWA) none of the considered alternative result sustainable if referred to GS water resources. But if we consider an annual fresh groundwater recharge of $102 * 10^6\ m^3/year$, which is the lowest value estimated by Dentoni (2012 [12]), some alternatives (A and B) result sustainable in terms of blue WF as shown in table 6.29. Obviously, if the upper limit of water availability estimated by Dentoni (2012 [12]) is taken into account, the results improve: in terms of blue water, also alternatives D and E result sustainable; alternative A results sustainable also in terms of total WF.

| **system** | **TOTWF($m^3$/yr)** | **BlueWF$m^3$/yr** |
|---|---:|---:|
| Alternative A | $-1.11 * 10^7$ | $3.02 * 10^7$ |
| Alternative B | $-1.82 * 10^8$ | $6.67 * 10^6$ |
| Alternative C | $-6.08 * 10^8$ | $-1.47 * 10^8$ |
| Alternative D | $-3.41 * 10^8$ | $-5.14 * 10^7$ |
| Alternative E | $-3.14 * 10^8$ | $-3.51 * 10^7$ |

**Table 6.29:** Evaluation of sustainability of water consumption of the different agricultural production systems, assuming an annual freshwater recharge of $102 * 10^6\ m^3/year$: if the value is negative (deficit) the protein production from that alternative is not sustainable, while if it is positive the alternative is sustainable

Finally, a balance between imported and exported water contained in the products, the so 'called virtual water trade', is assessed. With this analysis we can evaluate whether trade flows are advantageous or not in terms of water contained into products. Assuming that beef and flour are imported from the surrounding countries, we averaged the WF values of beef and wheat flour related to Israel, Lebanon and Egypt: the obtained values are shown in table 6.30.

| **Product** | **Green WF** | **Blue WF** | **Grey WF** |
|---|---:|---:|---:|
| Beef | 20490 | 1917 | 952 |
| Wheat flour | 1307 | 345 | 279 |

**Table 6.30:** Flour and beef water footprint values ($m^3$)(average among Israel, Lebanon and Egypt)

The results virtual water balance are shown in figure 6.14 (the complete calculation is shown in chapter C).

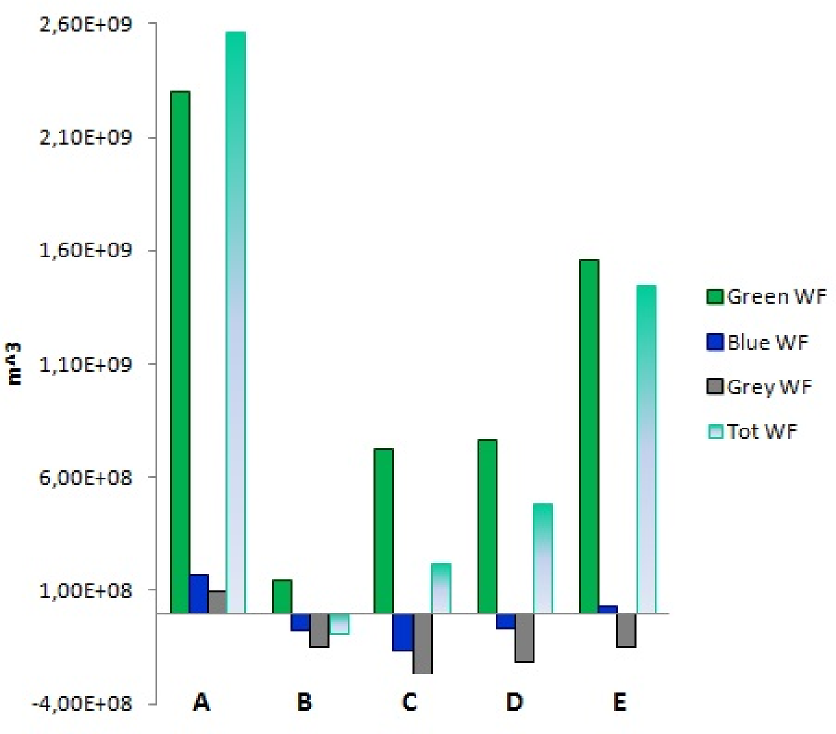

**Figure 6.14:** Balance between exported and imported virtual water ($m^3$)

The balance of virtual water for all the considered alternatives is advantageous for the GS in terms of total WF: this is mainly due to the high green water amount imported from other countries; in fact for some alternatives (B,C and D) the imported amounts of blue and grey water are lower than the exported ones; and for alternative E only the grey water flows are a not advantageous for the GS. Only alternative A (animals, tomato and cucumber, in greenhouse) can be completely defined advantageous.

Summarizing, the implementation of trading system, in which the flows of products are decided not only with economic perspective, but also taking into account nutrients and portions required for a balanced diet can improve the situation in the GS concerning both food security and environmental sustainability.

## 6.4 INDICATORS RELATED TO WATER FOOTPRINT

### 6.4.1 *Water Stress Indicators*

The first water stress indicator is WTA (equation (4.19)). The obtained value using the values from the two different sources for the Gaza Strip are:

- with data from PWA (2012 [32]) the obtained index is WTA=2.75;

- combining the extreme values of ranges proposed by Dentoni (2012 [12]) the obtained index values are: $WTA_1$=1.05, $WTA_2$=1.27, $WTA_3$=1.82, $WTA_4$=2.22.

