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Article

Impact of Climate and Land Use Changes on Water and Food Security in Jordan: Implications for Transcending "The Tragedy of the Commons"

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Abstract: This study investigates the impact of climate change and land use change on water resources and food security in Jordan. The country is dominated by arid climate with limited arable land and water resources, where the per capita share of water is less than 145 m^3/year. The study focused on crop production and water resources under trends of anticipated climate change and population growth in the country. Remote sensing data were used to determine land use/cover changes and rates of urbanization, which took place at the cost of the cultivable land. Recession of irrigated areas led to lesser food production and food security. Outputs from crop production and water requirements models, in addition to regression analysis, were used to estimate the projected increase in agricultural water demand under the scenarios of increased air temperature and reduced rainfall by the years 2030 and 2050. Results indicated that problems of water scarcity and food insecurity would be exacerbated by climate change and increased population growth. To move from the tragedy of the commons towards transcendence, the study emphasized the need for adaptive measures to reduce the impacts of climate change on water resources and food security. The challenge, however, would remain the development and the efficient use of new water resources as a means for future sustainable development.

Keywords: climate change; land use/cover change; food security; water scarcity

1. Introduction

According to Hardin's essay "The Tragedy of the Commons", human population growth and the freedom to use land were seen as major threats to the fragile commons [1]. Although the metaphor of the fragile commons may remain valid, however, it may be considered simplistic in its focus on population growth alone without considering the new ecological challenges caused by climate change. The adverse impacts of climate change and global warming are mainly threatening water and food security in developing countries. The vulnerability of agriculture and food security to both climate change and climate variability is well established. The general consensus is that changes in temperature and precipitation will impact plant growth and crop yield and, subsequently, affect food security. In many developing countries, climate change is also expected to change farming systems and to put more pressure on the rural community to cope with these changes and build up their adaptive capacities. The problems resulting from climate change are also worsening by the rapid population growth and the unplanned conversion of cultivable lands into urban areas. In West Asia and North Africa (WANA), most countries have serious problems in agricultural production as a result of limited economic resources, low levels of technology, limited cropping patterns and environmental limitations and stresses [2].

The link between adverse climate change and water and food security is related to changes in crop yield and levels of water consumption by agriculture and other sectors. The projected temperatures increase and precipitation reduction would adversely affect crops and water availability, thus critically influencing the patterns of future agricultural production. Crop yield is roughly proportional to transpiration; more yields require more transpiration. It takes between 500 and 4,000 liters of evapotranspiration (ET, the combined process of evaporation from soil surface and transpiration from plant leaves) to produce just one kilogram of grain. When grain is fed to animals, producing a kilogram of meat takes much more water, between 5 and 15 thousand liters [3]. The overall effect of climate change on crop productivity can be predicted with some levels of uncertainty, partly because local changes in radiation and evaporative demand and interactions with changing technology are unknown. For this purpose, computer crop simulation models can be used to predict yield changes caused by climate change [4].

In countries with scarce water resources, the adverse impacts of climate change on available water resources are increasing the problem of food security, as most of developed water resources are used for agriculture. The bottom line is that each individual needs 2 to 5 liters of drinking water, 20 to 400 liters of water for daily household use and about 2,000 to 5,000 liters of water for food production, depending on how productive their agriculture is and what kind of food they eat. On average, each of us requires about one thousand cubic meters of water each year for food, or about 3 cubic meters (3 tons or 3,000 liters) of water per day, considering that about one liter of water is required per calorie of food supply. These figures assume that 2,800 to 3,000 calories must reach the market in order for each of us to consume about 2,000 calories [5].

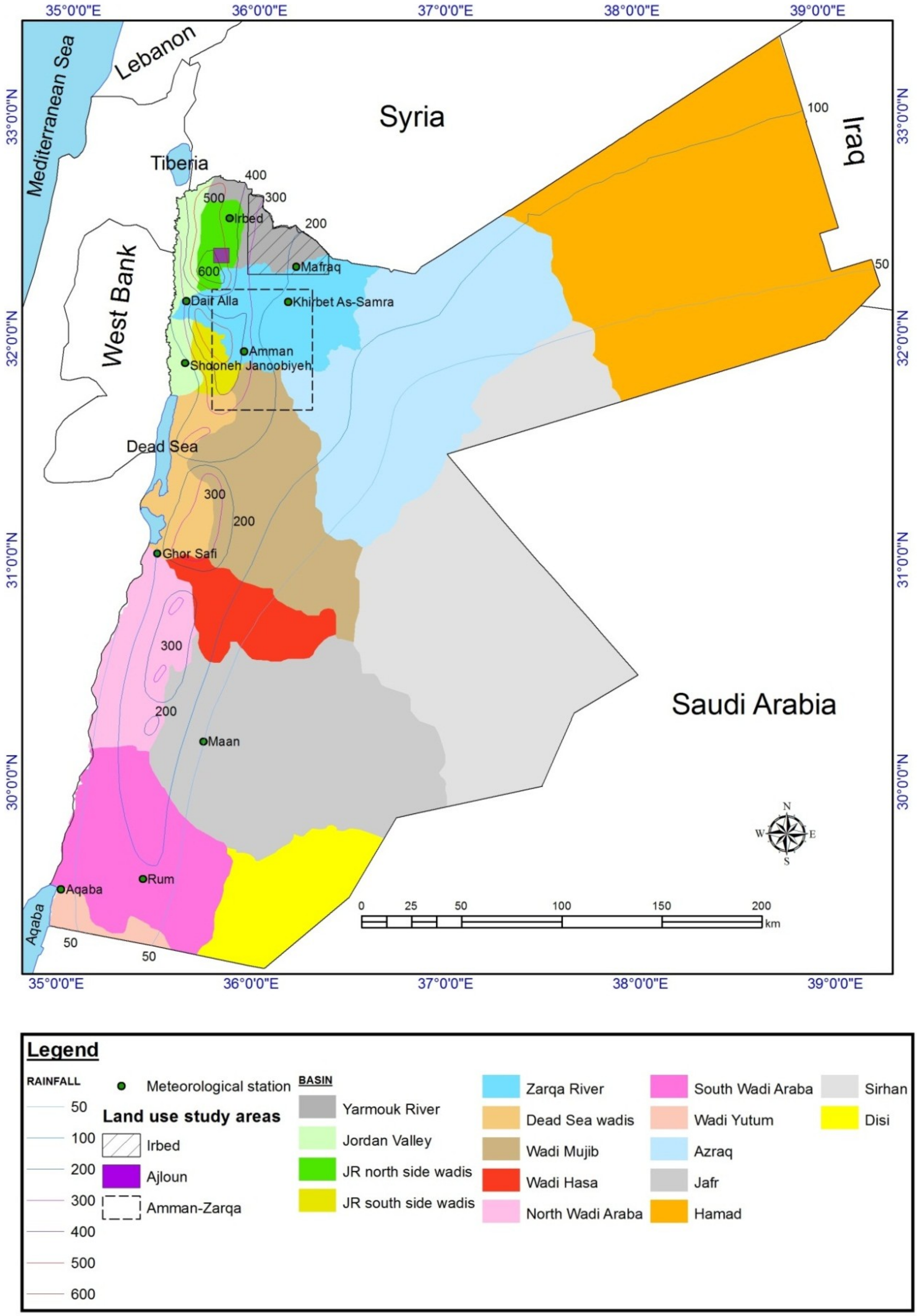
In Jordan, the challenge to meet population needs from food and water is well-known at all levels. Water availability is likely to be the most sensitive to climate change induced impacts. In terms of water availability, Jordan is among the four driest countries in the world, with a per capita fresh water share of 145 m^3 per year, which is far below the international water poverty line of 500 m^3 per year [6]. Due to the country's location (Figure 1) in the mid-latitudes, climate change is expected to have significant impacts on water supplies and agricultural production in Jordan. The country has limited water and land resources, which increases the competition for water among the different sectors. Jordan suffered from a high rate of population growth that resulted from the waves of refugees from the surrounding countries (West Bank, Iraq and Syria) suffering from the political instability

The combined effects of climate change and population growth are expected to put more pressure on the limited land resources in Jordan and to increase the challenge of sustainable development in the country. This study aims to assess the risks of climate change, population growth and land use change on water resources and food productivity in Jordan. The study forms a part of the efforts of the Food and Agriculture Organization of the United Nations (FAO) to support Jordan's activities in the area of capacity building and adaptation to climate change. Although the study may reflect on the "tragedy of commons", it can, however, help in providing implications for building adaptive capacities to minimize the adverse impacts of climate change on water and food security in Jordan.

