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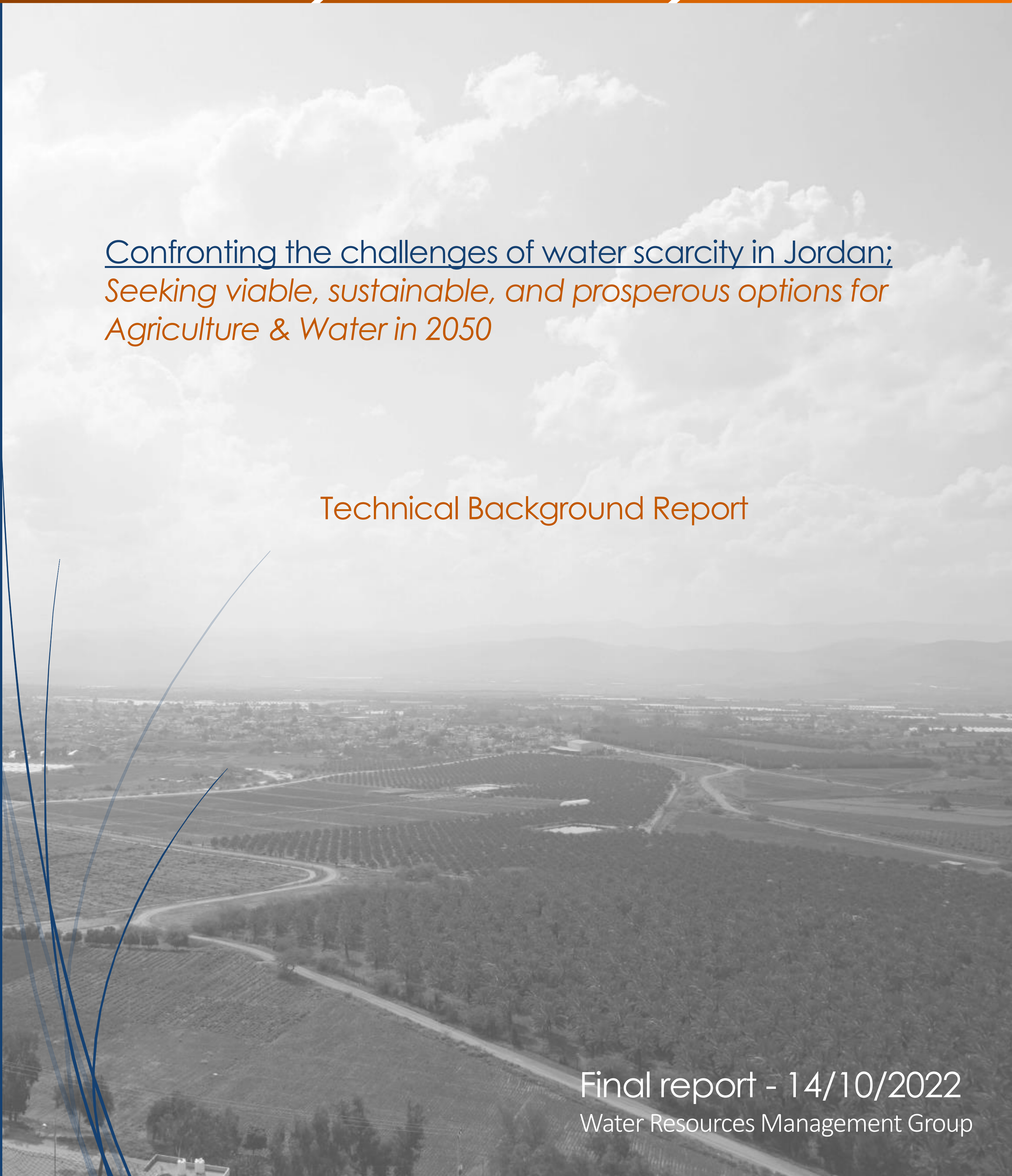

Confronting the challenges of water scarcity in Jordan;

Seeking viable, sustainable, and prosperous options for Agriculture & Water in 2050

Technical Background Report

Final report - 14/10/2022

Water Resources Management Group

Acknowledgements

The project 'Confronting the challenges of water scarcity in Jordan' aims to seek viable, sustainable and prosperous options for agriculture and water in 2050 by bringing different stakeholders together to discuss and explore future options. This would not have been possible without the engaged participation of the different stakeholders, ranging from ministers, ministerial officials, the international donor community, regional authorities, farmers and the private sector. Thus, we would like to sincerely thank all participants of the workshops for sharing their extensive knowledge and experiences.