The second step is the calculation of VF. Using the CRU rainfall data for the whole GS, the obtained values of the required standar deviations are:

- $s^*_{month}$= 29.6;
- $s^*_{year}$= 73.2.

Since in all the cases the value of WTA is bigger than 1, the obtained values of WSI are all equal to 1, that the GS is characterized by means severe water stress conditions.

### 6.4.2 *Damage assessment*

#### 6.4.2.1 *Damage on Human Health*

The equation for damage on human health equation (4.26) is essentially composed by two elements:

- the first one is $CF_{maln,i}$ and represents the expected specific damage per unit of consumed water;
- the second term is $WU_{cons}$ and represent the water (generally blue water) consumed in a country or in a process.

The $CF_{maln,i}$ value obtained for Gaza Strip is 0.0014 $DALY/m_{3consumed}$. Then, the $\Delta$ $HH_{maln,i}$ is different for each considered agricultural product and/or system.

The values of damage in Human Health obtained for the analyzed systems are shown in table 6.31

| **System** | **DamageHH** [DALY] |
|---|---|
| alternative A | 1.54 |
| alternative B | 1.27 |
| alternative C | 1.51 |
| alternative D | 1.71 |
| alternative E | 1.23 |

**Table 6.31:** Damage on Human Health of different agricultural systems in DALY

If the damages on human health are referred to the total agricultural area in the GS (each agricultural system is extended to the agricultural area, and the corresponding farms are 25000), each gazian loses about a week due to malnutrition caused by lack of water (table 6.32).

| System | DamageHH [day/person] |
|---|---|
| alternative A | 7.98 |
| alternative B | 6.54 |
| alternative C | 7.80 |
| alternative D | 8.85 |
| alternative E | 6.35 |

**Table 6.32:** Loss of day of life for each person in the Gaza Strip due to malnutrition cased by lack of water

#### 6.4.2.2 *Damage on ecosystem quality*

Following equation (4.27), the obtained results for the different agricultural systems are shown in table 6.34.

| System | DamageEQ [$m^2$*yr] |
|---|---|
| alternative A | 14040.1 |
| alternative B | 11503.8 |
| alternative C | 13701.6 |
| alternative D | 15561.6 |
| alternative E | 11165.7 |

**Table 6.33:** Damage on Ecosystem quality of different agricultural systems in $m^2$*yr

#### 6.4.2.3 *Damage on resources*

Following equation (4.28) and referring to section 5.3.3, the obtained values of damage on resources for different agricultural systems and different values of $F_{depletion}$

| System | ΔR [MJ] | | | | |
|---|---|---|---|---|---|
| | $F_{depl}1$ | $F_{depl}2$ | $F_{depl}$ 3 | $F_{depl}4$ | Average |
| alternative A | 5209.2 | 25723.1 | 54696.2 | 66451.4 | 38020 |
| alternative B | 4268.1 | 21076.3 | 44815.4 | 54447 | 31152 |
| alternative C | 5083.6 | 25102.9 | 53377.5 | 64849.3 | 37103 |
| alternative D | 5773.7 | 28510.6 | 60623.4 | 73652.5 | 42140 |
| alternative E | 4142.7 | 20456.8 | 43498.2 | 52846.7 | 30236 |

**Table 6.34:** Damage on Resources of different agricultural systems in MJ

Since the damage on resources are usually measured in $, the previous values are converted from MJ to $ using a ReCiPe conversion factor of 0.00375 (it is an average among the different energy resources). The obtained values are shown in table 6.35

| **System** | **$** |
|---|---|
| alternative A | 142.6 |
| alternative B | 116.8 |
| alternative C | 139.1 |
| alternative D | 158 |
| alternative E | 113.4 |

**Table 6.35:** Damage on resources due to water consumption in $

If a relative comparison among the alternatives is made, it emerges that for all the three damage categories they present the same proportional coefficients: the only variable part in the different equations concerns the amount of consumed water. These coefficients are shown in table 6.36.

| **System** | **%** |
|---|---|
| alternative A | 90.2 |
| alternative B | 73.9 |
| alternative C | 88 |
| alternative D | 100 |
| alternative E | 71.8 |

**Table 6.36:** Damage proportion (%) among different alternative systems for the three damage categories

The three damage indicators are normalized using the ReCiPe normalization set World ReCiPe H/H:

- 71.4 for damage on human health;
- 1090 for damage on ecosystem quality;
- 0.00408 for damage on resources.

The obtained adimensional values are shown in table 6.37.

| System | Human Health | Ecosystem quality | Resources |
|---|---:|---:|---:|
| alternative A | 114.4 | $1.53 * 10^7$ | 0.58 |
| alternative B | 93.7 | $1.25 * 10^7$ | 0.48 |
| alternative C | 111.6 | $1.49 * 10^7$ | 0.57 |
| alternative D | 126.8 | $1.70 * 10^7$ | 0.64 |
| alternative E | 90.97 | $1.22 * 10^7$ | 0.46 |

**Table 6.37:** Normalized damages indicators (adimensional)

An unique damage indicator is calculated using the following World ReCiPe H/H weights:

- 0.4 for human health;
- 0.4 for ecosystem quality;
- 0.2 for resources.

The obtained values are shown in table 6.38.

| System | ReCiPe points |
|---|---|
| alternative A | $6.12 * 10^6$ |
| alternative B | $5.02 * 10^6$ |
| alternative C | $5.97 * 10^6$ |
| alternative D | $6.78 * 10^6$ |
| alternative E | $4.87 * 10^6$ |

**Table 6.38:** Final unique value of damage in ReCiPe points

The single scores values are mainly influenced by ecosystem quality component (99.9%), which are characterized by an high normalization coefficient.