2. Study Area

In this study, impacts of climate change, land use change and population growth were assessed in relation to water and food security in Jordan. The country, located about 80 km east of the Mediterranean Sea (Figure 1), has a total area of 89.5 thousand km^2 and altitude that ranges from less than –400 m at the Dead Sea surface (lowest point on earth) up to 1,750 m at Jebel Rum. The country has three distinguished bioclimatic zones. The first zone is the Jordan Valley, which forms a narrow strip that is situated below the mean sea level with warm winters and hot summers and where irrigation is practiced. The second zone is the western highlands, where precipitation is in the range of 300 to 600 mm. The third zone, known as the "Badia", includes the arid and semiarid areas in the eastern parts of the country, where the annual rainfall is below 200 mm. Badia is an Arabic word describing the open rangeland inhibited by Bedouins (nomads) [7]. In this area, the fragile commons of land suffer from overgrazing of seasonal browse and over-pumping of groundwater to irrigate vegetables and fruit trees.

Figure 1. The map of Jordan with surface water basins, rainfall isohyets and locations of land use study sites.

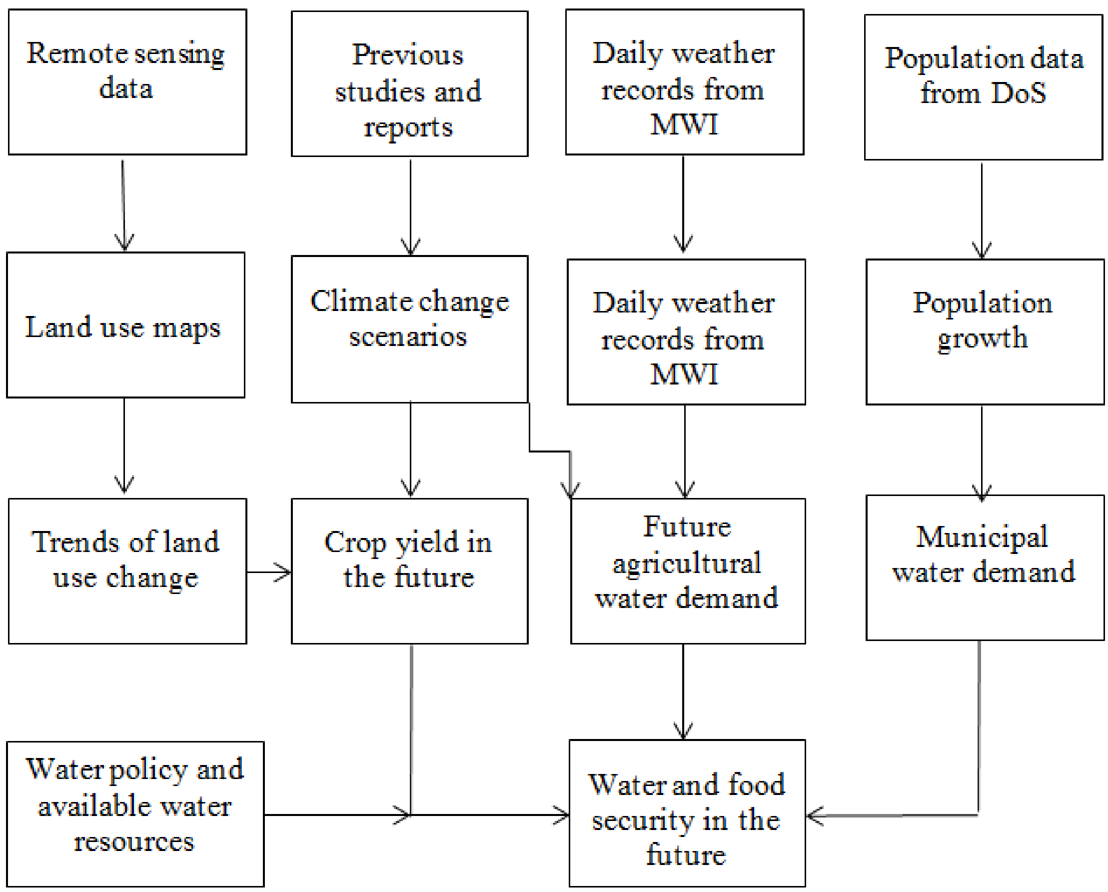


The climate of the country varies from one ecological zone to another. A dry sub-humid Mediterranean climate dominates a small area in the northwest of the country, where rainfall is more than 600 mm, while an arid climate dominates the areas with rainfall below 200 mm. An extremely dry hyper arid climate is found in the east, where rainfall is less than 50 mm. The rainy season is between October and May, with 80% of the annual rainfall occurring between December and March. The low rainfall amounts in Jordan limit the rainfed agriculture to the zone of the western highlands, where fruit trees and cereals are cultivated and to parts of the steppe (area between western highlands and the Badia), where barley is cultivated to support grazing herds of sheep and goats.

3. Methodology

The study was based on integration of official records from the Department of Statistics (DoS) (DoS official website, www.dos.gov.jo), climatic data, remote sensing images and geographic information systems (GIS) and published research to assess the impact of climate and land use change on water resources and food security. The methodology is summarized in the flow chart shown in Figure 2. The main impacts of climate change on rainfed and irrigated agriculture were assessed through data collection and analysis of crop production data (baseline conditions) and comparing them with predicted production in the future.

Figure 2. Flowchart of the methodology.



Land use/cover was derived from historical and current satellite images used to extract precise figures on the extent of cultivation of both rainfed and irrigated area. Also, records and reports were obtained from the Ministry of Water and Irrigation (MWI) on the amounts of available water from conventional and non-conventional water resources in the country. The country's strategy for water [6] was reviewed to identify water share among the different sectors till the year 2022. Future water demand, up to the year 2050, was predicted using climate change scenarios and the likely changes in crop water requirements, land use and the projected increase in population.

Identification of climate change risks and their impacts on water and food security was carried out through the analysis of climate change impacts on the available water resources and crop yield in Jordan. In addition, the impact of temperature increase on crop water requirements was assessed by varying daily climatic records based on the possible climate change (CC) scenarios. The output was summarized to enable comparison and assessment of CC impacts on agricultural production and food security (Tables 5 and 6). The overall risk assessment was based on food needs, as related to population growth, possible land use shifts and crop yield under the most probable climate change scenarios. The following subsections provide detailed description of the methodology.

3.1. Trends and Scenarios of Climate Change

Several studies [8–13] were carried out to characterize climate change in Jordan. A detailed analysis of mean monthly air temperature and mean annual rainfall was included in the country's second national communication (SNC) report to the United Nations Framework Convention on Climate Change (UNFCCC). The analysis was carried out for a time series of 45 years extending from 1961–2005 using a parametric trend test (linear trend) and non-parametric Mann-Kendall rank trend test [14]. The data included the normal period of 1970–2005, which complied with the requirements of the World Metrological Organization (WMO) regulations, stating that the latest 'normal period' extends from 1970 to 2000 [10]. The main findings were 8–20% decrease in rainfall occurring in most of the weather stations, with warming trends that showed an increase in the range of 1.0–1.8 °C in six stations, 0.5–0.9 °C in seven stations and 0.8–2.0 °C in nine stations [12].

The SNC report also presented results from three ocean-atmosphere general circulation models (GCMs) for monthly temperature and precipitation. The three models (CSIROMK3, ECHAM5OM, HADGEM1) predicted a reduction of the annual precipitation by 0%, 10% and 18% by 2050 and a maximum increase by 1.7 °C in air temperature by the year 2050 [4]. Accordingly, climate change scenarios in 2030 and 2050 were summarized for the different basins in Jordan (Table 1). The most probable scenario would be an increased air temperature of 1 °C and 2 °C by 2030 and 2050, respectively. On the other hand, most surface water basins would suffer from decreased rainfall amounts in the range of 10–20%. Only the basins of the eastern desert and the basins of the Jordan River north side wadis would have incremental increase in rainfall. This increase in rainfall, however, would not compensate for the negative impacts of climate change at the country level, as the rainfall amounts in these basins were low compared to other basins, where rainfall was decreasing and air temperature was increasing.

Table 1. Climate change scenarios with expected changes in air temperature and rainfall in the years 2030 and 2050 for the different surface water basins in Jordan.

