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Article

Mitigating the Risk of Extreme Water Scarcity and Dependency: The Case of Jordan

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Abstract: Jordan faces great internal water scarcity and pollution, conflict over trans-boundary waters, and strong dependency on external water resources through trade. This paper analyzes these issues and subsequently reviews options to reduce the risk of extreme water scarcity and dependency. Based on estimates of water footprint, water availability, and virtual water trade, we find that groundwater consumption is nearly double the groundwater availability, water pollution aggravates blue water scarcity, and Jordan's external virtual water import dependency is 86%. The review of response options yields 10 ingredients for a strategy for Jordan to mitigate the risks of extreme water scarcity and dependency. With respect to these ingredients, Jordan's current water policy requires a strong redirection towards water demand management. Actual implementation of the plans in the national water strategy (against existing oppositions) would be a first step. However, more attention should be paid to reducing water demand by changing the consumption pattern of Jordanian consumers. Moreover, unsustainable exploitation of the fossil Disi aquifer should soon be halted and planned desalination projects require careful consideration regarding the sustainability of their energy supply.

Keywords: water scarcity; water pollution; water footprint; virtual water trade; water dependency; water risk; water security; sustainability; water policy

1. Introduction

The water situation in Jordan is complex and unsustainable. Jordan experiences growing freshwater demands that already exceed availability and surface and groundwater resources are polluted [1–7]. At the same time, Jordan heavily relies on water resources outside its borders, in the physical sense through the sharing of rivers and aquifers with neighboring countries as well as indirectly through Jordan's strong dependence on virtual water imports [8]. Sharing water resources with Israel and Syria has led to tensions in the past [9–12]. On top of this, Jordan has experienced large influxes of refugees as a result of the ongoing conflicts in the surrounding countries [12,13], which increases Jordan's struggle to meet domestic water needs [1,2,4–6,14,15].

Jordan is partly arid and partly semi-arid [5,6,16,17] and therefore has naturally low water availability. Climate change has caused a decline in precipitation and hence surface water flows [4,6]. Based on model simulations for different climate change scenarios, Abdulla *et al.* [18] found that decreases in precipitation will lead to significant decreases in runoff and groundwater recharge in the Zarqa river basin (Figure 1). The percentage of time that the Jordan River basin and its surroundings will experience moderate, severe, and extreme drought conditions is expected to increase in the future [16]. Such droughts can have devastating effects when the agricultural and water management practices in place are unsustainable [19]. Furthermore, the (semi-)arid conditions in the Jordan Valley, characterized by a combination of high potential evapotranspiration and low precipitation, causes a lack of salt flushing and leaching of agricultural soils, leading to alarming soil salinity levels [20].

Naturally low water availability in Jordan is reduced further by (over)consumption of shared surface water resources by upstream and neighboring countries. Both the Jordan River and the Yarmouk River have been depleted by upstream (over)consumption in Israel and Syria [2,4,6,21]. The sharing of trans-boundary water resources has led to difficulties and tensions. In 1994, Jordan and Israel signed a peace treaty that included agreements on water allocations [22]. Jordan is allowed a certain outflow from Lake Tiberius (situated in Israel) into the Lower Jordan River. The current national water strategy of Jordan assumes 50×10^6 m³/year of water to be secured by the peace treaty [23]. When in 1999 the region was struck by a drought event, the agreed water allocation was threatened and bilateral talks temporarily broke down before the two parties found a resolution in the end [9,10]. With minimal outflow from Lake Tiberius controlled by Israel, the Lower Jordan River mainly depends on inflow from its main tributary, the Yarmouk River [3]. The Yarmouk River is shared by Jordan, Syria, and Israel [24]. Jordan and Syria signed an agreement on sharing the Yarmouk's water in 1987 [11,24]. Nevertheless, the countries have had continued tensions over the construction and operation of Syrian dams on the river [12]. In 2012, *The Jordan Times* [11] reported that Syria violated the agreement, thereby depriving Jordan of its legitimate water share.

Current water demand in Jordan exceeds the limited renewable water resources available in the country. Agricultural water demand is growing (by 38% in the period 2000–2010 [4]) despite efforts to improve irrigation efficiency and encouraging farmers to grow less water-intensive crops [1]. Domestic water demand is unmet and still increasing (by 40%–46% in the period 2000–2010 [4,6]). This increase is due to rapid population growth, caused by a high rate of natural population growth and periodic massive influxes of refugees [1,2,5,6,15]. In 2014, the refugee population in Jordan, mostly consisting of Syrians, was around 10% of the country's total population (Figure 2). These are officially registered refugees only and the actual number is likely to be higher. Since the conflicts in Syria, Iraq, and Israel/Palestine are ongoing, there is every reason to believe that the number of people seeking refuge in Jordan is growing.

Overconsumption of Jordan's surface and groundwater resources is associated with several environmental impacts. Due to the high amount of abstractions along its course, the Jordan River has shrunk to a small creek by the time it reaches the Dead Sea, with current discharge being less than 5% of historical levels [6,7]. This has led to an alarming decline of the Dead Sea level, which in turn causes lowering of groundwater tables in adjacent aquifers [4]. Since the 1970s, the water level of the Dead Sea has dropped at a rate of about 1 meter per year [25,26]. With each meter of reduction, 300×10^6 m^3 of fresh water is lost from neighboring aquifers [25]. Groundwater levels are rapidly dropping throughout the country [1,2,5]. This has led to the drying up of springs and disappearance of the Azraq wetlands [3], with reduced habitat for endemic species and migratory birds as a consequence [1].

Problems of surface and groundwater pollution are widespread in Jordan, which aggravates water scarcity [27]. Inadequate treatment of industrial and domestic wastewater and over- and misuse of fertilizers and pesticides pollute these resources [1,6,28]. The canals that distribute water throughout Jordan are more and more polluted by salts and other agricultural runoff [4]. Pollution of groundwater is exacerbated by overpumping, which leads to a concentration of salts and other pollutants [1,17,29–32]. Hotspots of groundwater pollution in the regions of Amman, Zarqa, and Balqa have been mapped by Alqadi *et al.* [33]. The pollution of water in Jordan is also partially a trans-boundary issue. The Jordan River Basin suffers from agricultural runoff and untreated wastewater from all riparian countries [1].

Jordan thus faces great internal water scarcity and pollution, conflict over trans-boundary waters, and strong dependency on external water resources through trade. Given the great variety of challenges, sustainable water management in Jordan is a challenging task, which thus far has not succeeded. The objective of this paper is to analyze Jordan's domestic water scarcity and pollution and the country's external water dependency, and subsequently review options to reduce the risk of extreme water scarcity and dependency. In the next section we discuss methods and data. In the third section we analyze the water situation in Jordan from a water footprint perspective, with the aim of accurately quantifying the severity of water scarcity and pollution in Jordan. In the fourth section, we analyze the country's dependency on external water resources by quantifying and mapping the world-wide water consumption associated with the products and commodities Jordanians consume. In the fifth section, we review possible responses to Jordan's water problems and external water dependency.