Moreover, we would like to express our gratitude to the Embassy of the Kingdom of the Netherlands in Amman. Through frequent meetings with Dr. Melle Leenstra, Rania Al-Zou'bi, Coen van Kessel and Suha Albitar, the project was shaped and constantly improved throughout its duration. We would also like to thank Advance Consulting and Delphy for mobilizing relevant contacts. Without the contributions of the above-mentioned people, the project would not have been the same.

Finally, we would like to thank the Netherlands Enterprise Agency (RVO) for their constant support and funding of the project through the Shiraka program (reference numbers: 202108114 and 202204008, and purchase order number: G2G21J071).

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Table of Contents

Introduction

For decades Jordan has been rapidly abstracting its groundwater resources in favour of domestic, industrial, but mainly agricultural purposes, while exceeding the yearly groundwater recharge. This has left vast areas of the main overlying aquifer already unsaturated, forcing both private and public well owners to drill deeper and deeper wells in a destructive race to the bottom (BGR & MWI, 2019). In total, up to 40% of Jordan's groundwater system is at risk of depletion by 2030 if current pumping rates continue (Mercy Corps, 2014). The water crisis in Jordan is further exacerbated by a continuous population growth and a changing climate, which will hit the Mediterranean disproportionally hard (Leal Filho & Manolas, 2022). Thus, as freshwater supplies have to be increasingly replaced by desalinated brackish or saline water and even treated wastewater, Jordan will sooner than later have to fully adhere to the Arab saying: *"Any water in the desert will do"*, if it is to meet all its demands in a sustainable manner.

This is a very inconvenient truth, but one that has to be faced by all Jordanians to collectively seek for viable, sustainable, and prosperous options in all demand sectors: agriculture, industry, and domestic. As the largest demand sector with the lowest economic return on water used, agriculture will face the biggest challenges to sustainably meet its needs in 2050. Thus, the main goal of the project conducted by the Water Resources Management (WRM) group from Wageningen University & Research with support from RVO and the Embassy of the Kingdom of the Netherlands (EKN), was the following:

Finding viable, sustainable, and prosperous options for Agriculture & Water in 2050

A distinction is made between options to achieve this goal in the 'Jordan Valley' and the 'Highlands', with the Jordan Valley representing the valley itself plus the Southern Ghors and Wadi Araba and the Highlands representing the rest of Jordan, as shown in Figure 1.

In each region a venue was selected to host a series of three workshops. These workshops focussed on facilitating dialogues for a wide array of regional stakeholders. Firstly, to discuss current water challenges and agricultural policies and their implications on the ground, secondly to collectively face the inconvenient truth of water scarcity in Jordan and thirdly to draw and discuss recommendations for agriculture and water to provide a water- and socio-economically secure future for the next generation.

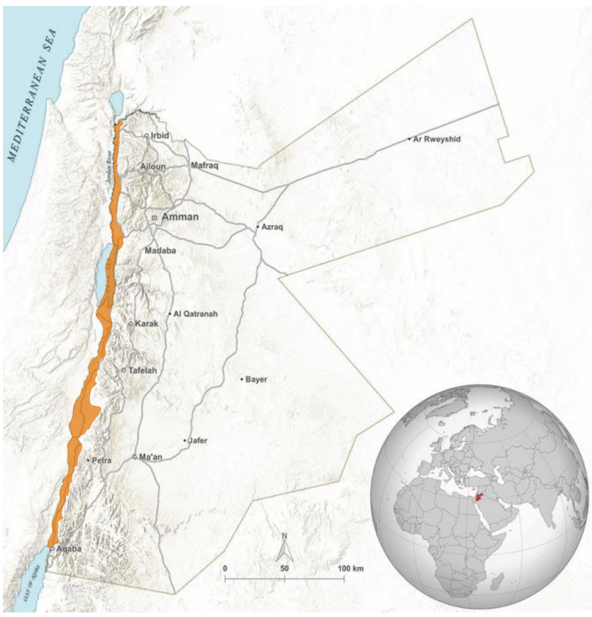


Figure 1: The Hashemite Kingdom of Jordan, divided into the 'Jordan Valley' and the 'Highlands' (BGR & MWI, 2019)

This report is part of a threefold dossier on reporting on the outcomes of the project. The dossier includes i) the policy recommendations report, reflecting on recommendations discussed during the workshops, ii) the technical background report (i.e., this report), where technical information is provided about the recommendations and the assumptions and sources used from the WUR team during the workshops, and iii) the workshop report, reporting on the discussions of the workshops. The presentations given by the WUR team during the workshops are provided in the supplementary documents.