Basin	Temperature change (°C)		Precipitation change (%)	
	2030	**2050**	**2030**	**2050**
Yarmouk River	+1	+2	–10	–20
Jordan River north side wadis	+1	+2	+5	+10
Jordan River south side wadis	+1	+2	–10	–20
Zarqa River	+1	+2	–10	–20
Dead Sea wadis	+1	+2	–5	–10
Wadi Mujib	+1	+2	–10	–20
Wadi Hasa	+1	+2	–10	–20
North Wadi Araba area	+1	+2	–10	–20
South Wadi Araba area	+1	+2	–10	–20
Wadi Yutum	+1	+2	–10	–20
Azraq	+1	+2	+5	+10
Jafir	+1	+2	+5	+10
Hammad	+1	+2	+10	+20
Sirhan	+1	+2	+5	+10
Southern Desert (Disi)	+1	+2	–10	–20

3.2. Climate Change and Crop Production in Jordan

The impact of climate change on the main cultivated crops in Jordan was studied using the findings from the first and the second national communication reports by Jordan's Government to UNFCC [11,12], relevant studies conducted in the country and from literature. The reduction in the crop yield was obtained using crop simulation process-oriented or statistical models. The former models were used to assess the impact of climate change on rainfed wheat and barley [4], while the latter models were developed to assess the impact of climate change on productivity of other rainfed crops and the main irrigated crops in Jordan. The following equation provides an example on a statistical model that correlates olive production in the highlands with rainfall (mm) and temperature (°C):

$$Y=(111.70)X_1 - (26.20)X_2 + (230.70)X_3 + (181.30)X_4 - (53.10)X_5+(0.05)X_6 \quad (1)$$

t-value: 0.1 – 0.3 2.1 2.1 –2.1 0.3

($p < 0.05$, $R^2 = 0.90$)

Where:

Y = Olive production (ton),
X_1 = Average temperature in the considered months,
X_2 = Rainfall in November,
X_3 = Rainfall in December,
X_4 = Rainfall in January,
X_5 = Accumulated rainfall in March and
X_6 = Cultivated area (10^{-1} ha).

The impact of climate change on crop production is attributed to the fact that each crop has a base temperature for vegetative development when growth commences, as well as an optimum temperature range during which the plant develops rapidly [15]. An increase in temperature often accelerates crop phenological phases that may lead to shorter lifecycles associated with small plants and low yields. Higher temperatures at the reproductive stage may also affect pollen viability, fertilization, grain filling and fruit development, thereby reducing crop yield potential [16]. The impacts may become severe for rainfed crops, such as barley and wheat [3,17]. A summary of climate change impacts on the main rainfed and irrigated crops in Jordan is shown in Table 2.

Table 2. Expected changes in crop productivity under the different climate change scenarios in Jordan.

Crop	Climate Change Scenario		Change in Yield	Reference
	Temperature	Rainfall		
Rainfed barley	+1°C	–10%	–18%	[4,11,18,19]
	+2°C	–20%	–35%	
Rainfed wheat	+1°C	–10%	–7%	[4,11,18,19]
	+2°C	–20%	–21%	
Rainfed olives	+1°C	–10%	–5%	[11,18,19]
	+2°C	–20%	–10%	
Irrigated vegetables	+1°C	–	–5%	[11,18–24]
	+2°C	–	–10%	
Rangelands	+1°C	+5%	+10%	[15,18]
	+2°C	+10%	+10%	

3.3. Mapping of Land Use and Its Change

Land use mapping was carried out using a set of images of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) with a resolution of 15 meters and Landsat Thematic Mapper (TM) with a resolution of 30 meters. The approach was based on a combination of digital classification and visual interpretation of the images. The images were geometrically corrected using an image-to-image approach, while radiometric correction was carried out using the histogram matching method [25]. A classification scheme (Table 3) was selected to represent all classes of land use/cover in Jordan based on previous studies [4,26–30]. The supervised classification method was used to generate a land use/cover map of the country using training data for the different land use/cover classes. To improve the mapping accuracy, a GIS layer of urban and agricultural areas was created using an on-screen interpretation and digitizing for the images. A layer of protected areas and grazing reserves was intersected with the map. The final land use/cover map (Figure 4) was verified by available land use maps [4,26–30] for different parts of the country and from the high resolution images of the Google Earth website.

In order to estimate the available agricultural lands in the future, trends of land use/cover change were identified by mapping current and historical land use and its change for three representative sites (Figure 1) that would represent most of the land use/cover changes in the country. The first site extends from the capital, Amman, to Zarqa City, where more than half of the country's population is living. The site suffers from intensive urbanization at the cost of rainfed and irrigated lands [19]. The second site includes the city of Irbed and represents an area that suffered from urbanization, desertification, deforestation and the change of land use from rainfed cereals into open rangelands [29]. The third site is located in the Ajloun highlands, where forests are shifted into agricultural lands and land degradation is accelerated by mismanagement of soils and crops [31,32]. The selection of three sites can be justified by the fact that 76% of the country's population is living in these areas, which extended over the high rainfall zone and the Badia. As for Jordan Valley, land use is assumed to remain unchanged, as the reclaimed agricultural lands in this area are owned by the Jordan Valley Authority (JVA), which leases the units of lands for farmers to cultivate irrigated crops.

For the first and the second site, land use/cover maps were prepared by visual interpretation of medium resolution images of Landsat TM and ETM+ and ASTER, while colored and panchromatic aerial photography with a scale of 1:25,000 was used to derive land use/cover maps for the third site [29]. The time series for land use change were 1983–2010, 1992–2010 and 1978–2002 for the first, second and third sites, respectively. For each site, the historical and the current land use/cover maps were cross tabulated to calculate the rate of land use change, as described by Al-Bakri *et al*. [30].

3.4. Climate Change and Water Deficit

The expected water consumption in the future was based on the country's water strategy [6], population growth and changes in crop water requirements. Since agriculture consumes about 60% of available water resources [33–37], the study focused on estimating crop water requirements for the main irrigated crops in Jordan. To estimate the net irrigation requirements under baseline conditions, it was important to use an accurate model to calculate the daily crop ET (ETc) and the seasonal net requirements of water. This was carried out using the FAO-56 method, which was proved to give the most reasonable estimates under various climatic conditions [38]. The approach uses the Modified Penman-Monteith equation for calculating the grass reference ET, known as ET_o, and converting this amount into a particular crop ET (ET_c) by multiplying ET_o with the crop coefficient (K_c). The equation requires standard climatological records of solar radiation, air temperature, humidity, wind speed and other derived variables. Daily records, for the period 1994–

2008 for 10 meteorological stations (Figure 1), were used to calculate ET_c for the main irrigated. The same procedure was followed to calculate ETc for the same crops after modifying daily climatic data according to climate change scenarios. Averages of ETc were calculated for each crop, and results were summarized under present (baseline) and future conditions (Table 5). Other crop water requirements for leaching salts and preparation of lands were assumed to be compensated by improvements in irrigation efficiency, which was relatively low and reached an average of 65% [39,40]. Future water demand for municipal use was based on projections of population without possible improvements in the per capita share of water. This assumption was attributed to the limited water resources of the country, which would suffer from adverse climate changes. Water allocation for the different sectors was also based on the country's water strategy [6] and on the trends of land use change. Water deficit was estimated based on the gap between demand and supply, taking into consideration the country plans to develop more water resources in the future.

3.5. Climate Change and Food Security

Food security is a flexible concept, as reflected in the many attempts at definition in research and policy usage [41]. According to FAO, "Food security is a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" [42]. In this study, the balance between food import and export was considered in assessing the impact of climate change on food security. The approach considered the household expenditures on food items, shown in Table 6, and the energy intake by individuals. Official figures showed that the average daily per capita intake of energy ranged between 2,900 and 3,100 calories [43,44]. Since the energy intake was within the accepted levels, without serious malnutrition or food access problems, food security was assessed in terms of self-sufficiency degree (SSD) for the main food items (Table 6). The SSD was based on the ability to meet consumption needs from own food production rather than from food imports.