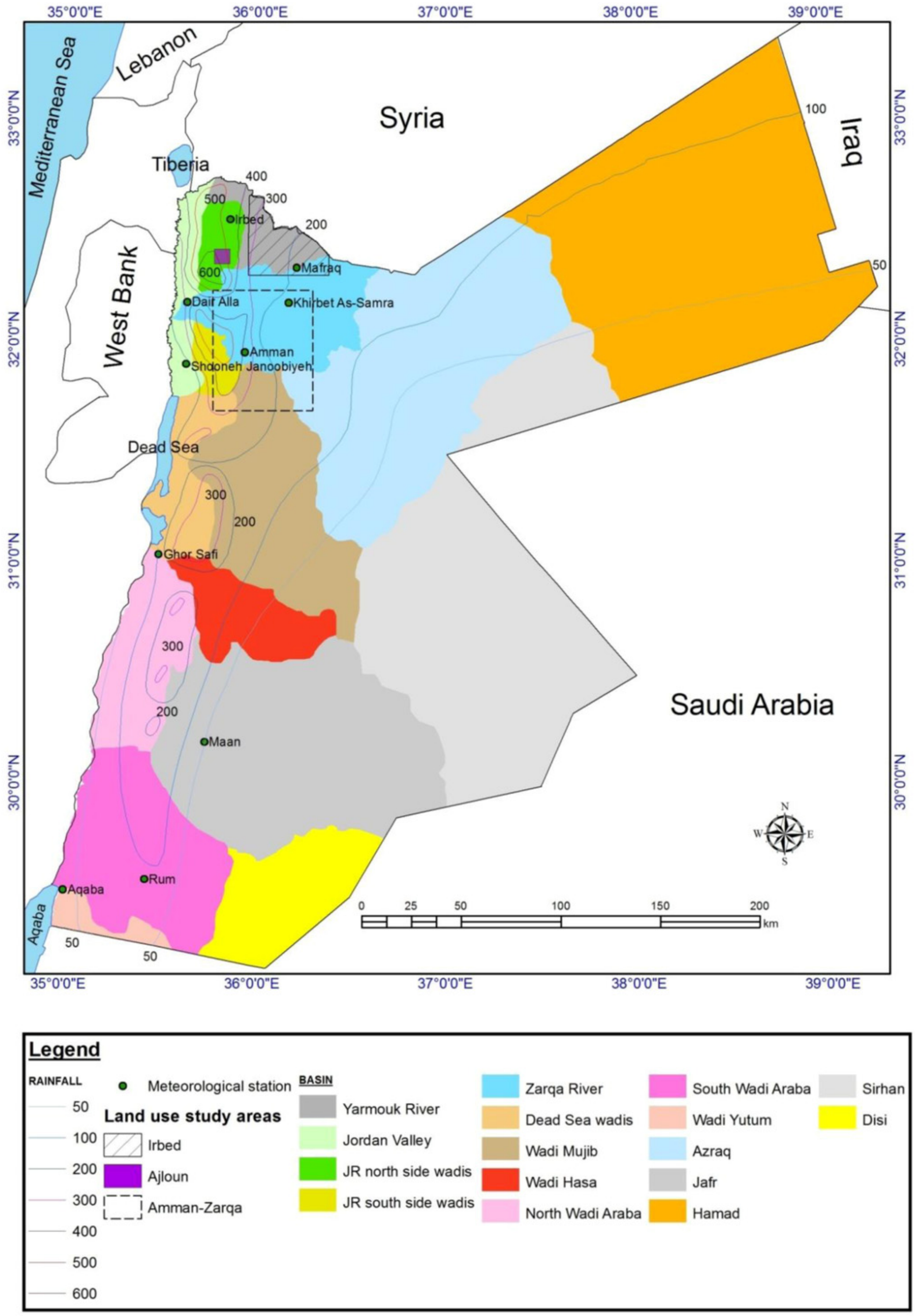

Figure 1. Map of Jordan with surface water basins and rainfall isohyets. Source: [34].

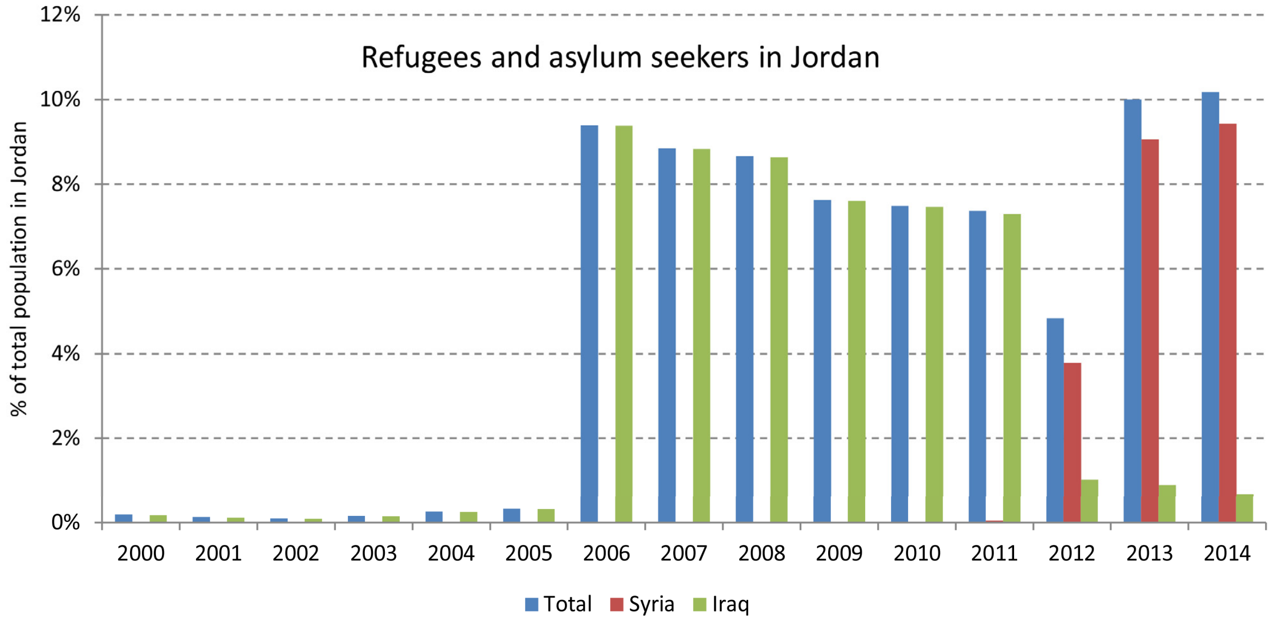

Figure 2. Refugees and asylum seekers in Jordan. Data: total population from [35]; refugee and asylum seekers population from [36].

2. Methods and Data

We estimate water footprints of production and consumption and virtual water trade following the global standard for Water Footprint Assessment [37]. We quantify the water footprint (WF) of five different sectors in Jordan: crop production, grazing, animal water supply, industrial production, and domestic water supply. Therein we distinguish three different WFs: green, blue, and gray. The green WF refers to the appropriation of the green water flow (*i.e.*, evapotranspiration of precipitation stored in the soil moisture and on top of vegetation) in crop production and grazing systems. The blue WF expresses the consumptive use of surface and groundwater (blue water resources), which excludes return flows to these resources. The gray WF expresses water pollution in the same unit as water consumption. It measures the volume of freshwater required to dilute the pollutants that enter blue water resources to such an extent that ambient water quality standards are not violated.

We estimate the WF of crops in Jordan for the period 1996–2005 following the method of and using the same underlying datasets as Mekonnen and Hoekstra [38]. The gray WF of crop production is calculated based on leaching of nitrogen to the groundwater, assuming an ambient water quality standard of 10 mg/L of nitrate–nitrogen (NO_3–N). The WF of grazing and the domestic and industrial sectors as well as imported and exported virtual water volumes are estimated following the methods of Hoekstra and Mekonnen [8]. The gray WFs of the industrial and domestic sectors relate to the aggregate of pollutants, but are conservative estimates since we take the part of the return flow which is disposed into the environment without prior treatment as a measure of the gray WF (thus assuming a dilution factor of 1), following Hoekstra and Mekonnen [8].

The WF of Jordan's consumption, defined as the volume of water consumed to produce all the products consumed by the Jordanian population, inside and outside Jordan, is calculated following Hoekstra and Mekonnen [8]. The national water saving through trade is the volume of water that

Jordan saved by importing products instead of producing them domestically, and is calculated following Mekonnen and Hoekstra [39].