The technical background report is structured in thematic units. First, we discuss the water balance for 2016 (chapter 1). Second, the past trends and the outlook of the water balance is explored (chapter 2). Third, the different water supply augmentation options are explored (chapter 3) and the developed 'Water Allocation Game' (WAG) is presented (chapter 4). Following, the food security in Jordan (chapter 5) and the economic value of water (chapter 6) are discussed. Last, the technical background on the recommendations mentioned during the workshops and the WAG are discussed (chapter 7).

1. Water Balance 2016

1.1 Data sources

Before viable, sustainable, and prosperous options for Agriculture & Water in 2050 can be found, insight should be provided into the actual water situation of Jordan. As recent data on detailed figures of the water resources and their beneficiaries is difficult to retrieve, a water balance for 2015/2016 has been created, based on various sources, see Table 1. The data for surface water and treated wastewater are from the year 2016, while the data for groundwater resources are from 2015. From herewith, however, the water balance will be referred to the year 2016.

Table 1: Sectoral water resources withdrawal (MCM/yr) in Jordan in 2016

Source Use	Domestic	Industrial	Irrigation	Livestock	Total
1. Surface Water (2016)[1]	123.75	3	155	7	288.75
a. Jordan Rift Valley	101.86	3	89.16	0	194.02
- KAC	68.82	0	52.88	0	121.7
- Southern Ghor & W. Araba	33.04	3	36.28	0	72.32
b. Highlands	21.89	0	65.84	7	94.73
- Springs	20.41	0	21	0	41.41
- Base & Floods	1.48	0	44.84	7	53.32
2. Treated Wastewater (2016)[1]	0	2.1	134.24	0	136.34
a. TWW registered in Jordan Valley	0	0	101.12	0	101.12
b. TWW non-registered in Highlands	0	2.1	33.12	0	35.22
3. Groundwater (official - 2015)[2]	336.7	31.59	260.47	0.18	628.94
a. Groundwater (fresh)	332.5	31.59	260.47	0.18	624.74
- Jordan Rift Valley, incl. W. Araba[3]	8.63	2.11	21.1	0	31.84
- Highlands	323.87	29.48	239.37	0.18	592.9
b. Groundwater (Brackish, Abo Zeighan)	4.2	0	0	0	4.2
4. Groundwater (unregistered - 2015)[4]	0	0	267[5]	0	267
Total utilised water resources	460.45	36.69	816.71	7.18	1321.03

[1] Al-Kharabsheh, 2020
[2] (Al-Karablieh & Salman, 2016)
[3] Excluding Southern Ghors, since no specific data for these areas could be obtained
[4] (BGR & MWI, 2019)
[5] Assuming all groundwater use apart from irrigation is registered

The unregistered groundwater use is defined by means of deducting the registered groundwater abstraction from the total simulated groundwater abstraction as presented in Figure 2 (BGR & MWI, 2019).

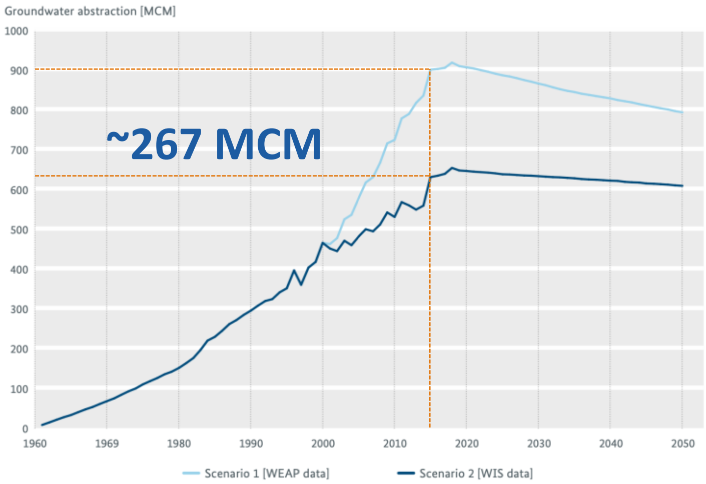


Figure 2: Simulated groundwater abstraction from 1960 to 2050 for all wells (BGR & MWI, 2019)