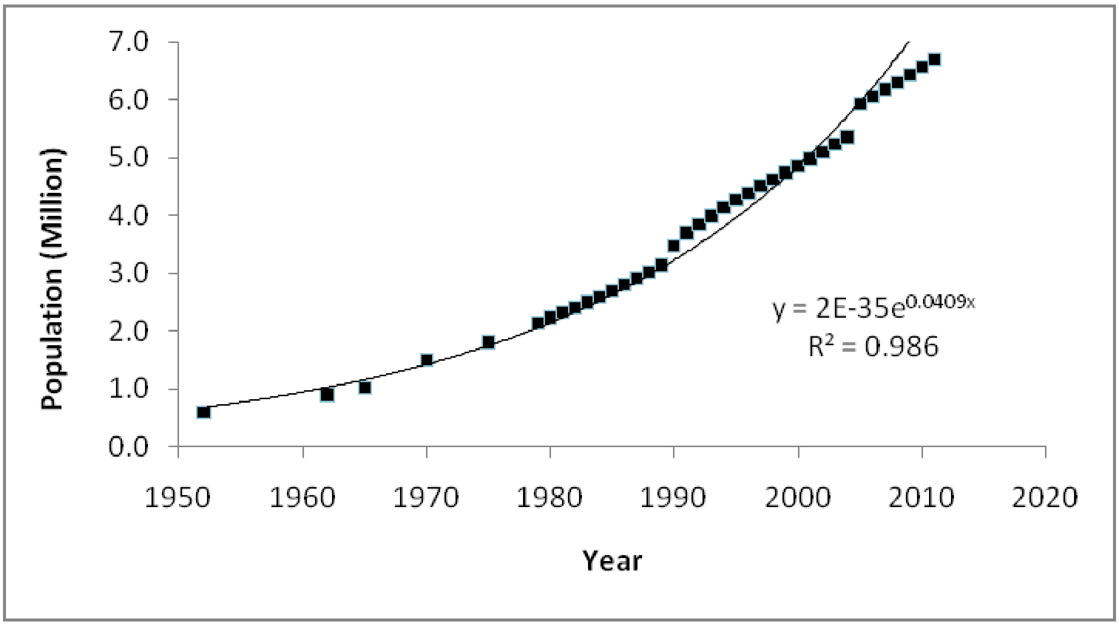
4. Results and Discussion

4.1. Population Growth and Land Use Change

Analysis of official records showed that Jordan had witnessed a rapid population growth during the period 1950–2010 [45]. The average growth rate of population was 3.7%, with three obvious sharp increases in the country's population (Figure 3). The first increase was after 1967 and was attributed to the refugees from the West Bank. The second increase was in 1990 and was attributed to the return of Jordanian labor (0.5 millions) from the Gulf countries following the 1990 Gulf War [30,45], while the third increase was attributed to the settlement of 0.45 to 0.50 million Iraqi refugees in Jordan after the year 2003 [46]. Without these three exceptional increases, the average population growth rate would be 2.4 % [45]. Currently, the refugees are living in the urban areas of Amman, Zarqa and Irbed or in camps close to these cities. All refugees have full access to water and food resources. They also share facilities of health, education, energy and transport with local communities.

Considering the current rate of population growth, future projections showed that Jordan's population would reach 10.6 and 17.0 million by years 2030 and 2050, respectively. These figures were based on the population of 2010, including the Iraqi refugees and with the assumption of no new waves of refugees from the neighboring countries. Excluding the number of refugees from these calculations, the figures of populations would reach 8.9 and 14.4 by years 2030 and 2050, respectively.

Figure 3. Population growth in Jordan.



The problem of the uncontrolled population growth in Jordan, accelerated by the political instability in the neighboring countries, had placed additional burdens on the country's limited resources. Analysis of the land use/cover map (Figure 4) for the year 2010 shows that the total rainfed and irrigated area in the country was about 44,000 ha (4.9% of the country's area). Obviously, this area had decreased with time, as indicated by the results obtained from land use/cover mapping from the series of satellite images. In the site of Irbed (Figure 5), the main land use/cover changes were the expansion of urban areas and the recession of rainfed cultivation. In this site, recession of irrigated areas was obvious, as the total irrigated lands decreased from 9.4% to 7.6% at a rate of 126 ha per year. This was attributed to decline in irrigation water quality resulting from over-pumping and the salinization of soils [19,29]. The same causes led to the decrease in irrigated lands area in Amman-Zarqa basin during 1994–2010 (Table 3).

Table 3. Summary of land use/cover changes in the selected study sites in Jordan.

Land use/cover	**Irbed**			**Amman-Zarqa**			**Ajloun ***	
	1992	**2002**	**2010**	**1983**	**1994**	**2010**	**1978**	**2002**
Urban	7.2	9.8	12.4	6.1	12.3	22.0	1.6	5.5
Mixed rainfed areas	42.4	39.8	29.4	35.4	39.4	36.9	29.7	50.0
Irrigated areas	9.4	8.4	7.6	1.1	3.3	2.4	—	—
Forests	0.6	0.6	0.6	2.0	1.8	1.8	37.6	34.6
Rangelands/ non-cultivated	40.0	41.2	49.9	55.3	43.0	36.7	31.1	9.9
Water bodies	0.4	0.2	0.1	0.1	0.2	0.2	—	—

* Source: Khresat *et al.*, 2008 [31].

Results of land use/change in the site of Amman-Zarqa (Figure 5) showed a higher growth in urbanized areas than in the site of Irbed. In Amman-Zarqa site, urban areas were nearly doubled every 20 years. This resulted in conversion of rainfed agricultural areas into urbanized areas. This land use change was enhanced by the lack of a land use law in Jordan. In the site of Irbed, rainfed areas were either urbanized or changed into non-cultivated areas. This decline in rainfed areas would also reflect the frequent drought and rainfall irregularity in the past two decades. Under climate change conditions, the expected decrease in rainfall would also result in the recession of rainfed areas. In the site of Ajloun, rainfed areas increased at the expense of forests. This uncontrolled deforestation was the main cause of land degradation in the high rainfall zone in northwest of Jordan [31,32].

Considering the trends of land use/cover change in the three study sites, the population growth, the country's water strategy and the scenarios of climate changes in Jordan, future land use in the country was predicted and summarized (Table 4). The main character of land use change was the recessions of irrigated areas by 20% in the highlands, the rainfed areas by 11–18% and the forests by 30–50%.

Figure 4. The land use/cover map of Jordan in year 2010.

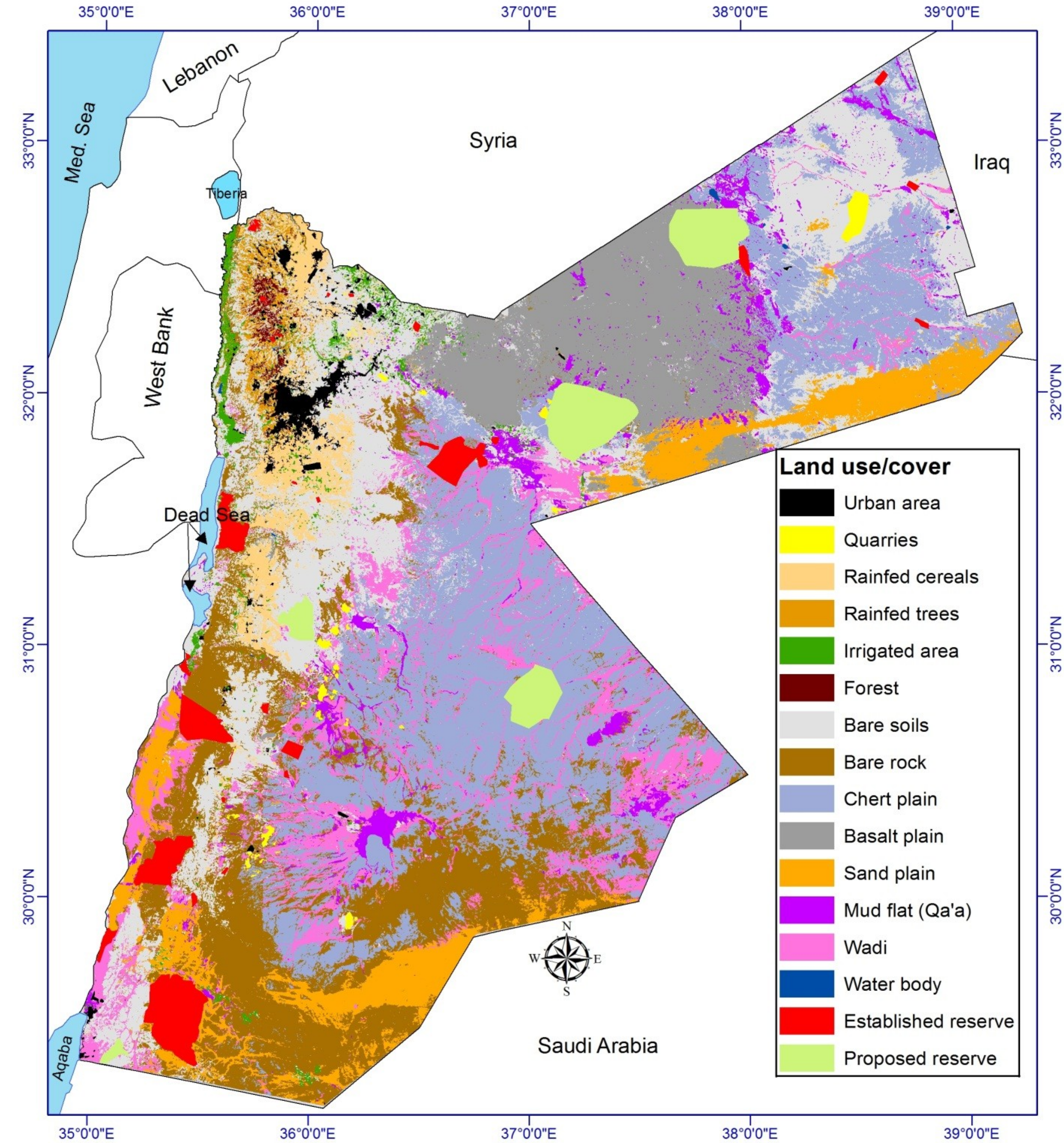
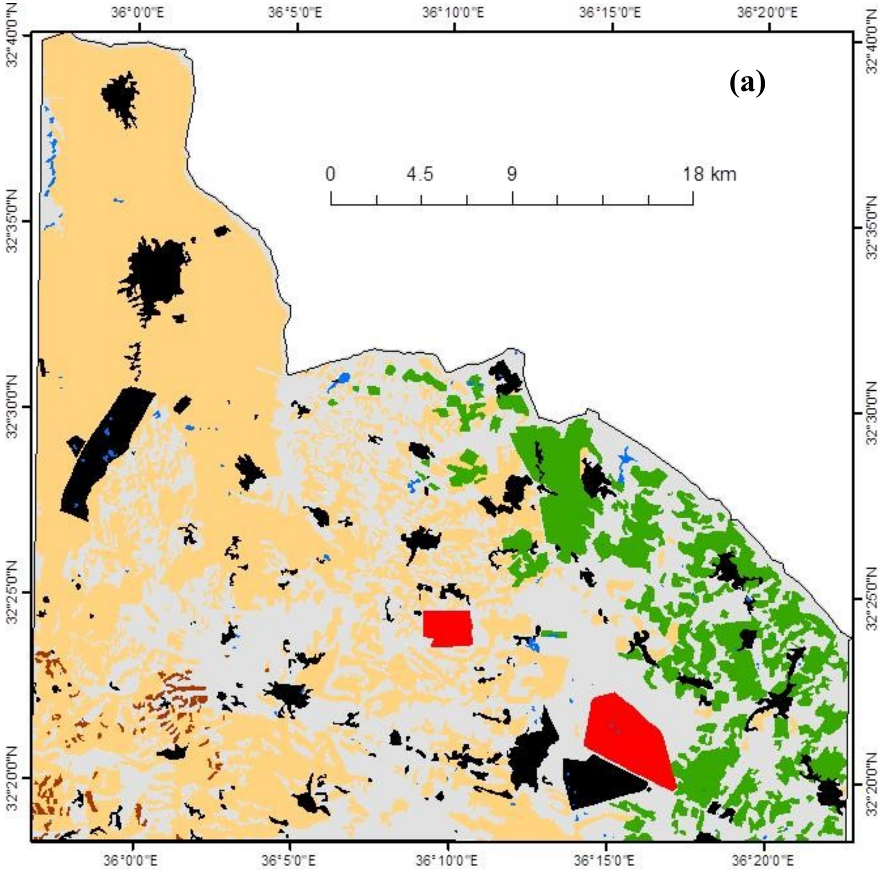