The total blue WF of each sector is split into a part originating from surface water (*i.e.*, blue surface-WF) and a part originating from groundwater (*i.e.*, blue ground-WF). This was done according to the origin of blue water use per sector (groundwater *versus* surface water) which we obtained from Alqadi and Kumar [4]. We scaled the estimated ground-WFs of industries and households to equal water withdrawals based on the consumptive use fraction following Schyns and Hoekstra [40]. The underlying assumption is that none of the water abstracted from groundwater for industrial production and domestic water supply returns (clean) to the groundwater in the same period of time.

Blue water scarcity is calculated as the ratio of the total blue WF in Jordan over total blue water availability [37]. Total blue water availability is defined as the total renewable surface and groundwater resources, as defined by the FAO [41]. We assess blue water scarcity for the sum of surface and groundwater, but also for groundwater separately. Jordan's renewable surface water resources are estimated by taking the sum of treaty allocations and surface run-off produced internally. Groundwater availability is defined as the groundwater recharge minus the fraction of natural groundwater outflow required to sustain environmental flow requirements in the river [37]. In practice, groundwater availability in Jordan is often reported as the "safe yield" of groundwater without further clarification [2,6,23,30,42]. The FAO [41] defines "safe yield" as the amount of water (in general, the long-term average amount) that can be withdrawn from the groundwater without causing undesirable results. Although it is a vague concept [43,44], we take reported figures on safe yield [2,6,23,30,42] as a proxy for groundwater availability, due to lack of data. We consider Jordan's blue water availability around the year 2000 as proper context for the WF estimates that relate to the period 1996–2005. We use the water scarcity classification by Schyns and Hoekstra [40], which is derived from that of Hoekstra *et al.* [45] but compensated for the fact that environmental flow requirements are not considered by using stricter threshold values for the different scarcity levels. A blue water scarcity level beyond 0.4 is classified as severe water scarcity and indicates that the blue WF exceeds 40% of the maximum sustainable blue WF. Levels in the ranges 0.3–0.4, 0.2–0.3, and <0.2 are classified as significant, moderate, and low blue water scarcity, respectively.

The water pollution level is calculated as the ratio of the actual to the maximum sustainable gray WF [37]. The maximum sustainable gray WF, an indicator of the assimilation capacity for water pollution, equals the actual runoff, which is estimated as natural runoff minus the blue water consumed. The water pollution level thus measures the degree to which the waste assimilation capacity of blue water resources has been consumed. A water pollution level above 100% means that the gray WF exceeds the sustainable level, thus ambient water quality standards are violated.

Finally, we review the sustainability of proposed solutions to Jordan's domestic water problems and external water dependency in literature, while involving the results from the analysis in this paper. We categorize the response options into five categories, which we use to position current water policy in Jordan. These categories are: (1) increasing water availability; (2) reducing water demand per unit of product; (3) reducing water demand by changing production and consumption patterns; (4) reducing risks related to the external water dependency; and (5) international assistance in taking in refugees.

3. The Unsustainability of Water Consumption and Pollution in Jordan

3.1. The Water Footprint of Activities in Jordan

The total WF in Jordan in the period 1996–2005 was 1446 × 10^6 m^3/year (53% green; 31% blue; 16% gray) (Table 1). The productive use of green water in crop production and grazing systems accounts for the largest share in the total. Unsurprisingly, the largest blue WF is related to irrigated agriculture. Forty-five per cent of all water consumed (green plus blue) in crop production is blue, showing the high dependency of Jordanian agriculture on irrigation water. Blue water use is predominant in the Jordan Valley and the desert areas, while green water use is predominant in the Highlands [15]. Water consumption in the domestic and industrial sectors constitutes only about 7% of all blue water consumed in Jordan. The gray WF in these sectors is 5.6 times their blue water consumption, due to poor wastewater treatment.

Table 1. Water footprint of activities in Jordan (10^6 m^3/year). Period: 1996–2005.

Activity	Green Water Footprint [1]	Blue Groundwater Footprint [2]	Blue Surface Water Footprint [2]	Total Blue Water Footprint [1,3]	Gray Water Footprint [1]	Total Water Footprint
Crop production	493	263	143	406	54.3	953
Grazing	277					277
Animal water supply		1.4	9.9	11.3		11.3
Industrial production		36.5	0.1	1.9	17.5	19.4
Domestic water supply		232	5.9	29.1	155	185
Total	770	533	159	449	227	1446

Notes: [1] Calculated following [8,38]; [2] Blue groundwater *versus* surface water footprint based on total blue water footprint and [4]; [3] Total blue water footprint is not equal to the sum of blue surface and groundwater footprint, because the blue groundwater footprints of industrial production and domestic water supply equal water abstraction instead of consumptive use only (Section 2).

The WF figures relate to water consumption (net water abstraction) as opposed to water withdrawal (gross water abstraction) and therefore exclude return flows to the natural system. This explains the difference between the WF estimates in Table 1 and the figures on water use distribution over the different sectors reported by Hadadin *et al.* [6] and Alqadi and Kumar [4] that indicate that around 35% of all blue water is used in the industrial and domestic sectors.

Part of the WF in Jordan is related to the production of crops and products for export. Total virtual water export from Jordan in the period 1996–2005 was around 1046 × 10^6 m^3/year (Table 2). This is nearly three-quarters of the WF in Jordan (Table 1), but it also includes the virtual water related to the re-export of imported products. The largest virtual water export volumes are related to cotton-based products, animal products, and industrial products. However, since cotton is not grown in Jordan, the virtual water export associated with seed cotton is due to the re-export of imported cotton that has been processed in Jordan's textile industry. This means that the virtual water export from Jordanian water resources is mainly related to the export of animal and industrial products, whereby the latter is largely related to pollution (gray WF). Large volumes of Jordanian blue water resources (*i.e.*, surface and groundwater) are also exported in the form of tomatoes, wheat, and olives.

Table 2. Jordan's virtual water export (VWE) by product category (10^6 m³/year). Period: 1996–2005. Data based on [8].

Product	Green VWE	Blue VWE	Gray VWE	Total VWE	% of Total
Seed cotton	270	149	53.8	473	45%
Animal products	228	49.8	20.7	298	29%
Industrial products	0.0	6.8	115	121	12%
Tomatoes	5.9	11.9	0.0	17.7	2%
Wheat	11.5	5.0	0.9	17.4	2%
Olives	7.3	4.6	1.5	13.4	1%
Oil palm fruit	8.3	0.0	0.3	8.6	1%
Artichokes	3.8	2.9	0.0	6.7	1%
Papayas	5.4	0.5	0.3	6.3	1%
Other crops	51.7	26.3	5.4	83.4	8%
Total export	592	256	198	1046	100%

3.2. Blue Water Scarcity: Actual versus Maximum Sustainable Blue Water Footprint

Precipitation over Jordan is highly variable in space and time [2,16,46]. According to Mohsen [2], precipitation varies from 6000 to 11,500 million m³/year. The rainy season stretches from October/November to April/May, with 80% of precipitation occurring in the period from December to March and practically zero outside the rainy season [16,32,46]. The northwest of Jordan is semi-arid, receiving 200–600 mm/year of precipitation. Much of the eastern and southern part of the country, constituting about 80%–90% of Jordan's surface area, is classified as arid and receives only 50–100 mm or less of precipitation each year [2,3,6,16,46]. Groundwater availability is assumed to be equal to the "safe yield" from renewable groundwater resources (see Section 2), which is approximately 277×10^6 m³/year [2,6,23,30,42]. We estimate Jordan's renewable surface water resources in the period 1996–2005 at 373×10^6 m³/year by taking the sum of treaty allocations (220×10^6 m³/year) and flow from wadis in the Jordan River Valley (153×10^6 m³/year) in the year 2000 according to Hadadin *et al.* [6]. Total renewable water resources (surface and groundwater) are therefore estimated in this study at 650×10^6 m³/year. This is slightly lower than the 671×10^6 m³/year of renewable blue water in 2000 as estimated by Van Aken *et al.* [3] and slightly higher than the sum of developed surface water resources, flow secured by the peace treaty with Israel, and safe yield from groundwater as reported for the year 2007 in Jordan's national water strategy [23], namely 620×10^6 m³/year. Due to Jordan's high dependency on water from upstream and neighboring countries, total blue water availability in Jordan is not purely natural runoff. Rather, it is actual inflow into Jordan from upstream countries (natural inflow minus what has been consumed through upstream WFs) plus naturally generated runoff from precipitation over Jordan.