### 6.4.3 *A unique water footprint value integrating consumptive and degradative water use*

In this section we try to calculate a unique index for WF integrating consumptive and degradative use water use: it composed by two components, CWU and DWU. These two values are calculated for each farm product and then for each alternative system. The obtained values are shown in table 6.39, figure 6.15, table 6.40 and figure 6.16.

| Crop type | Ml $H_2O$/yr |
|---|---:|
| cabbage | 3.96 |
| cauliflower | 5.29 |
| cucumber | 6.61 |
| eggplant | 8.81 |
| lentil | 2.20 |
| pea | 5.51 |
| pepper | 7.71 |
| tomato | 11.01 |
| fish | 0.62 |
| sheep | 0.03 |
| egg | 0.04 |
| chicken meat | 0.00405 |

**Table 6.39:** CWU of each farm product

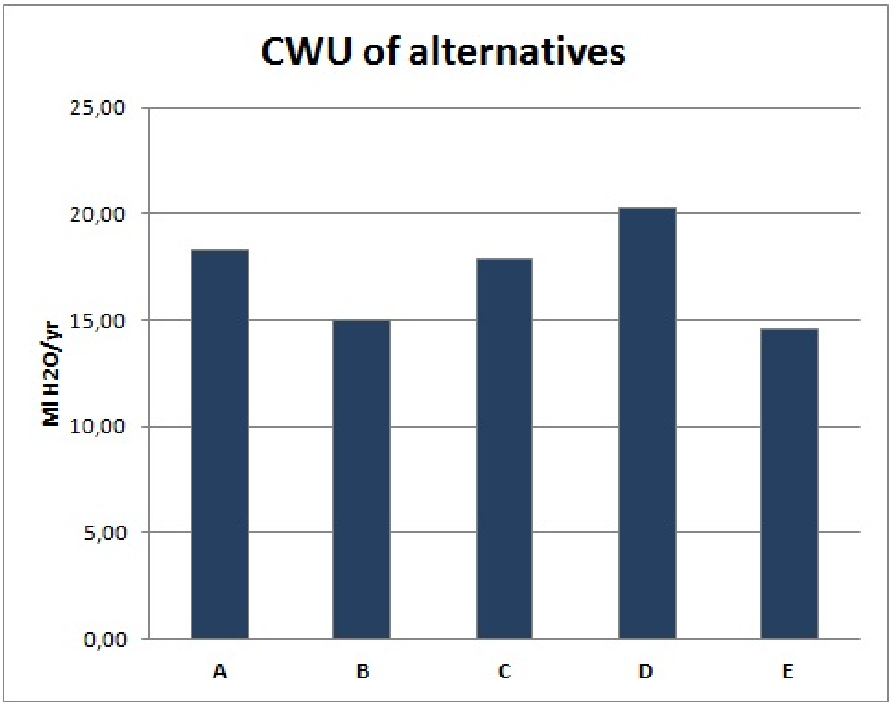

**Figure 6.15:** CWU of different alternative systems

| Crop type | RECIPE points/yr |
|---|---:|
| cabbage | 41.9 |
| cauliflower | 41.9 |
| cucumber | 0 |
| eggplant | 167.7 |
| pea | 21 |
| pepper | 83.9 |
| tomato | 50.3 |

**Table 6.40:** DWU of each farm product

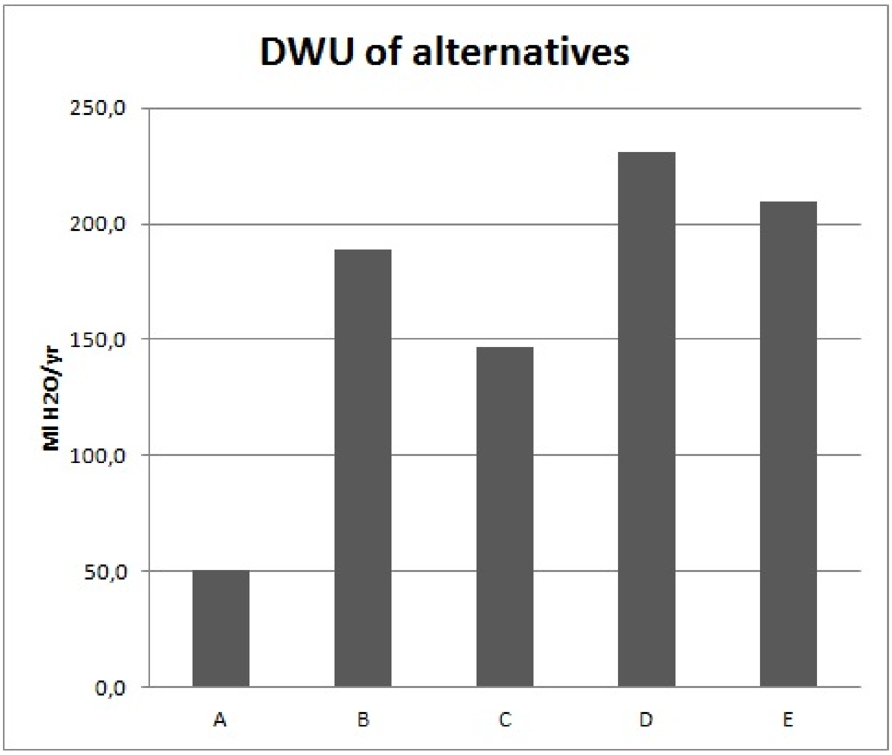

**Figure 6.16:** DWU of different alternative systems (Ml $H_2O$/yr)

The DWU values are only influenced by the P component of fertilizers because the impact categories included in the ReCiPe single score are only influenced by P and its related substances. This calculation is not correct in this case study because other substances are involved in the analyzed processes.