Figure 5. Land use/cover maps of Irbed in 1992 (**a**) and in 2010 (**b**) and for Amman-Zarqa in 1983 (**c**) and 2010 (**d**).



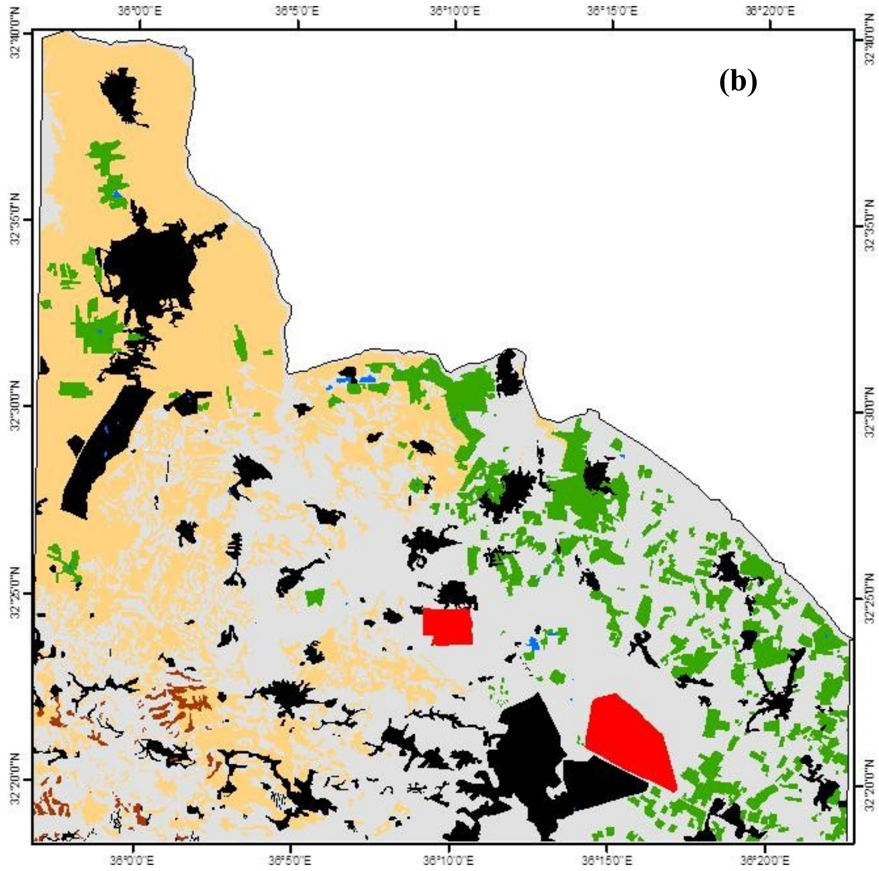


Figure 5. *Cont*.

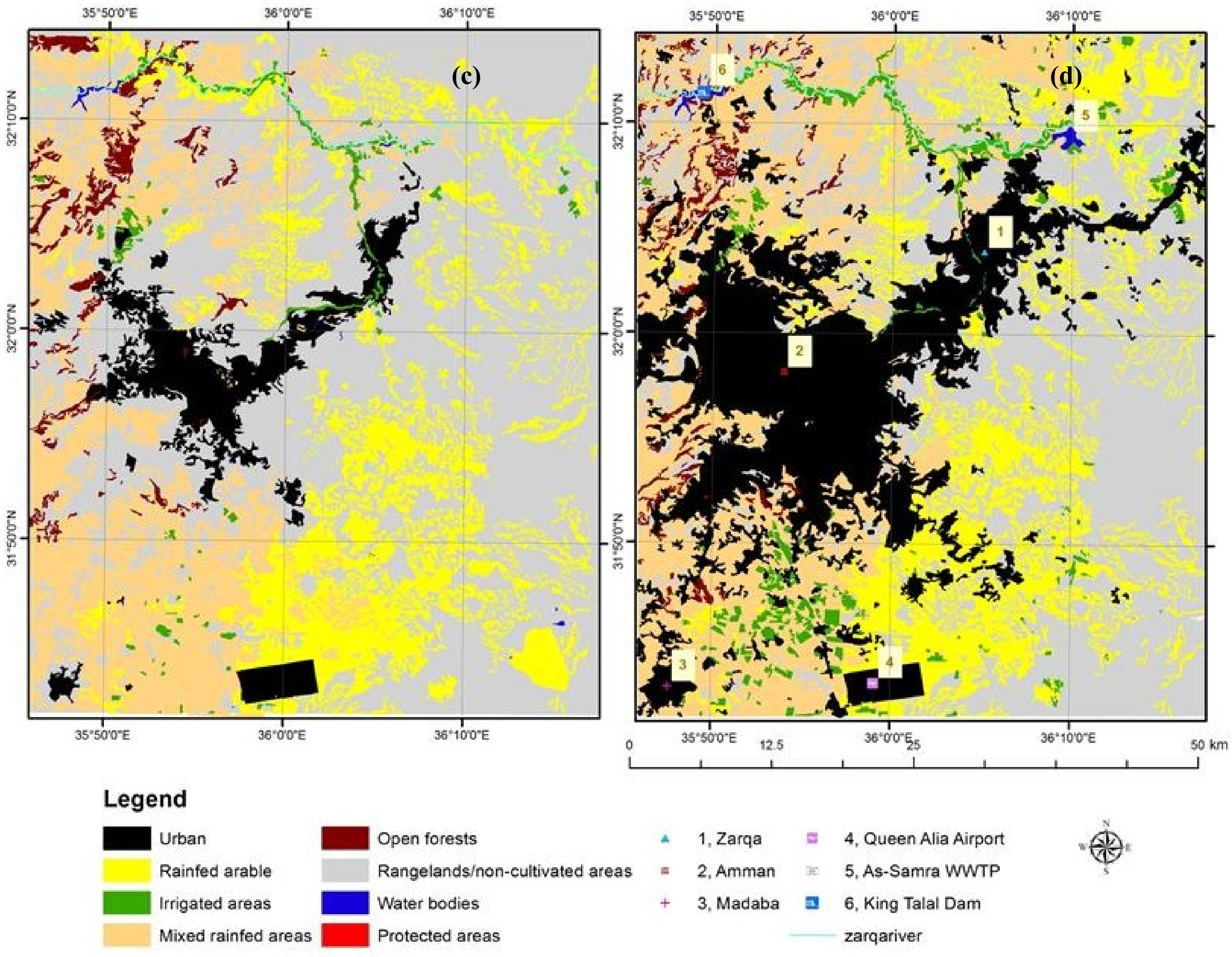


Table 4. Summary of Jordan's land use/cover (% of the total area) in year 2010 and in the future.