When comparing the blue WF to blue water availability, we find that, overall, Jordan is severely water scarce (water scarcity ratio >0.40), and that groundwater is overexploited (water scarcity ratio >1) (Table 3). The groundwater scarcity index indicates that the blue ground-WF in Jordan is nearly double the groundwater availability. Other quantitative estimates of the country-average ratio of groundwater withdrawal over safe yield range from 1.6 [30] to 1.9 [2,4]. Although other studies have also described water scarcity in Jordan as severe, our estimate is even more alarming, since we have looked at water consumption (excluding return flows) rather than withdrawals.

Table 3. Blue water scarcity in Jordan regarding total runoff and groundwater only.

Water Resource	**Water Footprint [1] (10^6 m³/year)**	**Water Availability [2] (10^6 m³/year)**	**Water Scarcity [1] (−)**	**Water Scarcity Level**
Total (surface and groundwater)	449	650	0.69	Severe
Groundwater	533	277	1.92	Overexploited

Notes: [1] Calculated in this study; [2] Surface water availability from [6]; Groundwater availability from [2,6,23,30,42].

3.3. Water Pollution Level: Actual versus Maximum Sustainable Gray Water Footprint

Although the gray WFs of the various sectors as calculated relate to different forms of pollution (the gray WFs of the industrial and domestic sectors relate to the aggregate of pollutants, while the gray WF of crop production relates to nitrate–nitrogen only), we find it appropriate, as a rough estimate, to compare the total gray WF in Jordan with actual runoff. The latter is calculated as the total blue water availability in Jordan minus the total blue WF in Jordan, thus representing runoff after depletion by human consumption. This is the volume of water that is available to dilute pollutants and is termed "waste assimilation capacity" [37]. The water pollution level, the ratio of the actual to the maximum sustainable gray WF, is found to be 1.13 (Table 4). This indicates that the gray WF in Jordan exceeds waste assimilation capacity, meaning that ambient water quality standards are violated, which confirms the widely-voiced pollution of Jordan's water resources [1,2,4,6,17,29–31].

Table 4. Water pollution level in Jordan.

Water Footprint and Pollution Level	**Value**
Total gray water footprint	227×10^6 m³/year
Maximum sustainable gray water footprint	201×10^6 m³/year
Water pollution level	1.13

4. Jordan's Dependency on Foreign Water Resources

With respect to trans-boundary water resources, total treaty allocations to Jordan (from the Jordan and Yarmouk rivers and various springs) around the year 2000 sum up to 220×10^6 m³/year [6]. Comparing this with renewable blue water availability in Jordan around that time (650×10^6 m³/year), we find that the ratio of external to total water resources of Jordan is 34%. In other words, Jordan is dependent on upstream and neighboring countries for one-third of its annual renewable water resources.

Jordan's virtual water import dependency is even larger. Of all the water consumption associated with the production of the products and commodities Jordanians consume, 86% takes place outside Jordan's borders and is spread all over the world (Figure 3). The total WF of Jordan's consumption in the period 1996–2005 is estimated at 8316×10^6 m³/year, of which 6712×10^6 m³/year is virtual water import (Table 5). With virtual water import being more than six times larger than virtual water export

(Table 2), Jordan is a large net virtual water importer. Jordan obtained a national water savings of 7113 × 10^6 m³/year through trade in the period 1996–2005. This is the volume of water that would have been required had Jordan produced all imported commodities itself.

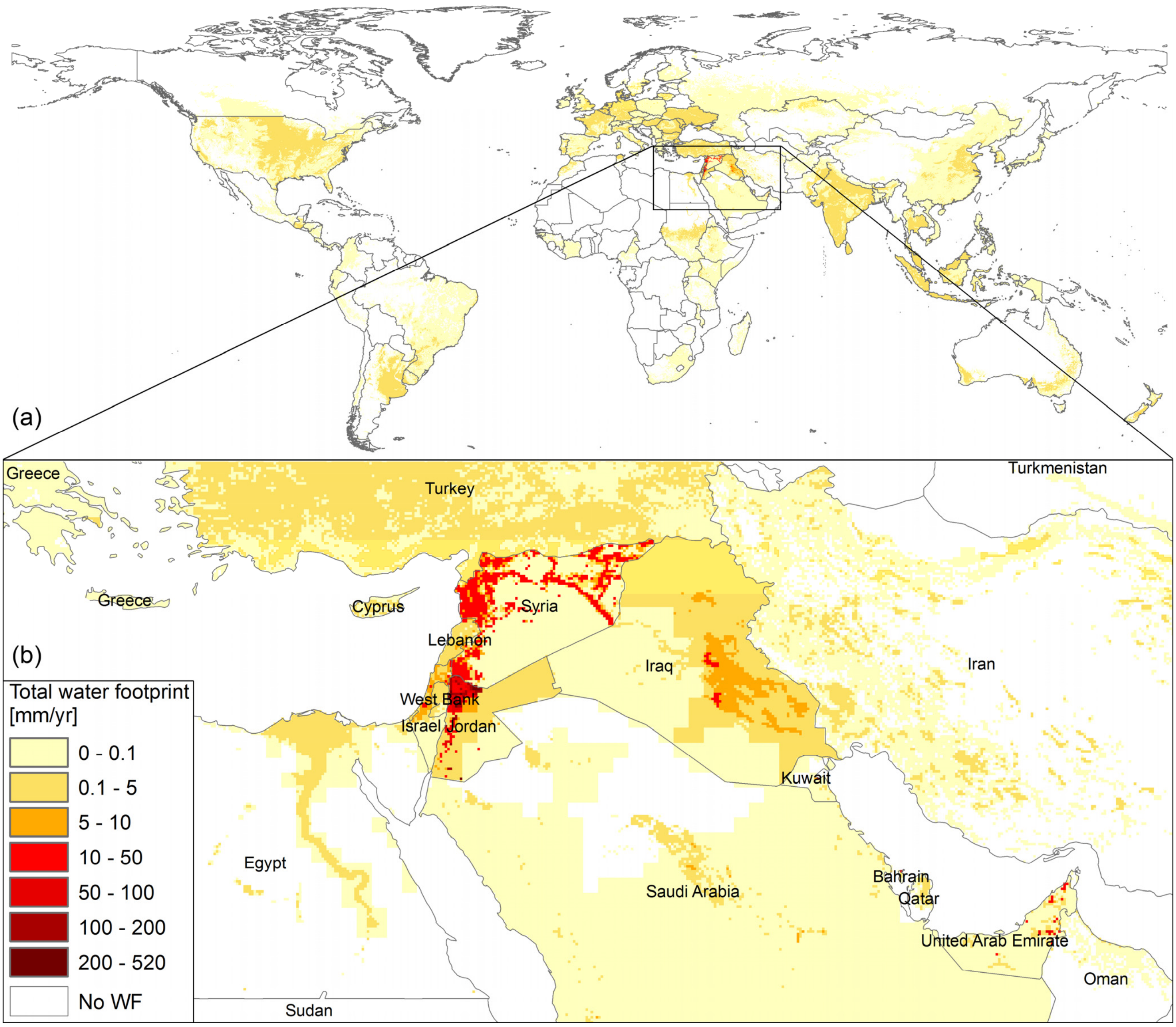

Figure 3. The global water footprint of Jordan's consumption (**a**) and an enlarged view of the Middle East (**b**). Both follow the legend depicted in (**b**). Period: 1996–2005. Data based on [8].