Finally the unique index is obtained by adding CoWU and DWU: the results are shown in figure 6.17. They result lower than the values obtained with the method provided by Aldaya et al. (2012 [2]), and also the ranking changes. This new method should be refined for this case study, especially in terms of DWU.

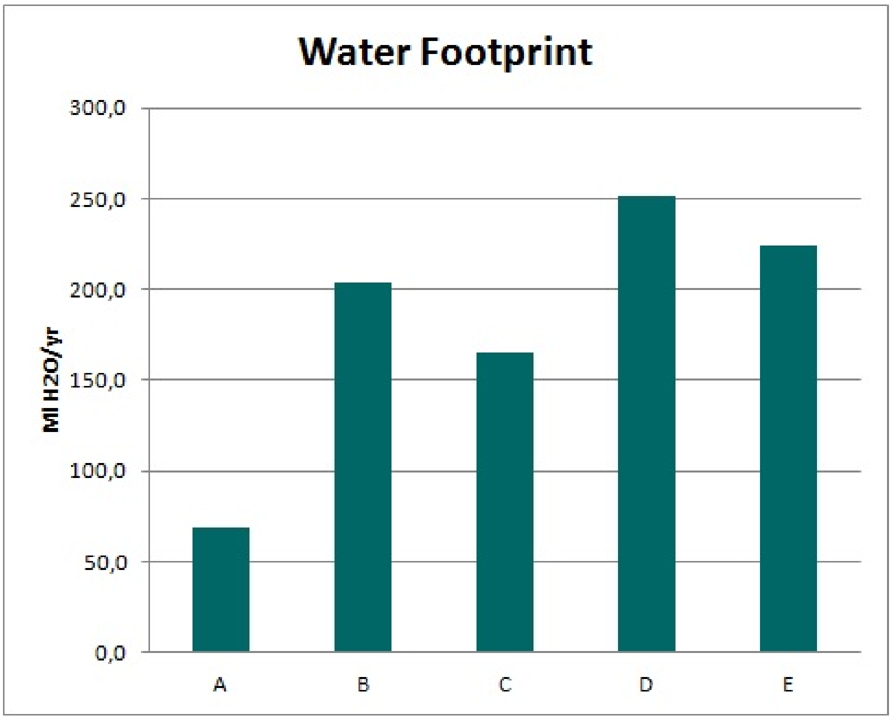

**Figure 6.17:** Water Footprint of different alternatives (Ml $H_2O$/yr).

# 7

# FINAL REMARKS: OUR CONTRIBUTION AND SOME OPEN QUESTIONS

## 7.1 OUR CONTRIBUTION TO THE FIELD OF STUDY

Sustainable food production is a fundamental goal to achieve food security in a global development context. For this reason, the FAO dedicates the World Food day (16 October 2013) to this topic. The main goal of this work, as said in the introduction, is to assess the sustainability of existing food production systems in the GS.This region is particularly interesting because its living conditions are highly affected by water and food scarcity. The complexity of the analysis is increased due to the particular context of the GS, where environmental and historical conditions make development a difficult goal to achieve. In this last chapter we try to give an answer to the question raised at the beginning of the work, summarizing the main results obtained. Firstly, each single products is evaluated in terms of WF, and the results of this evaluation could help in choosing the kind of crop to grow. The main observations about green, blue and grey WF are:

- green: cabbage, cauliflower, lentil and pea4 have the highest green WF values, because they are grown during the first part of the wet season; in January, no crops are grown (probably due to low temperatures), not even crop resisting to cold climates, like cabbage, and the high rainfall amount cannot be exploited by agricultural raising process;

- blue: tomato is the crop with the highest blue water requirements per unit area, and thus has the worst impact on the GS water resource. However, due to the high productivity of this crop its relative value of blue WF per tonne does not result the highest (see table 6.5). On the other hand, lentil presents the lowest blue WF value, but the production rate is very low if compared to other crops (because the production of lentils is referred to the produced dry matter, while for other crops it refers to fresh vegetables, which are heavier than the dried ones), and it caused a high blue WF value per produced tonne (see table 6.5); the obtained blue WF values have been referred to a produced tonne and then compared with the blue WF obtained with CROPWAT software: the blue WF estimates with field data results higher than the model output for each involved crops; this results support Al-Najar's thesis, 2011 [1]: the farmer irrigation practice exceeding the irrigation water require-ment;

- grey: eggplant is the crop with the highest grey WF value (highest N application) and lentil does not need fertilizers in this type of agricultural system (this could cause the low production rate), and consequently its related grey WF is equal to zero $m^3$/year.