1.2 Safe groundwater yield

Safe yield is a politically deemed groundwater abstraction rate that defines the rate that may be extracted from aquifers, as deemed appropriate by society (Molle, 2011). Sustainable or renewable yield is a hydrological term that defines the groundwater abstraction rate as the quantity that is yearly renewed by rainfall and surface water inflow and seepage. As long as this rate is not exceeded, groundwater levels remain stable, and groundwater abstraction can continue indefinitely and sustainably, as the used groundwater resources are replenished. In the context of Jordan, safe groundwater yields are defined at a rate higher than the renewable yield for the Disi and Jafer groundwater basins, with a total difference of 143 MCM (MWI, 2017). This means over-extraction/depletion of aquifers occurs at a rate that is currently deemed acceptable by society, as the Disi aquifer can be extracted 'safely' for fifty years (Al-Hadidi & Al-Kharabsheh, 2015). Within this report, however, these quantities are not deemed acceptable, as they cannot be sustainably abstracted indefinitely and are therefore not included in the actual renewable supply figures.

For means of simplicity in playing the Water Allocation Game (WAG), this report uses the term 'actual renewable supply'. This is defined as the sum of internal renewable resources (IRWR) and external renewable resources (ERWR), considering the quantity of flow reserved to upstream and downstream countries through formal or informal agreements or treaties and possible reduction of external flow due to upstream water abstraction (FAO, Review of World Water Resources by Country - Water Reports 23, 2003). Within the boundaries of available data, the derivative terms 'assumed renewable surface- or groundwater supply' are not considering the interconnectedness of surface- and groundwater nor the negative externalities of groundwater abstraction on downstream use(r)s. Therefore, they have only been used as indicative values for the sustainable yields of both water bodies.

Thus, based upon the data that is available, the assumed renewable groundwater supply, i.e., the amount of groundwater that is recharged yearly, is set to 275 MCM. This value has not been adapted for more than 20 years and thus it does not take into account variations in rainfall due to climate change (Mohsen & Al-Jayyousi, 1999) (Al-Kharabsheh, 2019). The overall renewable supply has also remained unchanged and is still discerned as 835 MCM (MWI, 2017). Thereby, assuming a maximum renewable surface water supply of 560 MCM. The Jordan River basin is, however, already considered closed, with all its flow allocated for uses other than the maintenance of its aquatic ecosystem services (Venot, Molle, & Courcier, 2008) (Smakhtin, 2008). Thus, the actual surface water extraction in 2016, 289 MCM, is considered as the assumed renewable surface water supply, whereby any extra surface water extraction, i.e., capturing of flood waters, would harm already highly degraded Jordanian ecosystems even more (Chen & Weisbrod, 2016). In conclusion, the total actual renewable water supply, i.e., the total sustainable yield in Jordan in 2016 is 275 MCM plus 289 MCM, which is 564 MCM.

Based upon these actual renewable supplies and the data from Table 1, Figure 3 was created, depicting all the supply flows from the various resources divided over the Jordan Valley and the Highlands.