The largest volumes of imported virtual water in the study period are associated with import of: wheat from the USA; barley from Syria and Iraq; maize, soybeans, and wheat from Argentina; animal products and soybeans from India; oil palm from Malaysia and Indonesia; and cotton from China (Table 6). However, it should be noted that the import pattern has changed since then. Data from FAO [47] shows that since 2004/2005 barley imports from Syria and Iraq have ceased and instead have mainly come from Ukraine, Germany, Russia, and, more recently, Romania. Also since 2004/2005, Jordan mainly imports wheat from Russia, Ukraine, and Syria, with only relatively small amounts from USA and practically zero from Argentina [47]. Nevertheless, Jordan's dependency on virtual water imports remains evident.

Table 5. Jordan's virtual water import (VWI) by major product (10^6 m³/year). Period: 1996–2005. Data based on [8].

Product	Green VWI	Blue VWI	Gray VWI	Total VWI	% of total
Barley	1067	217	155	1439	21%
Wheat	937	63	102	1102	16%
Animal products	524	66	17	607	9%
Oil palm fruit	524	0	28	551	8%
Cotton	221	169	107	497	7%
Soybeans	454	14	9	477	7%
Maize	367	20	57	444	7%
Sugar cane	212	70	17	300	4%
Other crops	626	259	67	952	14%
Industrial products	0	23	319	342	5%
Total import	4933	902	878	6712	100%

Table 6. Jordan's virtual water import (VWI) per major trade partner (10^6 m³/year). Period: 1996–2005. Data based on [8].

Country	Green VWI	Blue VWI	Gray VWI	Total VWI	Major Products
USA	697	88	123	908	Wheat–66%, maize–16%, rice–8%
Syria	626	92	122	840	Barley–78%, animal products–4%
Argentina	641	11	31	683	Wheat–25%, maize–38%, soybean–35%
India	434	35	29	498	Animal products–40%, soybean–34%, coffee–7%, wheat–6%, cotton–4%
Iraq	172	222	156	550	Barley–69%, industrial products–29%
Malaysia	319	0.5	14	333	Oil palm–97%
Indonesia	238	0.1	17	255	Oil palm–88%
China	133	22	83	239	Cotton–71%, industrial products–14%, animal products–6%
Turkey	172	21	25	218	Wheat–41%, barley–29%, cheakpeas–13%, cotton–7%
Ukraine	173	4	30	208	Barley–60%, sunflower seed–16%, industrial products–14%, wheat–9%,
Australia	93	41	3	138	Animal products–53%, rice–32%, barley–12%

The largest component in the total WF of the average Jordanian consumer relates to the consumption of animal products such as meat, hides and skins, and milk (Figure 4). This WF is largely located outside Jordan. For example, imports of animal products associated with large WFs came from India and Australia. Higher standards of living in Jordan [48] are likely associated with an increased share of animal products in the average diet and hence an increased WF of consumption.

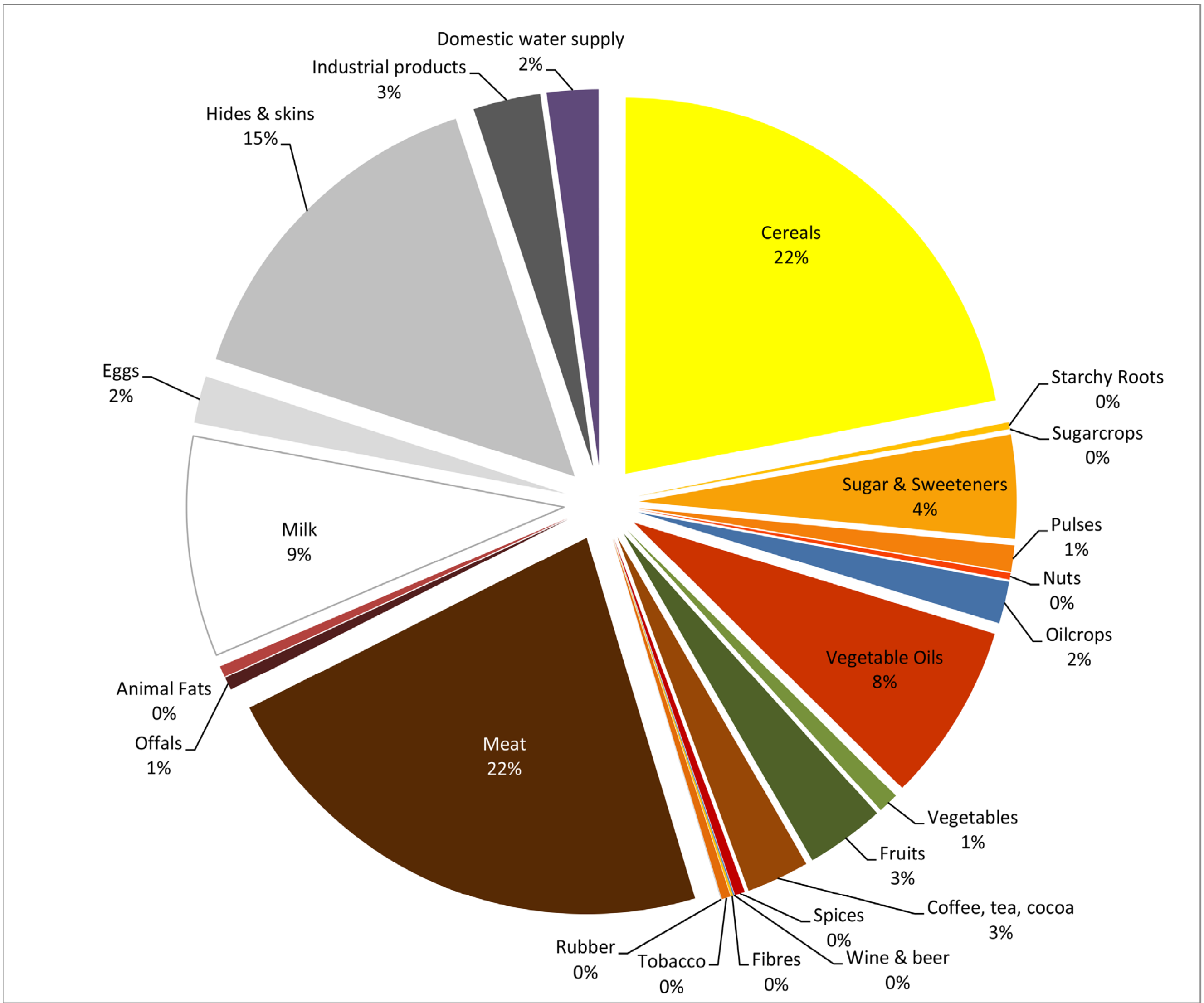

Figure 4. The average water footprint of a consumer in Jordan. Period: 1996–2005. Data based on [8].

5. Options to Respond to Jordan's Domestic Water Problems and External Water Dependency

We review various solutions that have been discussed in the past to greater or lesser extent to address Jordan's domestic water problems and external water dependency. We categorize the various response options into five categories, which are subsequently addressed in the following sections: (1) increasing water availability; (2) reducing water demand per unit of product; (3) reducing water demand by changing production and consumption patterns; (4) reducing risks related to the external water dependency; and (5) international assistance in taking in refugees. Lastly, we reflect upon the position of current water policy in Jordan with respect to the first three categories.