Considering the yearly WF values, the direct impact on the GS water resources is analyzed: tomato has the highest impact in terms of blue freshwater consumption and eggplant in terms of grey WF; on the other hand, lentil presents the lowest in terms of both blue and grey WF; cabbage, cauliflower and pea4 has the highest green WF, because they are grown during the wet season, and they can exploit the rainfall. Concerning animals, the aquaculture, introduced to increase the protein production and to exploit the already existent water ponds, is not efficient in terms of water use if compared to other animal products: aquaculture activities take place between April and December, because fish need warm temperature to live, especially in the first months; for this reason, aquaculture goes through the dry season, when evaporation is bigger than rainfall, and it is necessary to pump water from aquifer to maintain the minimum required level of water in the ponds. For this reason, aquaculture does not seem to be a good investment in terms of water consumption. On the other hand, in this type of agricultural system, water consumption related to sheep livestock is moderate and mainly relying on green water, because the animals graze in the courtyard and eat forage produced during the rest period (a little amount of blue water is consumed for drinking). Finally, the water consumption related to chicken products are mainly caused by feed production, which does not take place in the GS. Since this work jointly analyzes water consumption and food production, the values of WF per produced tonne are considered. As said above, if we consider the WF per unit product, the crops ranking changes and lentil becomes the crop with the highest blue WF value per produced tonne, while tomato is characterized by the lowest. Concerning the livestock activities, blue water consumption related to aquaculture appears to be the worst.

From the comparison among the different alternative crop rotation systems it emerges that alternative D (involving aquaculture, terrestrial livestock, cauliflower, eggplant4, and pea3) has the highest WF values (blue, grey and total). Alternative A (animals, and tomato and cucumber in greenhouse) is characterized by the lowest total WF value, but in terms of blue WF alternative E (animals, lentils, cabbage and eggplant, in open field) has the lowest value. Alternative A is characterized by the lowest green WF, because the cultivations are covered by greenhouses and the and total value of WF results only higher than alternative E: for this reason, A could be considered the best alternative; on the other hand, the blue WF is one of the highest (only lower than alternative D); the proteins production results the highest due to the high yield of involved crops (even though tomato and cucumber have a low protein contents).

Observing the outcomes from LCA, alternative A (animals, and tomato and cucumber in greenhouse) is the most impacting for the majority of the impact categories selected, because of the high rate of application of fertilizers and pesticides: this results conflict with those emerging from the WF analysis.

If we extrapolate our results holding for a single 'average' farm, to the entire agricultural area of the GS, we found that, even though most of the analyzed alternatives (A,B,C, and D) would allow to meet the protein demand of the gazian population,quantitatively, they would exploit the groundwater resources in an unsustainable way. Moreover, none of these alternatives would be feasible from the individual viewpoint, because it would require an intake of vegetables largely exceeding that of a standard diet. For this reason, import and export mechanisms are introduced: the recommended portions of vegetable for the GS population and all the animal products from the sample farms remain in the GS, and the rest is exported; beef and wheat flour can be imported with the earned profit: according to this scenario, the proteins requirement is achieved with both internal production and imported products: the imported amounts of beef and flour are determined considering the deficit of proteins of internal production. This new scenario presents a reduction of agricultural production and, consequently, a reduction of water consumption related to protein production. The new blue WF values of some alternatives could be sustainable referring to the GS hydrological freshwater resources. Referring to the virtual water trade, if we consider the total WF balance, it is advantageous for the GS. However, the use of Gazian water resources in food production systems is excessive (even though they are sustainable, they consume about half of the available resources just to produce proteins), because also other civil uses need aquifer resources.

Finally, a last analysis of each single product is made to verify whether the total amount of proteins can be produced consuming water in a sustainable way: sustainability is achieved only with terrestrial livestock activities (sheep and chicken livestock), because the analyzed systems are not industrial, but grazing ones and the consumption of water due to feed production are not located in the GS. However, even if these products are sustainable referring to the freshwater resources, they consume about 40% of the total available water just for producing proteins: in the last 70 years, water demand has been increasing and the civil consumption exceeds the agricultural ones (PWA, 2012 [32]); thus, the production of a complete balanced diet is not sustainable for the GS and trade mechanisms seem to be necessary.

Concerning the methodology, the major outcomes are:

- the WF methodology presents critical aspects regarding the assessment of gray WF; to cope with this, another WF index is calculated, which integrates CoWU and DWU. For this case study, however, it seems unsuitable because it does not take into account relevant pollutant substances; moreover, the green WF contribution is considered, but it is not a real water consumption because it comes from rainfall: its consumption could only reduce the groundwater recharge;
- even if a complete database including values of WF of crops and animal products in every country exists, estimated using the CROPWAT model, it would be better using field data about water consumption or fertilizers application rates, whenever they are available; moreover, the WF strongly depends on the growing period of crops (the values included in the database are average values over the year);
- concerning the damage to human health, ecosystem quality and resources, especially in regions affected by water scarcity it is important to assess also the damages caused by water consumption, since they are different from those calculated with the ReCiPe method: the damages assessed with LCA method are obtained referring one of the three damage categories to the impacts ones and they are mainly related to the toxicity of substances and to resources consumption (water depletion is not taken into account and this gap can be filled using the damage indicators related to water consumption proposed by Pfister, Koehler, and Hellweg, 2009) ;
- finally, introducing the aspects related to nutrition, it is not sufficient to analyze the global quantitative aspects of nutrients production , but it is also important to observe the obtained diet for the population and evaluating whether it is balanced.