Class	Year 2010	Year 2030	Year 2050
Urban	1.7	3.4	6.1
Mixed rainfed areas	3.8	3.3	2.7
Irrigated area	1.1	0.9	0.8
Forests	0.3	0.2	0.1
Rangelands and non-cultivated areas	93.0	92.1	90.2
Water bodies (dams and TWW plants)	<0.1	0.1	0.1

4.2. Climate Change Impact on Crop Production and Food Security

A summary of production changes for the major irrigated crops in the Jordan Valley and highlands is shown in Table 5. The irrigated area for each crop was obtained from the records of the DoS, while the ETc values were calculated using the FAO-56 method for the daily weather data for the period 1994–2008. The changes in production included the impacts of climate change (10% reduction by year 2050) and the trends of land use change in each area. Analysis of figures presented in Table 5 showed that the increase of air temperature by 2 °C would increase the net irrigation amount for potato and squash by 23%, while the combined impacts of increased air temperature and land use change would reduce the total production of most irrigated crops by 27%. These figures were pretty close to those reported for similar conditions in the West Bank [47].

Important findings from this study were also the variations in ETc and productivity among crops. These variations would suggest possible shifts in cropping patterns to cope with the problem of water shortage in the country. Apparently, banana and alfalfa would be seen as the main crops with highest water consumption among the irrigated crops, as their average annual ETc values reached 1,536 and 1,935 mm, respectively. Considering the ratio between productivity and ETc, known as water use efficiency (WUE), farmers might abandon the cultivation of important crops like wheat and olives. This could be concluded from the results of this study, which showed that WUE was higher for the vegetable crops of tomato and potato than for wheat and olives. Under climate change scenarios, WUE would decrease for all crops planted in Jordan (Table 5). Without improving irrigation efficiency, the average decrease in WUE would reach 9 and 17% by years 2030 and 2050, respectively.

Considering the reduction in crop productivity under climate change scenario (Table 2) and the recession of irrigated and rainfed areas (Table 4), self-sufficiency degree (SSD) for most food items would decline in the future (Table 6). In terms of vegetables production, Jordan would be self-sufficient. The SSD of the meat, eggs and fresh milk would depend on availability of forages in the international markets. Of great concern, production of red meat would be highly affected by climate change, as rangelands would not provide enough forage for sheep and goats. Currently, rangelands provide 25% of forages for livestock, while irrigated crops provide 5% of the total forages [48]. The low contribution of rangelands is attributed to the high levels of degradation resulting from the continuous overgrazing of these fragile commons [7,48,49].

Table 5. Current and projected change in crop production for major irrigated crops in Jordan.

Crop	Location	Present				Year 2050			
		ETc (mm)	Area (ha)	Production ($\times 10^3$ ton)	WUE (kg/ha/mm)	ETc (mm)	Area (ha)	Production ($\times 10^3$ ton)	WUE (kg/ha/mm)
Alfalfa	Khirbet As-Samra	1673	609	34.2	33.6	1754	444	24.9	32.0
Alfalfa	Aqaba	1935	479	25.5	27.5	2092	349	18.6	25.5
Apple	Maan	505	1,293	18.3	28.0	561	944	12.1	22.8
Banana	Shooneh Janoobiyeh	1536	826	13.7	10.8	1640	603	10.0	10.1
Citrus	Shooneh Janoobiyeh	731	388	5.3	18.7	781	283	3.8	17.2
Citrus	Deir Alla	834	661	6.7	12.2	929	483	4.9	10.9
Egg Plant	Deir Alla	267	532	17.2	121.1	305	389	11.3	95.2
Olive	Mafraq	562	7,039	11.2	2.8	607	5,138	7.3	2.3
Potato	Deir Alla	205	888	21.4	117.6	253	648	14.1	86.0
Potato	Rum	512	282	8.8	60.9	547	206	5.8	51.5
Squash	Deir Alla	185	580	10.6	98.8	228	424	7.0	72.4
Tomato	Ghour Safi	218	2,441	101.5	190.7	253	1,782	66.7	147.9
Tomato	Deir Alla	254	870	46.9	212.2	299	635	30.8	162.2
Tomato	Mafraq	499	1,850	96.2	104.2	533	1,350	63.2	87.8
Wheat	Irbed	736	5,027	6.2	1.7	832	3,519	3.5	1.2

Table 6. Self-sufficiency degree (%) for the main food items in selected years and in the future.

Food items	Year						
	1994 *	**2002**	**2007**	**2008**	**2009**	**2030**	**2050**
Cereals	6.1	5.0	1.6	1.3	2.9	2.8	1.7
Wheat	10.2	6.6	2.7	0.7	2.0	1.7	1.1
Potatoes	95.4	90.7	85.8	79.7	80.9	63.0	53.0
Pulses	15.0	12.2	3.5	2.5	2.8	1.7	1.6
Vegetables	121.4	139.0	161.0	153.0	162.0	127.0	106.0
Fruits	115.2	82.2	65.5	82.6	86.2	70.0	61.0
Olive oil	107.0	102.0	113.6	99.6	82.2	56.0	54.0
Meat (Mutton)	48.2	41.8	46.0	45.0	45.4	27.5	18.0
Meat (Beef)	9.6	11.9	16.8	22.6	15.9	**	**
Meat (Chicken)	85.3	85.5	85.8	90.0	90.0	**	**
Fish	4.3	6.9	4.8	3.6	4.0	4.0	4.0
Eggs	101.0	102.6	110.0	105.0	108.4	**	**
Fresh milk	49.2	100.0	100.0	100.0	100.0	**	**

*Source: AOAD, 1995 [50]. **Will depend on availability of forage in the international markets.

4.3. Climate Change Impact on Water Security

The total gross irrigation demand in a median year under unstressed conditions (no climate change) would reach 910 and 760 MCM (million cubic meters) in the years 2030 and 2050, respectively. This was predicted using the trends of land use change and future water allocation plans [6]. Results from this study indicated that climatic change would increase irrigation water demand by 14 and 28% for years 2030 and 2050, respectively. This change could be attributed to the increased crop water requirements, resulting from decreased rainfall and increased temperature. Considering climate change impacts on crop water requirements and available water resources, the demand would be 1,037 MCM in 2030 and 973 MCM in 2050.

Results showed that the expected municipal demand would be around 580 and 760 MCM in the years 2030 and 2050, respectively (Table 7). These figures were based on population growth and the water strategy, which assumed reduction in losses due to network rehabilitation, and the implementation of supply augmentation projects, together with higher standards of living in the future, which would demand more water per capita than at the present time.

Table 7. Present and future annual water demand (MCM) for the different sectors in Jordan.

Year	Irrigation	Industry	Tourism	Municipal	Total
2010	1,072	77	10	405	1,564
2022	983 (1,000) *	120	20	494	1,617
2030	910 (1,037) *	150	35	580	1,675
2050	760 (937) *	220	48	760	1,788

* Based on expected changes of ETc under climate change scenarios.

For the tourism sector, the demand would increase and reach 35 and 48 MCM by 2030 and 2050, respectively. The calculations were based on a bed occupancy rate of 47% and an average regular increase of 7.5% in bed capacity. The main consumer in the tourism sector would be the Dead Sea East Coast Development Project at Swaimeh and Zara, which would require 25 MCM by the year 2050. For the industry sector, calculations for the demand were based on the nationwide average regular growth rate of 4.5% in industry and assumed network losses of 3–20%. In total, the industrial water demand would reach 150 MCM by 2030 and 220 MCM by 2050 (Table 7).

It was expected that climate change scenarios of decreased rainfall and increased air temperature would have adverse impacts on water resources of Jordan [51–53]. A reduction of runoff by 25–40% would be likely to occur [52], with more pronounced effects on groundwater recharge than on surface water resources [53]. Therefore, the main future challenge for water sector in Jordan would be the development of water resources to narrow the gap between supply and demand. Currently, the Disi groundwater conveyor is under implementation and will provide 100 MCM/year of non-renewable water from the Disi aquifer (near Rum) to the Capital Amman for the coming fifty years. Other plans would focus on expanding treated wastewater projects and the development of surface water through construction of more dams. The governmental plans, including the Disi conveyor, would develop additional amounts of 419 MCM by year 2022. Also, improvements in irrigation efficiency and water networks leading to fewer losses would add 88 MCM for water supply in year 2022. By summarizing the figures of demand and supply, it was possible to estimate annual water budget for Jordan in the present time and in the future years of 2022, 2030 and 2050 (Table 8).