5.1. Increasing Water Availability

5.1.1. Dams for Inter-Seasonal Water Storage

Between 1950 and 2008, 28 dams were built in Jordan, with a total storage capacity of 368×10^6 m³ [32]. The newest and largest is the Al-Wehdah Dam on the Yarmouk River with a storage capacity of 110 × 10^6 m^3 [42], although it only received 41 × 10^6 m^3 from 2006 to 2010 and its utility is reduced due to water quality issues [49]. Constructing more dams does not seem to be the way to increased water availability and reduced water scarcity in Jordan. A lot of water is lost by evaporation from surface water reservoirs [40,50], especially in arid regions such as Jordan. There comes a point where inter-seasonal storage and release of water during low flow conditions no longer outweighs the water loss by evaporation [51].

5.1.2. Disi Water Conveyance Project

The recently realized Disi Water Conveyance Project [52], supplies the greater Amman region from the fossil Disi aquifer, mainly to prevent public water supply shortages [1,6,53]. This is, however, a short-term, unsustainable solution. The annually abstracted volume from the Disi aquifer is about 100 × 10^6 m^3/year [54,55], which can be regarded as a blue fossil ground-WF since there is no return flow from this abstracted volume to the aquifer. It has been estimated that the Disi aquifer can be exploited at a rate of 125 × 10^6 m^3/year for 50 years [2,56]. This means that if current abstraction rates continue in the future, the Disi aquifer will be significantly depleted about 50 years from now. The already visible consequences of mining the Disi aquifer in the past are discussed by Salameh *et al.* [55]. In addition, the Disi Water Conveyance Project has a big energy footprint due to the distance and altitude difference that need to be bridged [15]. Furthermore, the quality of the Disi water has been under discussion, since it has been shown that the Disi aquifer contains high amounts of radioactive isotopes [57]. It would be wise to cap the fossil ground-WF in Jordan to zero and use the water from non-renewable resources only when it is urgently needed, in low amounts and at low frequencies.

5.1.3. Desalination

According to several authors [2,4,6,55], the most promising long-term solution to the water problems in Jordan is desalination. The main project regarding desalination is the Red Sea-Dead Sea Canal project. Early in 2015, Jordan and Israel signed a “green-light” agreement for this project [58]. Jordan’s national water strategy projects for 2022 an additional amount of 510 × 10^6 m^3/year desalted water compared to 2007, mainly to be realized by the Red Sea-Dead Sea Canal project [23]. Besides desalination, a major goal of the project is to restore the water level of the Dead Sea to around 400 meters below sea level with imported water from the Red Sea [59]. The Red Sea-Dead Sea Canal project, which also aims to supply Israel and Palestine, should also bring increased political stability to the region by improved regional water security [59]. According to estimates by Al-Omari *et al.* [60,61], the additional freshwater supply from the Red Sea-Dead Sea Canal could reduce the domestic and irrigation water deficit in the Jordan Valley down to zero, even under increased water demand and reduced water availability in their climate change scenario.

Increasing Jordan’s water availability by desalination of salt or brackish water seems like an attractive option, especially to ensure public water supply. However, this is under the provision that the required energy for the very energy-intensive process of desalination is driven by sustainable solar and/or wind power. The Red Sea-Dead Sea Canal requires additional energy for intake of the water from the Gulf of Aqaba and transport through the canal and to the public water supply stations. Part of the energy is generated in the project itself by hydro turbines driven by the large elevation differences, but a significant energy demand remains [59]. Meeting this demand with fossil energy is of course not sustainable. Moreover, it would also make Jordan increasingly dependent on foreign energy resources, since Jordan is poor in oil and gas [62]. The most recent data, for 2011, show that Jordan already imports 96% of the energy it uses [35]. Jordan's energy dependency is thus even larger than its dependency on foreign water resources (86%; see Section 4).

5.1.4. Water Harvesting and Productive Use of Precipitation

Various options have been proposed to make better use of the precipitation that falls over Jordan: (a) building micro-dams along major water courses to store flood water during winter [2,6]; (b) improved soil management to increase soil moisture storage in rain-fed agriculture (leading to less unproductive evaporation and higher yields) [6]; (c) productively using the limited rainfall over desert areas by growing more drought-tolerant crops [15]; and (d) rainwater harvesting in urban areas for domestic purposes that do not require drinking water quality [6,17,63]. Regarding the latter, Abdulla and Al-Shareef [63] estimate that a maximum of 15.5×10^6 m³/year of rainwater can be harvested from the roofs of Jordanian residential buildings, that is, if all rain on all surfaces is collected. For drinking purposes, this water would require proper treatment [63]. All these options seem worthwhile for investigating and implementing. Most likely, they would be able to reduce the frequency and size of domestic and agricultural water shortages, when supply temporarily falls short of demand, e.g., in weeks in which the potable water supply through the official network is cut, stored urban rainwater from the previous week can partially alleviate the shortage for some household purposes. Regarding agriculture, one could think of a short-term dry spell experienced at a particular site—which normally severely limits crop yields—but which the crop can survive through better soil management, because previous precipitation events sufficiently recharged the soil moisture. However, their potential seems insufficient to significantly alleviate water scarcity in Jordan, which is characterized by an imbalance between water availability and demand on a larger spatial and temporal scale [27].

5.1.5. Treatment and Reuse of Wastewater

An important track followed by Jordan is the treatment and reuse of wastewater, mainly in agriculture [23,48]. The percentage of total generated wastewater in Jordan that was actually reused increased from 30% to 38% in the period 2004–2007 [64]. Treated domestic and industrial wastewater supplies 12% of Jordan's irrigation water [65] and the effect of that on soils and crops remains a topic of study [66]. Potential future uses of treated wastewater are groundwater recharge and industrial cooling [48].

Obviously, implementation of proper wastewater treatment will improve the water quality of Jordan's surface and groundwater resources. However, reuse of treated wastewater is not always possible and is limited by the presence of certain substances [65]. It is also a challenge to overcome negative perceptions towards the reuse of treated wastewater, some of which may be due to cultural and religious concerns [67,68]. Furthermore, one should avoid the pitfall of viewing wastewater as a new freshwater source that comes in addition to other water sources such as ground- and surface water and desalinated water [37]. Wastewater originates from one of those other sources, so one cannot increase water availability through reuse.

5.2. Reducing Water Demand per Unit of Product

5.2.1. Rationalization of Irrigation Water Use

Irrigated agriculture has the largest blue WF in Jordan (Table 1). In theory, irrigation water use can be reduced by increasing the price of irrigation water [3,69–71], introducing improved irrigation systems [6,72–74], and training farmers in irrigation practices [29,69]. Furthermore, reinforcing private ownership of wells may be an option, since well owners have been shown to use irrigation water and groundwater resources in a more sustainable way than well leasers [69].

In practice, the effectiveness of these options is limited, though. Molle *et al.* [72] argue that the scope for pricing mechanisms to improve irrigation and economic efficiency in the Jordan Valley is limited. Substantial water price increases are expected to have an effect, but then farmers should be offered alternatives (e.g., less water-intensive crops or the chance to exit agriculture) and positive incentives that lower capital and risk constraints for farmers should be co-implemented [72]. According to Van Aken *et al.* [3], improving irrigation efficiencies will merely reduce return flows (resulting from over-applied water) to the underlying aquifers and hence do not lead to actual water savings from a catchment point of view. Furthermore, since a great deal of the irrigation area in Jordan has already been converted to advanced irrigation systems supplied from a pressurized pipe network [21,72,74,75], the remaining potential for increasing irrigation efficiency is probably limited. However, there is room for water savings by better design and maintenance of the drip irrigation systems and better irrigation scheduling [72,74].