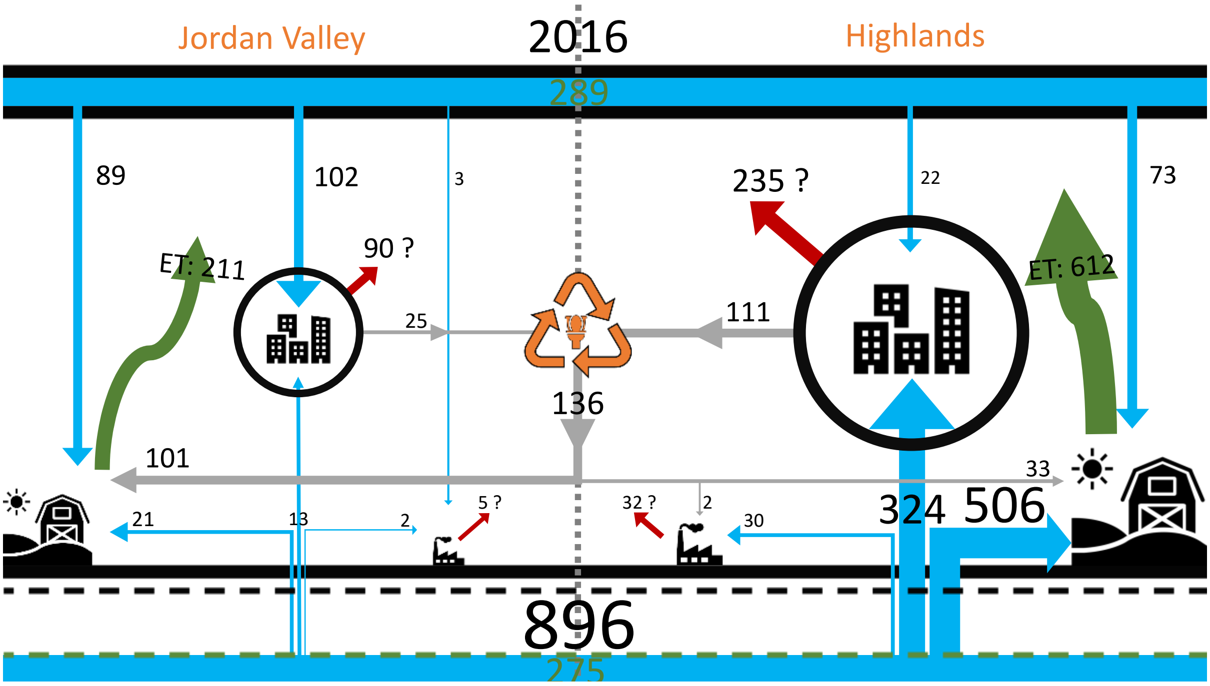


Figure 3: Water balance 2016 (Values in MCM)

1.3 Over-abstraction & outlook to 2050

Current actual renewable supplies are under pressure of climate change, which in general is expected to reduce precipitation in Jordan by 10-20 %, hence a diminution of 15 % is assumed to calculate the actual renewable supply in 2050 (Taleb Al-Bakri, et al., 2013).

$$Assumed\ renewable\ surface\ water\ supply = 289 \times 0.85 = \ 246\ MCM$$

$$Assumed\ renewable\ groundwater\ supply = 275 \times 0.85 = 234\ MCM$$

$$Total\ assumed\ renewable\ water\ supply\ 2050 = 246 + 234 = 480\ MCM$$

When the assumed renewable groundwater supply is compared to the actual groundwater abstraction, a massive gap appears, as shown in Figure 4.

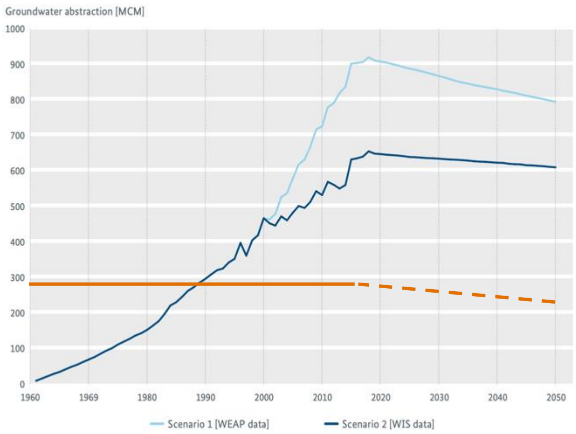


Figure 4: Simulated groundwater abstraction from 1960 to 2050 for all wells, including actual renewable groundwater supply (orange) ((MWI) & (BGR), 2019)

The impact of this over-abstraction of groundwater resources is already felt by farmers and domestic consumers alike, as vast areas in the A7/B2 aquifer have already become unsaturated, while other areas have seen a major decrease in saturated thickness. As the most important aquifer in Jordan, the A7/B2 aquifer is highly exploited for industrial, domestic, and agricultural purposes, primarily in the central and northern highlands. If current exploitation rates continue, the still (partly) saturated areas will befall a same faith, e.g., the unsaturated areas west and northwest of Amman, between Zarqa and Mafraq, and between Amman and Madaba, as shown in Figure 5. This will subsequently lead to a further exploitation of the underlying A4 and A1/A2 aquifers, where the groundwater level is already dropping with an average of more than 0.6 m/yr (BGR & MWI, 2019). The consequences of this overexploitation can be clearly seen in the A4 aquifer, which is already substantially unsaturated. The underlying A1/A2 aquifer still has, for the majority, a considerable saturated area, however, due to the great depth (>400 m) at which its groundwater has to be abstracted, the economic feasibility is highly questionable (BGR & MWI, 2019).