Table 8. Annual water supply and deficit (MCM) in Jordan with and without climate change.

	Without climate change				With climate change		
	2010	**2022**	**2030**	**2050**	**2020**	**2030**	**2050**
Supply without Red-Dead conveyor	1,144	1,360	1,460	1,540	1,292	1,314	1,232
Supply with Red-Dead conveyor	1,144	1,940	2,040	2,120	1,872	1,894	1,812
Water Demand	1,564	1,617	1,675	1,788	1,666	1,802	2,001
Water balance without Red-Dead conveyor	–420	–257	–215	–248	–374	–488	–769
Water balance with Red-Dead conveyor	—	323	365	332	206	92	–189

Results from water budget showed that water deficit would be 215 MCM by year 2030 and would reach 248 MCM by year 2050. The reduction of the present water deficit could be attributed to the recession in irrigated areas and the development of additional water resources, particularly treated wastewater, which would increase from the present 110 MCM/year to 256 and 400 MCM by years 2030 and 2050, respectively. Under climate change scenarios, water demand would increase for all sectors, while water supply would decrease. Subsequently, the annual water deficit would reach 488 and 769 MCM by years 2030 and 2050, respectively. These figures assumed that agricultural water demand would be reduced due to water allocation policy and trends of land use change in the highlands. Eventually, SSD would decrease due to the problem of inadequate food supply in the country.

In the light of the expected deficit in water resources, mega projects would be needed to overcome the problems of water and food security in Jordan. The main mega project in the future would be the Red Sea–Dead Sea water project, known as the Red-Dead conveyor. The project would restore water levels of the Dead Sea and would desalinate water and generate energy at affordable prices. The expected water share of Jordan from this project would be around 580 MCM per year. The main obstacle for the project, however, would be the high investment cost (10 billion US dollars).

4.4. Implications for Building Adaptive Capacity

Results showed that climate change and land use change would have adverse impacts on water and food security. The impacts would reflect on the "tragedy of the commons" under the scenario of "do nothing". Although the conversion of agricultural land to urban land use might be considered beneficial to water budget, as the municipal water requirements would be lower than the irrigation water requirements. This conversion, however, would indirectly increase water demand as more crop production would be needed to achieve food security. Therefore, building the adaptive capacity would still be needed at all levels to move towards transcendence. Adaptation measures in Jordan could include a wide range of activities targeting water scarcity. Findings from this study, however, implied that all measures should minimize the gap between supply and demand. Since the agricultural sector would remain the main consumer of water, some of the proposed measures at farm and community level might include, but are not limited to, the following:

(a) Modification of cropping pattern

This adaptation measure was supported by findings from this study, which showed that some crops had lower WUE than other crops, *i.e.*, they consumed more water and produced less food. Among these irrigated crops are banana and olives. Also, WUE would differ from one geographical location to another. For example, WUE for potato in Deir Alla (in Jordan Valley) would reach 86 kg/ha/mm compared to 52 kg/ha/mm for the same crop in Rum (desert area). These figures would favor the cultivation of potato in the Jordan Valley rather than in the highlands. This adaptation measure would also include the intrusion of new crop varieties with high WUE.

(b) Improvement of irrigation efficiency

Since climate change scenarios would reduce WUE and since the current irrigation efficiency was relatively low (65%), adaptation measures should include the improvement of irrigation systems efficiency. This adaptation measure "more crop per drop" would increase production and WUE without developing new water resources.

(c) Reuse of treated wastewater

Due to population growth, more wastewater would be generated from urban and rural areas. Therefore, this source of water should be developed and utilized in a sustainable manner. One option would be the reuse of treated wastewater for irrigating fodder crops, provided that water would meet the standards for its reuse. Also, soil suitability for this option should be investigated [54].

Adoption and implementation of the above measures would require planned adaptation at decision-making levels. Some of these measures were included in Jordan's water strategy [6] for the year 2022. The planned adaptation for climate change by years 2030 and 2050 might include:

(a) Water demand management options

This measure should include the control and/or reallocation of water consumption among sectors of utilization. Demand management would also encompass the institutional arrangements supervising the water sector and the allocation patterns to avoid conflicts among sectors.

(b) Water supply management options

Findings from this study showed that the Red-Dead conveyor would be the main water supply to narrow the gap between supply and demand. The other options might include the improvement of efficiency of water use at the system level and the development of marginal water resources of brackish and treated wastewater.

(c) Capacity building and public awareness campaigns

Adaptation measures would not be achieved without creating public awareness as means to knowledge transfer and to helping people develop attitudes necessary to adopt practices and formulate new positive behavior patterns towards water conservation. Although the problem of water scarcity had been recognized at the community level, however, transfer of knowledge and technology would be needed to implement adaptation measures.

It is worth mentioning that the above adaptation measures were categorized as "no-regret" measures [12]. This could be attributed to the fact that the proposed measures would overcome the problem of water scarcity in Jordan; a problem that would form a major challenge for sustainable development in the country, even in the complete absence of the projected climate change.

5. Conclusions

The current study shows that Hardin's "tragedy of the commons" is observed in terms of population growth and the freedom to use of land. However, the impact of climate change is the new issue that reflects on the "tragedy of the commons" and influences our understanding for the problem as related to both environmental and human-induced factors of land degradation. In a country like Jordan, where land and water resources are limited, the "tragedy of the commons" is directly related to food and water security. Although the impact of climate change and land use shifts may create serious challenges to sustainable development, it may, however, imply some guidelines for transcending the "tragedy of the commons" by building adaptive capacities to narrow the gap between water supply and demand. Stabilization of the country's population, as stated by Hardin's essay [1], is not a likely solution in countries like Jordan, where social barriers and political instability in the neighboring countries exist. Alternatively, the study proposes some measures for adaptation to climate change. At the decision maker level, the development of water resources to increase supply is a top priority. At the user level, adaptation measures are focused at managing the demand by increasing water use efficiency and the adoption of appropriate cropping patterns that consume less water and produce more food. Without adaptation plans and measures, the country will suffer from severe reduction in cultivated area and crop production and subsequent reduction in the self-sufficiency degree of food.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. Hardin, G. The tragedy of the commons. *Science* **1968**, *162*, 1243–1248.
2. Agoumi, A. *Vulnerability Studies on Three North Africa Countries (Algeria, Morocco and Tunisia) With Respect to Climatic Changes*, *2001*; final report of UNEP-GEF project RAB94G31; The International Institute for Sustainable Development: Manitoba, Canada, 2003.
3. Chiras, D. D. *Environmental Science*, 9th ed.; Jones and Bartlett Publishers: Sudbury, MA, USA, 2012; pp. 154–196.
4. Al-Bakri, J.T.; Suleiman, A.; Abdulla, F.; Ayad, J. Potential impacts of climate change on the rainfed agriculture of a semi-arid basin in Jordan. *Phys. Chem. Earth* **2011**, *35*, 125–134.
5. Molden, D.; De Fraiture, C.; Rijsberman, F. Water Scarcity: The Food Factor, Issues in Science and Technology, 2007. Available online: http://www.issues.org/23.4/molden.html (accessed on 12 February 2013).
6. MWI (Ministry of Water and Irrigation). *Water for Life: Jordan's Water Strategy, 2008–2022*; MWI: Amman, Jordan, 2009.
7. Al-Bakri, J.T.; Ajlouni, M.; Abu-Zanat, M. Incorporating land use mapping and participation in Jordan: An approach to sustainable management of two mountainous areas. *Mt. Res. Dev.* **2008**, *28*, 49–57.
8. Al-Hadidi, L. *Evaluation of Desertification Risk in Jordan Using Some Climatic Factors*. Unpublished MSc Thesis, University of Jordan, Amman, Jordan, 1996.
9. Tarawneh, Q.; Kadıoğlu, M. An analysis of precipitation climatology in Jordan. *Theor. Appl. Climatol.* **2003**, *74*, 123–136.
10. Freiwan, M.; Kadioglu, M. Spatial and temporal analysis of climatological data in Jordan. *Int. J. Climatol.* **2007**, *28*, 521–535.