5.2.2. Reduce Green and Blue Water Footprints of Crops: Benchmarks

Introducing crop-specific benchmarks is a way to make sure that the green and blue water consumption to produce a ton of a certain crop in Jordan remains below reasonable levels [76,77]. These benchmarks can, for example, be developed by looking at the best X% performing farmers in Jordan regarding WFs, or in neighboring countries with comparable climate and soil conditions. This can set a target for other farmers, who can reduce their water consumption per unit of crop by adopting advanced irrigation techniques with smart and efficient irrigation scheduling and improving soil and crop management (affecting both green and blue water use), all to avoid unproductive evaporation and increase yields. The challenge will be to provide sufficient stimuli and capital for farmers to achieve the benchmarks (or penalties for not achieving them).

Although crop production has the largest WF and hence reduction of the WF per unit of crop will have the largest overall effect on reducing the WF in Jordan, benchmarks can also be developed for other water-consuming sectors in Jordan, for example the large animal industry. It should be noted, however, that with options to reduce the water demand per unit of product, the rebound effect lures. This refers to the situation in which the saved water is used for extra production, thus (partially) offsetting the environmental gains of the efficiency improvement [76].

5.2.3. Reduce Gray Water Footprints: Prevent and Treat

To reduce gray WFs, water pollution should in the first place be prevented as much as possible and unavoidable waste streams should be properly treated. Educating farmers in the use of fertilizers could reduce agricultural pollution caused by over- and misuse of fertilizers. Also here, benchmarks could serve as a target for industries and farmers to minimize their gray WFs. By properly treating unavoidable wastewater streams, much of the current pressure that pollution puts on blue water resources can be relieved. Therefore, Jordan should further invest in wastewater treatment plants.

5.2.4. Rehabilitation of Public Water Supply Network

Water savings are expected by rehabilitation of the potable water distribution network and subsequent proper maintenance of these systems, especially in the capital, Amman [1,3,14,53,73]. Currently, much water is lost in these networks by leakages (30%–50% [3]). However, from a catchment perspective this water that leaks from underground pipes is not considered a loss, because it will probably return to the groundwater and surface water rather than evaporate. In other words, this option will help in reducing public water supply shortages, but does not reduce water scarcity in Jordan from an environmental point of view.

5.3. Reducing Water Demand by Changing Production and Consumption Patterns

5.3.1. Maximum Sustainable Water Footprints: Caps and Permits

To prevent resource overconsumption, a WF cap that equals the maximum sustainable WF in a river basin or aquifer and a system of WF permits could be established [76,78]. This is especially urgent for Jordan's groundwater resources. We have estimated that the ground-WF in Jordan is nearly double the groundwater availability (Section 3.2). All sectors in Jordan heavily rely on groundwater (Table 1; [4]). To prevent this vital resource from drying up, Jordan should protect its groundwater from overexploitation by making sure that the ground-WFs remain below maximum sustainable levels. For each aquifer, the Ministry of Water and Irrigation and the Water Authority of Jordan could issue ground-WF permits among the water consumers. The sum of these permits shall not exceed the groundwater availability for each aquifer, defined as the groundwater recharge minus the fraction of natural groundwater outflow required to sustain environmental flow requirements in the river fed by the aquifer [37]. It would be wise to formally establish the groundwater availability of each aquifer as a ground-WF cap, which represents the maximum sustainable ground-WF for the aquifer. Ideally, such ground-WF caps are reconsidered on a yearly basis [77], to account for the high inter-annual variability in rainfall and groundwater recharge in Jordan.

Although in the past efforts have been made to limit groundwater abstractions, limits have not been respected and too many abstraction permits have been issued [3,29,72]. Clearly, it will be a challenge to establish ground-WF caps and proper issuing and enforcement of ground-WF permits while managing the social and economic consequences of reducing groundwater consumption. Promising additional policies include regulations on the number of new wells being drilled [4] and selective closure of wells by restricted permitting and buyouts [29]. Moreover, increases in the price of energy (electricity and fuels) could give farmers an incentive to reduce groundwater (over)pumping [1].

A cap on the surface WF in the Jordan River Basin and its sub-catchments would also benefit the environment by (partially) restoring historical runoff and flow into the Dead Sea. However, because the basin is shared by five countries in a politically tense region, this remains fairly far-fetched for the near future. Nevertheless, when first focusing on capping ground-WFs, one should be aware of, and try to manage, the risk of increased surface-WFs as a result. The opposite happened when surface water diversions were capped in the Murray-Darling river basin [77].

5.3.2. Produce High Value-Added Products and Crops: Allocation Efficiency

Maximum sustainable WFs dictate how much water can be used in total (in a specific basin or aquifer). Optimal use of the sustainably available water can be achieved by changes in the production pattern. It has been voiced that Jordan should promote a shift from water-intensive low value added crops to less water-intensive and high value-added crops [1–3,79,80] or completely towards sectors other than agriculture [1,2].

Wise water allocation in Jordan should focus on meeting the domestic water demand and production of high value-added products and crops with relatively low WFs for export. The income generated by export can then be used to import water-intensive commodities (mainly agricultural products) required by the Jordan population. This will indeed be socially difficult to obtain, although Jordan is not so dependent on agriculture as one might think [2], and will make Jordan even more dependent on foreign water resources than it already is. However, the latter scenario is practically unavoidable for countries poor in natural resources such as Jordan.

Politics is perhaps the biggest reason that water reallocation between crops and sectors has not been successful so far. As elaborately discussed by Van Aken *et al.* [3] and Zeitoun *et al.* [81], there are influential tribes and political elites who exert powerful opposition against such measures. Furthermore, pricing mechanisms do not affect a large part of the farms where water-intensive crops are grown, which are owned by absentee owners who are interested in prestige or leisure rather than farm returns [3].

5.3.3. Change Consumption Patterns

A further step in water demand management is to influence consumption patterns that ultimately drive the demand for water and thus the domestic water scarcity and external water dependency. Several authors have noted that programs to educate water users and raise awareness among the public could help in reducing water use [2,6,29,32]. Specifically, such campaigns should focus on the WF associated with the products Jordanians consume and how changes in their consumption pattern could significantly lower the pressure on water resources. This would be far more effective than focusing on water conservation techniques in the household, since the WF of an average consumer in Jordan relates to only 2% to water consumption in and around the house (Figure 4). On the other hand, nearly half of the WF of the average Jordanian consumer is associated with the consumption of animal products (of which 22% is meat) and this share is likely to increase due to higher standards of living. Therefore, effective campaigns to stimulate reduced meat consumption, such as meat-free days, seem to be the way to a smaller WF in Jordan (and elsewhere). Also product labels, physical or digital, that inform the consumer about the WF of a product and the degree of water scarcity in the catchment where it was produced and/or provide a simple "yes or no" advice based on certain sustainability criteria [77], would raise awareness and ultimately influence consumer choices for the better (*i.e.*, reduced environmental impact).

5.4. Reducing Risks Related to the External Water Dependency

It has long been recognized that Jordan is strongly water-dependent on other countries, because the country is a large net virtual water importer [6,80,82–87]. Externalizing its consumption-related WF is an important mechanism for Jordan to reduce water demand within its borders.

The previously discussed solutions potentially enable sustainable use of Jordan's domestic water resources, accepting that the country remains heavily dependent on external water resources. Jordan is by far too poor in water resources to be self-sufficient or even near self-sufficient. Hence, Jordan's already large external water dependency will unavoidably continue in the future. There are two important strategies for Jordan to mitigate the associated risks.