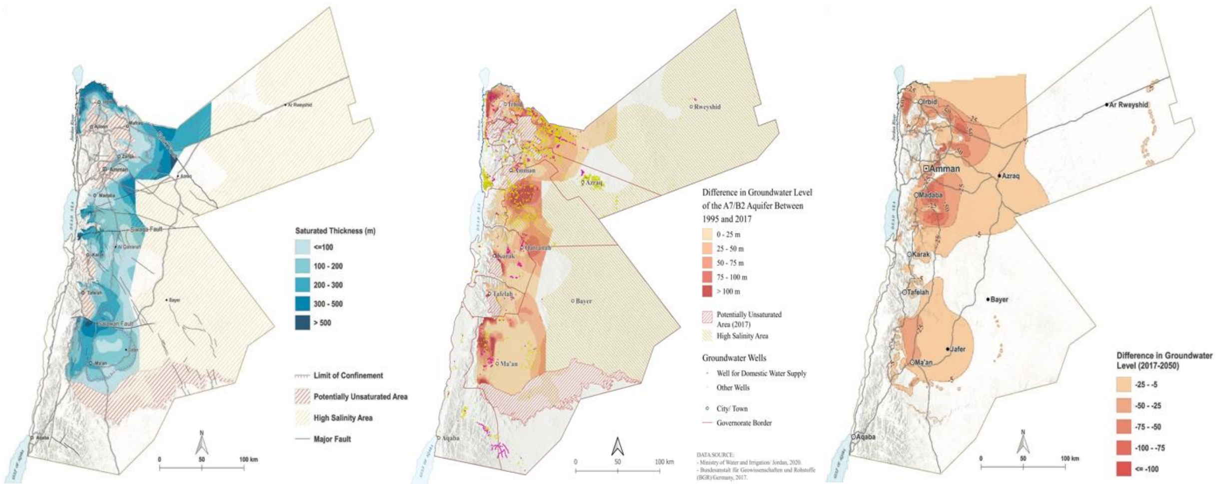


Figure 5: The development of the A7/B2 aquifer over time (BGR & MWI, 2019)

Thus, Jordan is currently highly dependent on overextraction of its groundwater resources to fulfil its industrial, domestic, and agricultural needs, hereby only buying time, thus postponing the inevitable. If this rate of overextraction is continued, Jordan will have consumed most of its economic extractable (non-)renewable fresh groundwater reserves by 2050. Hereby Jordan deprives itself of the possibility of closing any future unexpected gap in the water balance.

2. History of the water balance and outlook to 2050

When studying historical water balances, trendlines can be distinguished, culminating into an outlook to the water demands of 2050 as shown in Table 2 and Figure 6 (Taleb Al-Bakri, et al., 2013). The future domestic demand was calculated based on projections of population, increasing up to 17 million by 2050 and a capped per capita share of water of approximately 122 l/d, close to 45 m^3/c/yr.

$$Total\ domestic\ demand\ 2050 = (17 \times 45) + 48 = 808\ MCM$$

Irrigation demand was predicted using the trends of land use change, Jordan's national water strategies, and a 28% increase in crop water requirements due to reduced precipitation and increased temperature because of climate change, culminating into a total irrigation demand of 937 MCM by 2050 (Taleb Al-Bakri, et al., 2013).

The tourism demand figures were considered as part of the domestic demand and were expected to increase to 48 MCM by 2050 (Taleb Al-Bakri, et al., 2013).

The total industrial demand by 2050 was estimated to be 220 MCM, based on the nationwide average regular growth rate of 4.5% in industry and assumed network losses of 3–20% (Taleb Al-Bakri, et al., 2013).