Summarizing the observations made above, and taking into account the goals of the work, the main conclusions are:

1. the analyzed systems could quantitatively provide the required amount of proteins, but causing the overexploitation the groundwater resources in a non sustainable way: the water consumed just to produce proteins exceeds the freshwater availability; moreover, it is necessary to underline the importance of taking into account qualitative aspects related to the daily diet of each person, and not only the quantitative aspects;

2. aquaculture is not convenient neither in terms of water consumption nor in terms of proteins production; maybe the creation of a complete integration between agriculture and aquaculture and the introduction (Efole Ewoukem et al., 2012 [13] and Phong, De Boer, and Udo, 2011 [31]) of mechanisms to reduce the evaporation might reduce the disadvantages related to aquaculture in the GS;

3. available water for food production and civil/domestic use per person (34-100 $m^3$/person/year) is lower than the water consumed by the analyzed systems just to produce proteins (246-480 $m^3$/fed person/year).

## 7.2 PROPOSED IMPROVEMENTS AND OPEN QUESTIONS

This study is a first approach to coupling food security and environmental sustainability issues in the GS. To obtain a wider and complete range of scenarios and solutions, a multi-objective optimization problem could be formulated: the optimization criteria would concern food production, balanced nutrition and environmental resources, and the decision variables would refer both to agricultural sector and trade system. The analyzed agricultural production sector is a simplification of the real one, because only few applied systems are involved: the real current national value of the WF could be estimated collecting more precise, detailed data on the current situation of agricultural sector. Strategies to reduce water consumption and improve water quality could be planned considering this estimation. Furthermore, the introduction of aquaculture as done up to now in the GS has not been based on an integrated system between aquaculture and agriculture, because only the water flows from ponds to agricultural fields connect these two sectors. Devising a really integrated system could bring advantages also for the GS. Finally, the GS area is characterized by a high variability of environmental conditions among the different governorates (e.g. see table 2.2), and the analysis made using average values for local variables (meteorological, morphological ) of the area could be performed separately for each single governorate. Moreover, given the fact that rainfall during the 2010/11 season were 28 percent lower than the historical average (FAO, 2012 [15]) , and reached as low as 50 percent in many areas, it could be interesting to simulate different agricultural systems under climate change scenarios (e.g. using the FAO AQUACROP model).

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Part III

# APPENDIX

# A

# GREY WATER FOOTPRINT CALCULATION

As explained in chapter 5, the values of grey WF involve the contributions of the main fertilizers applied for the different crops. The intermediate calculation steps are reported. The calculated parameters are:

- the fertilizer AR of different substances for the different crops per unit of area (kg/ha);
- total fertilizer applied (tot.FERT), obtained multiplying AR and the cultivated area (8.5 ha);
- the leaching substance (Leaching), which is the 10% of the total applied fertilizer;
- total annual grey WF ($m^3$/year), using the equation (4.8) and the maximum allowable concentration provided by WHO (see chapter 5
- grey WF per produced tonne of vegetable.

The calculation steps are reported and divided into the different fertilizer substances in table A.1, table A.2, table A.3, and table A.4 (which is applied only for cucumbers).

| Crop type | AR | tot.FERT | Leaching | annual greyWF | greyWF |
|---|---|---|---|---|---|
| | kg/ha | ton/year | ton/year | $m^3$/year | $m^3$/ton |
| cabbage | 150 | 0.1275 | 0.01275 | 255 | 6.7 |
| cauliflower | 150 | 0.1275 | 0.01275 | 255 | 12 |
| cucumber | 700 | 0.595 | 0.0595 | 1190 | 15.55 |
| eggplant4 | 860 | 0.731 | 0.0731 | 1462 | 43 |
| eggplant5 | 860 | 0.731 | 0.0731 | 1462 | 28.67 |
| lentil | 0 | 0 | 0 | 0 | 0 |
| pea3 | 25 | 0.02125 | 0.002125 | 42.5 | 7.143 |
| pea4 | 25 | 0.02125 | 0.002125 | 42.5 | 5 |
| pepper4 | 580 | 0.493 | 0.0493 | 986 | 58 |
| pepper5 | 580 | 0.493 | 0.0493 | 986 | 46.4 |
| tomato | 1000 | 0.85 | 0.085 | 1700 | 13.3 |

**Table A.1:** Grey WF calculation steps for N fertilizer.

| Crop type | AR | tot.FERT | Leaching | annual greyWF | greyWF |
|---|---|---|---|---|---|
| | kg/ha | ton/year | ton/year | $m^3$/year | $m^3$/ton |
| cabbage | 120 | 0.102 | 0.0102 | 1020 | 26.7 |
| cauliflower | 120 | 0.102 | 0.0102 | 1020 | 48 |
| cucumber | 450 | 0.3825 | 0.03825 | 3825 | 50 |
| eggplant4 | 250 | 0.2125 | 0.02125 | 2125 | 62.5 |
| eggplant5 | 250 | 0.2125 | 0.02125 | 2125 | 41.67 |
| lentil | 0 | 0 | 0 | 0 | 0 |
| pea3 | 500 | 0.425 | 0.0425 | 4250 | 714.3 |
| pea4 | 500 | 0.425 | 0.0425 | 4250 | 500 |
| pepper4 | 260 | 0.221 | 0.0221 | 2210 | 130 |
| pepper5 | 260 | 0.221 | 0.0221 | 2210 | 104 |
| tomato | 230 | 0.1955 | 0.01955 | 1955 | 15.3 |