11. GCEP (General Corporation for Environment Protection, Jordan). *Jordan's First National Communication to the UNFCCC*; GCEP: Amman, Jordan, 1999.
12. MoEnv (Ministry of Environment, Jordan). *Jordan's Second National Communication to the UNFCCC*; Deposit No. 2009/11/4731; Ministry of Environment: Amman, Jordan, 2009.
13. Shakhatreh, Y. Trend Analysis for Rainfall and Temperatures in Three Locations in Jordan. In *Proceedings of the International Conference on Food Security and Climate Change in Dry Areas*, Amman, Jordan, 1–4 February, 2010; Solh, M., Saxena M.C., Eds.; ICARDA: Aleppo, Syria, 2010.
14. Helsel, D.R.; Hirsch, R.M. *Statistical Methods in Water Resources,* U.S. Geological Survey, Techniques of Water-Resources Investigations Book 4, Chapter A3; USGS: Virginia, USA, 2002; pp. 326–342. Available online: http://pubs.usgs.gov/twri/twri4a3/ (accessed on 12 February 2013).
15. CCSP (Climate Change and Science Program). *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*; A Report by the U.S. Climate Change Science Program and the Sub-committee on Global Change Research; U.S. Environmental Protection Agency: Washington, DC, USA, 2008.
16. Ortiz, R. Crop Genetic Engineering under Global Climate Change. *Ann. Arid Zone* **2008**, *47*, 1–12.
17. Anwar, M.R.; O'Leary, G.; McNeil, D.; Hossain, H.; Nelson, R. Climate change impact on rainfed wheat in south-eastern Australia. *Field Crop Res.* **2007**, *104*, 139–147.
18. Cruz, R.V.; Harasawa, H.; Lal, M.; Wu, S.; Anokhin, Y.; Punsalmaa, B.; Honda, Y.; Jafari, M.; Li, C.; Huu Ninh, N. Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the *Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E., Eds.; Cambridge University Press: Cambridge, UK, 2007; pp. 469–506.
19. FAO (Food and Agriculture Organization). *Assessment of the Risks From Climate Change and Water Scarcity on Food Productivity*; Final Report of deliverable FAO/ RFP/ 2010/01; FAO and STRTM: Amman, Jordan, 2010.
20. Reynolds, M.P.; Ewing, E.E.; Owens, T.G. Photosynthesis at high temperature in tuber-bearing solanum species. *Plant Physiol.* **1990**, *93*, 791–797.
21. Reynolds, M.P.; Ewing E.E. Effects of high air and soil temperature stress on growth and tuberization in *Solanum tuberosum. Ann. Bot.-London* **1989**, *64*, 241–247.
22. Lafta, A.M.; Lorenzen, J.H. Effect of high temperature on plant growth and metabolism in potato. *Plant Physiol.* **1995**, *109*, 637–643.
23. Hazra, P.; Samsul, H.A.; Sikder, D.; Peter, K.V. Breeding tomato (*Lycopersicon Esculentum Mill*) resistant to high temperature stress. *Int. J. Plant Breeding* **2007**, *1*, 31–40.
24. Adams, S.R.; Cockshull, K.E.; Cave, C.R.J. Effect of Temperature on the Growth and Development of Tomato Fruits. *Ann. Bot.-London* **2001**, *88*, 869–877.
25. Jensen, J. R. *Introductory Digital Image Processing: A Remote Sensing Perspective*, 3rd ed.; Prentice Hall: Upper Saddle River, NJ, USA, 2005; p. 526.
26. MoA (Ministry of Agriculture, Jordan). *The Soils of Jordan: Semi-detailed Level (1:50,000)*, *The National Soil Map and Land Use Project, NSMLUP*; MoA: Amman, Jordan, 1995.

27. Rababa'a M.M.; Al-Bakri J.T. Mapping land cover in the Dead Sea basin from Landsat TM satellite imagery. *Dirasat* **2006**, *33*, 103–113.
28. Al-Bakri, J.T. *Remote Sensing Techniques for Environmental Monitoring of the Semiarid Zone of Jordan*. Unpublished PhD Thesis, Cranfield University, Bedfordshire, UK, 2000.
29. Al-Bakri, J.; Nickling W. *Assessment and Monitoring of Desertification in Jordan Using Remote Sensing and Bioindicators*; Report to NATO-SfP983368; NATO-SfP: Brussels, Belgium, 2011.
30. Al-Bakri, J.T.; Taylor, J.C.; Brewer, T.R. Monitoring land use change in the Badia transition zone in Jordan using aerial photography and satellite imagery. *Geogr. J.* **2001**, *167*, 248–262.
31. Khresat, S.; Al-Bakri, J.; Tahhan, R. Impacts of land use change on soil properties in the Mediterranean region of northwestern Jordan. *Land Degrad. Dev.* **2008**, *19*, 397–407.
32. Khresat, S.A.; Rawajfih, Z.; Mohammad, M. Land degradation in north-western Jordan, causes and processes. *J. Arid Environ.* **1998**, *39*, 623–629.
33. MWI (Ministry of Water and Irrigation). *Wastewater Management Policy, Paper No. 4: Management of Wastewater*; MWI: Amman, Jordan, 1998.
34. MWI (Ministry of Water and Irrigation, Jordan). *Annual Report*; MWI, Amman, Jordan, 2007.
35. MWI (Ministry of Water and Irrigation, Jordan). *Annual Report*; MWI: Amman, Jordan, 2009.
36. MWI (Ministry of Water and Irrigation, Jordan). *Special Report on Water Resources in Jordan*; MWI: Amman, Jordan, 2009.
37. MWI (Ministry of Water and Irrigation, Jordan). *Annual Report*; MWI: Amman, Jordan, 2010.
38. Allen, R.G.; Pereira, L.A.; Raes, D.; Smith, M. *Crop Evapotranspiration*; FAO Irrigation and Drainage Paper 56; FAO: Rome, Italy, 1998.
39. Fardous, A.A.; Jitan, M.A. *Water Use Efficiency in Agriculture: Jordan Experience*; National Center for Agricultural Research and Extension (NCARE): Baqa'a, Jordan, 2004.
40. Shatanawi, M.; Fardous, M.; Mazahrih, N.; Duqqah, M. Irrigation Systems Performance in Jordan. In: *Irrigation Systems Performance*, Proceedings of the 2nd WASAMED Workshop, Hammamet, Tunisia, 24–28 June 2004; Lamaddalena, N., Lebdi, F., Todorovic, M., Bogliotti, C., Eds.; CIHEAM: Bari, Italy, 2004; pp. 126–137.
41. FAO (Food and Agriculture Organization). *Trade Reforms and Food Security: Conceptualizing the Linkages*; FAO: Rome, Italy, 2003.
42. FAO (Food and Agriculture Organization). *The State of Food Insecurity in the World*; report no. 4; FAO: Rome, Italy, 2002.
43. DoS (Department of Statistics). *Food Balance Sheet of 2008*; DoS: Amman, Jordan, 2008.
44. DoS (Department of Statistics, Jordan). *Study of Households Income and Expenditures 1987–2010*; DoS: Amman, Jordan, 2010.
45. DoS (Department of Statistics). *Jordan in Figures: 2011*, report no.14; DoS: Amman, Jordan, 2012.
46. DoS (Department of Statistics). *Iraqis in Jordan: Their Number and Characteristics*; DoS, Fafo and UNFPA: Amman, Jordan, 2007.
47. Mimi, Z.A.; Abu Jamous, S. Climate change and agricultural water demand: Impacts and adaptations. *AJEST* **2010**, *4*, 183–191.
48. MoEnv (Ministry of Environment, Jordan). *National Action Plan and Strategy to Combat Desertification*; Deposit no. 2004/1/70; Ministry of Environment: Amman, Jordan, 2006.

49. Abu-Zanat, M.; Ruyle, G.B.; Abdel-Hamid, N.F. Increasing range production from fodder shrubs in low rainfall areas. *J. Arid Environ.* **2004**, *59*, 205–216.
50. AOAD (Arab Organization for Agricultural Development). *Arab Agricultural Statistics Yearbook*; AOAD: Khartoum, Sudan, 1995; Volume 15.
51. Abu Taleb, M.F. Impacts of global climate change scenarios on water supply and demand in Jordan. *Water Int.* **2000**, *25*, 457–463.
52. Abdulla, F.; Al-Omari, A. Impact of climate change on the monthly runoff of a semi-arid catchment: Case study Zarqa River Basin (Jordan). *JABS* **2008**, *2*, 43–50.
53. Abdulla, F.; Eshtawi, T.; Assaf, H. Assessment of the impact of potential climate change on the water balance of a semi-arid watershed. *Water Res. Manag.* **2009**, 23, 2051–2068.
54. Schacht, K.; Gönster, S.; Jüschke, E.; Chen, Y.; Tarchitzky, J.; Al-Bakri, J.; Al-Karablieh, E.; Marschner, B. Evaluation of soil sensitivity towards the irrigation with treated wastewater in the Jordan River region. *Water* **2011**, *3*, 1092–1111.