By externalizing its WF Jordan creates additional pressure on foreign water resources. Importing virtual water from regions that are under a degree of water scarcity similar to or worse than Jordan is not sustainable and carries the risk of unreliable import flows caused by water limitations elsewhere (e.g., failure of yields due to drought). Major trade partners of Jordan that have river basins facing severe water scarcity during several months of the year are, for example, Australia, China, India, Turkey, and the USA [45]. An important strategy for Jordan is therefore to aim at importing water-intensive commodities from nations that are not under a high degree of water scarcity, e.g., from countries in Northern Europe, South America, Central Africa, or Canada [45,88]. This is a growing challenge, since water scarcity is becoming increasingly important, not only blue but also green water scarcity [27]. When an increasing number of regions in the world face water limitations to production, externalizing water consumption to other, less water-scarce, nations will become more difficult.

As a second strategy, Jordan can reduce the risk of import dependency by diversifying its imports over various trade partners. Looking at Jordan's external WF in the period 1996–2005 and food imports since (see Section 4), we already see a shift in Jordan's import partners away from Syria and Iraq, most probably inevitable due to the unstable situations in these countries.

Moreover, as noted in the previous section, to be able to maintain a high virtual water import dependency economically, Jordan should generate sufficient income to finance imports. Therefore it should use its domestic resources to produce high value-added, low water-consuming products for export.

In contrast to our view, Alqadi and Kumar [4] state that further reliance on virtual water import is not the way to go for Jordan and that desalination is the only means to replace current virtual water imports. However, it is unthinkable that Jordan domestically produces the majority of the commodities it currently imports. Jordan's national water saving by trade is huge, being in the order of annual precipitation over Jordan and more than 10 times larger than renewable blue water resources. In other words, even in the hypothetical situation that all rainfall over Jordan would be used productively to make the commodities consumed by the people in Jordan, this would barely suffice. To put it differently, nearly 14 times the projected volume of desalted water in 2022 (520×10^6 m^3/year [23]) would be required to replace the water Jordan saved by virtual water imports, notwithstanding the limitations of available arable land in Jordan to becoming more self-sufficient.

Reduced risk from Jordan's dependency on trans-boundary rivers and aquifers will need to come from international cooperation towards improved regional water security. It shall be clear that this is a major challenge considering the history of the region [22], recent conflicts in the region [12,13], and biased knowledge production [89].

5.5. International Assistance in Taking in Refugees

Jordan has serious problems with securing its domestic water supply and has to cope with large refugee influxes [1,2,5,6,15]. Because Jordan's water resources are currently insufficient to support the already large and rapidly increasing population in a sustainable manner, the international community should assist Jordan in taking in refugees.

Alongside Lebanon, Turkey, Iraq, and Egypt, Jordan is in the top five host countries of Syrian refugees, together hosting roughly 95% of Syrian refugees by 2014 [90]. A year later, with the Islamic State having taken over large parts of Syria and Iraq and the upheaval of the Israeli-Palestinian conflict in the summer of 2014, the number of refugees in Jordan has expanded even more (Figure 2). As Jordan and other first-host countries do not have the capacity to cope with the sudden large population growth, this could eventually lead to economic and social instability in these countries [91].

Financial humanitarian aid is mainly coming from the European Union (EU) [90,92]. However, only about 4% of all Syrian refugees sought asylum in the EU [93] and they are predominantly taken in by Germany and Sweden [90]. Furthermore, the Gulf Cooperation Council (GCC) could potentially provide more assistance. According to Amnesty International [90], the countries of the GCC (Bahrain, Qatar, Saudi Arabia, Oman, Kuwait, and the United Arab Emirates) have contributed zero resettlement places for Syrian refugees.

5.6. Positioning Current Water Policy in Jordan

With respect to the first three response categories discussed above (Sections 5.1–5.3), current water policy in Jordan is mainly focused on the first category of response: increasing water availability [4,81]. To a lesser extent, policy is directed at reducing water demand per unit of product by improving efficiency in irrigation and public water supply networks and treatment and reuse of wastewater.

Efforts in the category of reducing water demand by changing production and consumption patterns concentrate on limiting over-exploitation of water resources. Besides efforts to combat groundwater over-abstraction [29], Jordan's national water strategy [23] includes plans to limit and regulate irrigated agriculture. Allocation efficiency is also a topic in the national water strategy, which acknowledges that water should be allocated to high value-added purposes with relatively low water consumption, while ensuring that domestic water needs are fulfilled [23]. Better water pricing and removing import tariffs on agricultural commodities should stimulate this [23]. However, despite the attention to these strategies in Jordan's water strategy, practice shows a focus on meeting demand with supply-side measures, while efforts to manage demand face opposition from powerful entities, as previously mentioned [81].

Influencing dietary consumption patterns to reduce water demand remains unmentioned in the national water strategy [23] and does not seem to be on Jordan's policy agenda. The document does include goals on raising awareness, but these rather focus on informing the public of the water problems in Jordan so as to create support for intended regulations to increase water prices and limit abstractions and to provide "concrete suggestions on economically cost-efficient measures every individual can implement to reduce water demand" [23]. The latter applies to water conservation techniques in the household, rather than choices in what to consume.

6. Conclusions

We have analyzed Jordan's domestic water scarcity and pollution and the country's external water dependency and conclude that:

1. Even while taking into account the return flows, blue water scarcity in Jordan is severe;
2. Groundwater consumption is nearly double the groundwater availability;
3. Water pollution aggravates blue water scarcity;
4. While Jordan's dependence on trans-boundary resources is already large (34%), its dependency on external water resources through trade is much larger, with 86% of the water consumption associated with the production of products and commodities consumed by the Jordan population taking place in foreign countries all over the world.

Subsequently, we have reviewed sustainable solutions that reduce the risk of this extreme water scarcity and dependency. A strategy for Jordan to mitigate the risks of extreme water scarcity and dependency should involve the following ingredients:

1. Do not tap into fossil groundwater resources; use only in urgent times, in low amounts and at low frequencies.
2. Drive desalination projects with sustainable solar and wind energy.
3. Investigate and implement options for water harvesting and productive use of rainfall to overcome water shortages on the small scale.
4. Prevent pollution, treat inevitable waste streams, and possibly reuse wastewater flows, but consider that treated wastewater is not a new freshwater resource in addition to ground- and surface water and desalinated water.
5. Develop WF benchmarks for crops and products that reflect reasonable levels of water consumption per unit of production and work towards achieving those benchmarks by focusing on smart and efficient irrigation scheduling and improved soil and crop management.
6. Cap the WF in each river basin and aquifer to the maximum sustainable WF, focusing on groundwater first, while managing the risks of averted impact on surface water.
7. Increase allocation efficiency by making sure domestic water demand is met and using the remaining available water below the maximum sustainable level for the production of high value-added products and crops with relatively low WFs for export.
8. Use the revenue obtained by export to finance the inevitable imports of water-intensive products and commodities from a diverse number of countries that are under a significantly lower degree of water scarcity than Jordan.

9. Stimulate a change towards consumption patterns with a lower WF, e.g., by means of introducing meat-free days and product labeling.
10 The international community should assist Jordan in taking in the large numbers of refugees from neighboring conflict regions, to reduce the domestic water demand.

With respect to these ingredients, Jordan's current water policy requires a strong redirection towards water demand management. Actual implementation of the plans in the national water strategy (against existing opposition) would be a first step. However, more attention should be paid to reducing water demand by changing the consumption patterns of Jordanian consumers. Moreover, unsustainable exploitation of the fossil Disi aquifer should soon be halted and planned desalination projects require careful consideration on the sustainability of their energy supply.

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Author Contributions

Arjen Y. Hoekstra and Arwa Hamaideh initiated the study; Joep F. Schyns and Arjen Y. Hoekstra designed the study; Mesfin M. Mekonnen and Joep F. Schyns performed the calculations; Joep F. Schyns analyzed the data and wrote the paper with contributions from all co-authors; Marlou Schyns specifically contributed Section 5.5.

Conflicts of Interest

The authors declare no conflict of interest.

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