**Table A.2:** Grey WF calculation steps for K fertilizer.

| Crop type | AR | tot.FERT | Leaching | annual greyWF | greyWF |
|---|---|---|---|---|---|
| | kg/ha | ton/year | ton/year | $m^3$/year | $m^3$/ton |
| cabbage | 120 | 0.102 | 0.0102 | 2040 | 53.3 |
| cauliflower | 120 | 0.102 | 0.0102 | 2040 | 96 |
| cucumber | 0 | 0 | 0 | 0 | 0 |
| eggplant4 | 600 | 0.51 | 0.051 | 10200 | 300 |
| eggplant5 | 600 | 0.51 | 0.051 | 10200 | 200 |
| lentil | 0 | 0 | 0 | 0 | 0 |
| pea3 | 50 | 0.0425 | 0.00425 | 850 | 142.8 |
| pea4 | 50 | 0.0425 | 0.00425 | 850 | 100 |
| pepper4 | 240 | 0.240 | 0.0240 | 4080 | 240 |
| pepper5 | 240 | 0.240 | 0.0240 | 4080 | 192 |
| tomato | 125 | 0.10625 | 0.010625 | 2125 | 16.7 |

**Table A.3:** Grey WF calculation steps for P fertilizer.

| Crop type | AR | tot.FERT | Leaching | annual greyWF | greyWF |
|---|---|---|---|---|---|
| | kg/ha | ton/year | ton/year | $m^3$/year | $m^3$/ton |
| cucumber | 450 | 0.3825 | 0.03825 | 255 | 3.33 |

**Table A.4:** Grey WF calculation steps for Mg fertilizer.

# B

# CROPWAT DATA

The FAO CROPWAT model can estimate the crop water requirement, which is the water needed for evapotranspiration under ideal growth conditions, measured from planting to harvest. Basically, it is calculated by multiplying the reference crop evapotranspiration (ETo) by the Kc. It is assumed that the crop water requirements are fully met, so that actual crop evapotranspiration (ETc) will be equal to the crop water requirement: ETc = CWR. The reference crop evapotranspiration ETo is the evapotranspiration rate from a reference surface, not short of water. The reference crop is a hypothetical surface with extensive green grass cover with specific standard characteristics and therefore the only factors affecting ETo are climatic parameters. ETo expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors. The actual crop evapotranspiration differs distinctly from the reference crop evapotranspiration, as the ground cover, canopy properties and aerodynamic resistance of the crop are different from the grass used as reference. The effects of characteristics that distinguish field crops from grass are integrated into the Kc. It cannot be specified per day but only for three different periods in the growing period, so that the effect of different irrigation techniques can be simulated in CROPWAT only by roughly adjusting Kc as a function of the irrigation technique used. On average, Kc will be higher when irrigation techniques are applied that wet the soil intensively than when techniques are used that do not wet the top soil much. As an alternative to CROPWAT, one can decide to use AQUACROP (FAO, 2010e), a crop model that better simulates crop yield under water stress conditions. Effective precipitation ($P_{eff}$) is the part of the total amount of precipitation that is retained by the soil so that it is potentially available for meeting the water need of the crop. It is often less than the total rainfall because not all rainfall can actually be appropriated by the crop, for example, due to surface run-off or percolation. There are various ways to estimate effective rainfall based on total rainfall; one recommended method is the USDA SCS method (the method of the United States Department of Agriculture, Soil Conservation Service). This is one of the four alternative methods that the users of CROPWAT can choose from. In this study CROPWAT model is used to estimate blue WF od different crops and compared the obtained results with the field data provided by gazian agronomists. To fill in CROPWAT dataset the required data are:

- Minimum Temperature [°C]

| Month | Min T | Max T | Hum | Wind | Sun | Rad | ETo |
|---|---|---|---|---|---|---|---|
| | °C | °C | % | km/day | hours | MJ/m$^2$/day | mm/day |
| Jan | 10.7 | 17.8 | 64 | 281 | 4.8 | 10 | 2.47 |
| Feb | 11.2 | 18.1 | 67 | 278 | 6.2 | 13.4 | 2.70 |
| Mar | 13.2 | 19.8 | 68 | 262 | 7.6 | 17.8 | 3.31 |
| Apr | 16.7 | 22.5 | 67 | 250 | 8.2 | 20.9 | 4.16 |
| May | 19.2 | 24.4 | 71 | 230 | 9.8 | 24.4 | 4.74 |
| Jun | 21.7 | 27 | 74 | 238 | 9.8 | 24.7 | 5.08 |
| Jul | 23.9 | 29.4 | 74 | 233 | 10.5 | 25.5 | 5.54 |
| Aug | 24.6 | 29.4 | 71 | 238 | 10.5 | 24.5 | 5.54 |
| Sep | 23.1 | 28.7 | 69 | 250 | 9.6 | 21.1 | 4.95 |
| Oct | 20.1 | 26.3 | 68 | 257 | 8.2 | 16.5 | 3.94 |
| Nov | 16.1 | 23 | 61 | 262 | 6 | 11.6 | 3.24 |
| Dec | 12.6 | 19.2 | 65 | 262 | 3.9 | 8.5 | 2.43 |

**Table B.1:** Climatic data for Gaza Strip required by CROPWAT

- Maximum Temperature [°C]
- Humidity [%]
- Wind [km/day]
- Sun [hours]
- Rad [MJ/m$^2$/day]
- ETo [mm/day]

They are provided by Al-Najar: The used rainfall data and the relative Effective rain are shown in table B.2 (the rainfall data have been already shown in figure 5.1).

After the climate data, the crops parameters are required:

- planting date;
- harvest;
- Kc values of crops;
- stages of growing periods (days);
- rooting depth in the different stages (m);
- critical depletion (fraction);
- yield response;

| month | Rain (mm) | Eff rain (mm) |
|---|---:|---:|
| January | 109.9 | 90.6 |
| February | 71.9 | 63.6 |
| March | 37.4 | 35.2 |
| April | 7.8 | 7.7 |
| May | 0 | 0 |
| June | 0 | 0 |
| July | 0 | 0 |
| August | 0 | 0 |
| September | 1.4 | 1.4 |
| October | 22.3 | 21.5 |
| November | 57.9 | 52.5 |
| December | 83.7 | 72.5 |
| Total | 392.3 | 345 |

**Table B.2:** Rainfall and effective rain data for Gaza Strip required by CROPWAT

- cropheight (m) (it is optional);

Most of these required parameters are provided by Allen et al. (1998) [3]. The main parameters are reported in table B.3 The different growing periods are provided by gazian agronomist working on the territory, and are presented in chapter 3. Using these data the irrigation requirement for each crop is estimated.

| Crop type | **Kc values!** (**Kc values!**) | | | Rooting depth (m) | |
|---|---|---|---|---|---|
| | initial | mid-season | total | inital | final |
| cabbage | 0.7 | 1.05 | 0.95 | 0.25 | 0.50 |
| cauliflower | 0.7 | 1.05 | 0.95 | 0.4 | 0.7 |
| cucumber | 0.6 | 1 | 0.75 | 0.7 | 1.2 |
| eggplant4 | 0.6 | 1.05 | 0.9 | 0.7 | 1.2 |
| eggplant5 | 0.6 | 1.05 | 0.9 | 0.7 | 1.2 |
| lentil | 0.4 | 1.15 | 0.35 | 0.3 | 1 |
| pea3 | 0.4 | 1.15 | 0.35 | 0.3 | 1 |
| pea4 | 0.4 | 1.15 | 0.35 | 0.3 | 1 |
| pepper4 | 0.6 | 1.05 | 0.9 | 0.25 | 0.8 |
| pepper5 | 0.6 | 1.05 | 0.9 | 0.25 | 0.8 |
| tomato | 0.6 | 1.15 | 0.8 | 0.25 | 1 |

**Table B.3:** Blue WF values for tonne of crop [$m^3$/ton] and for the annual farm production [$m^3$]

# C

# VIRTUAL WATER TRADE

Table C.1 shows the values of virtual water imported to the GS.

| Product | Import ($m^3/t$) | | | |
|---|---|---|---|---|
| | **Green WF** | **Blue WF** | **Grey WF** | |
| A | $2.30 * 10^9$ | $2.44 * 10^8$ | $1.35 * 10^8$ | $2.68 * 10^9$ |
| B | $1.7 * 10^8$ | $1.8 * 10^7$ | $9.98 * 10^6$ | $1.98 * 10^8$ |
| C | $8.01 * 10^8$ | $8.5 * 10^7$ | $4.71 * 10^7$ | $9.33 * 10^8$ |
| D | $7.93 * 10^8$ | $8.42 * 10^7$ | $4.66 * 10^7$ | $9.24 * 10^8$ |
| E | $1.6 * 10^9$ | $1.7 * 10^8$ | $9.4 * 10^7$ | $1.86 * 10^9$ |

**Table C.1:** Virtual water import to Gaza Strip

Table C.2 shows the values of virtual water exported from the GS.

| Product | Export ($m^3/t$) | | | |
|---|---|---|---|---|
| | **Green WF** | **Blue WF** | **Grey WF** | |
| A | $6.49 * 10^4$ | $7.18 * 10^7$ | $4.12 * 10^7$ | $1.13 * 10^8$ |
| B | $2.75 * 10^7$ | $9.53 * 10^7$ | $1.61 * 10^8$ | $2.84 * 10^8$ |
| C | $7.61 * 10^7$ | $2.49 * 10^8$ | $3.85 * 10^8$ | $7.10 * 10^8$ |
| D | $3.13 * 10^7$ | $1.53 * 10^8$ | $2.58 * 10^8$ | $4.43 * 10^8$ |
| E | $3.89 * 10^7$ | $1.37 * 10^8$ | $2.4 * 10^8$ | $4.16 * 10^8$ |

**Table C.2:** Virtual water export from Gaza Strip

Finally, we calculated the virtual water balance for the considered simple scenario (see Table C.3).

| Product | Balance ($m^3/t$) | | | |
|---|---|---|---|---|
| | **Green WF** | **Blue WF** | **Grey WF** | |
| A | $2.30 * 10^9$ | $1.72 * 10^8$ | $9.41 * 10^7$ | $2.57 * 10^9$ |
| B | $1.42 * 10^8$ | $-7.73 * 10^7$ | $-1.51 * 10^8$ | $-8.6 * 10^7$ |
| C | $7.25 * 10^8$ | $-1.64 * 10^8$ | $-3.38 * 10^8$ | $2.23 * 10^8$ |
| D | $7.62 * 10^7$ | $-6.92 * 10^7$ | $-2.12 * 10^8$ | $4.81 * 10^8$ |
| E | $1.56 * 10^9$ | $3.26 * 10^7$ | $-1.46 * 10^8$ | $1.45 * 10^9$ |

**Table C.3:** Virtual water balance for Gaza Strip