Table 2: Sectoral water demands (MCM/yr) in Jordan in 2050 (Taleb Al-Bakri, et al., 2013)

Sector	Domestic	Industrial	Irrigation	Total
Total demand	808	220	973	2001

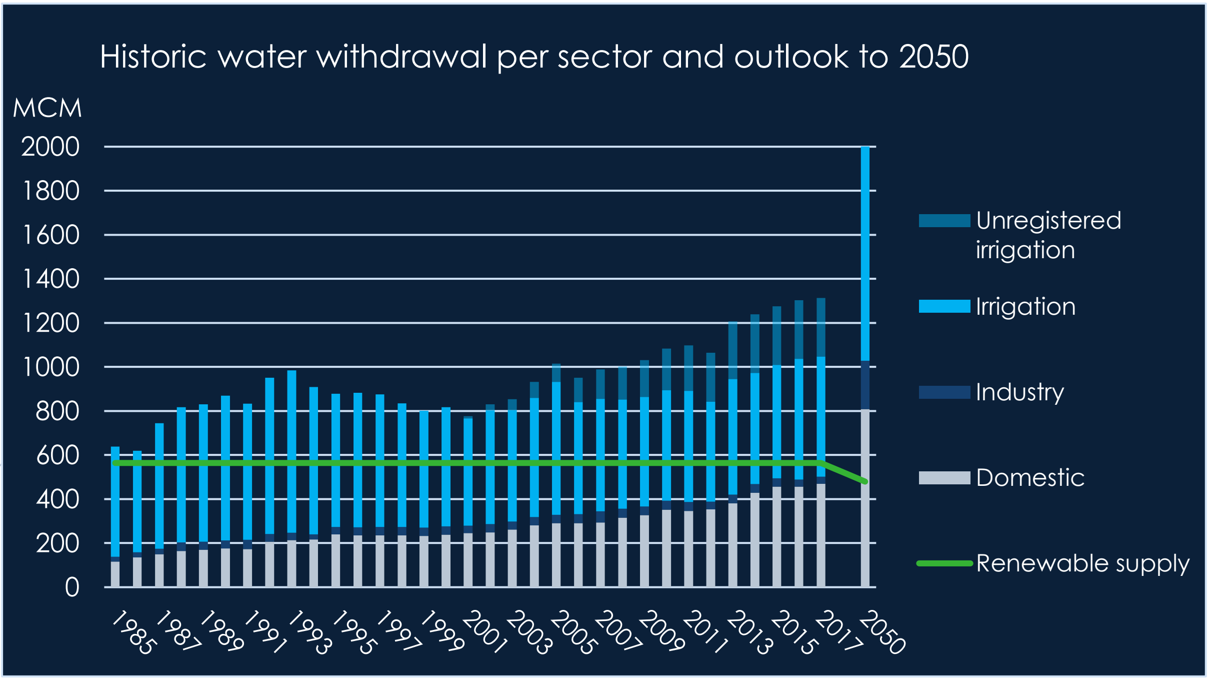
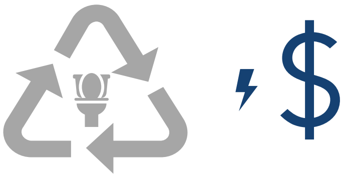


Figure 6: Historic water withdrawal per sector and outlook to 2050 demands (Al-Kharabsheh, 2019) (BGR & MWI, 2019) (Taleb Al-Bakri, et al., 2013)

3. Water Supply Augmentation Options

To bridge the considerable gap between the assumed renewable supply and the demand in 2050, potential supply augmentation options have to be considered and studied, not only in terms of their potential attribution to bridging the gap, but also in terms of technical and economic feasibility. Thus, the following options have been reviewed.

3.1 Wastewater Treatment (TWW)



Treated wastewater (TWW) is often perceived as an additional source of water, allowing extra consumption on top of the total renewable supply. However, as illustrated in Figure 7, implementation of wastewater treatment and its subsequent use is often at least partly a rerouting of either ground- or surface water flows that were already consumed elsewhere. Where water use is defined as the total amount of water withdrawn from its source to be used, and water consumption is defined as the portion of water use that is not returned to the original water source after being withdrawn, and is thus lost into the atmosphere through evaporation or incorporated into a product or plant (Reig, 2013). In other words, TWW can only satisfy additional demands if the untreated return flow to surface- or groundwater was not consumed yet. Otherwise, it can only function by replacing current surface- or groundwater abstractions, which is the situation Jordan finds itself in (Figure 7).

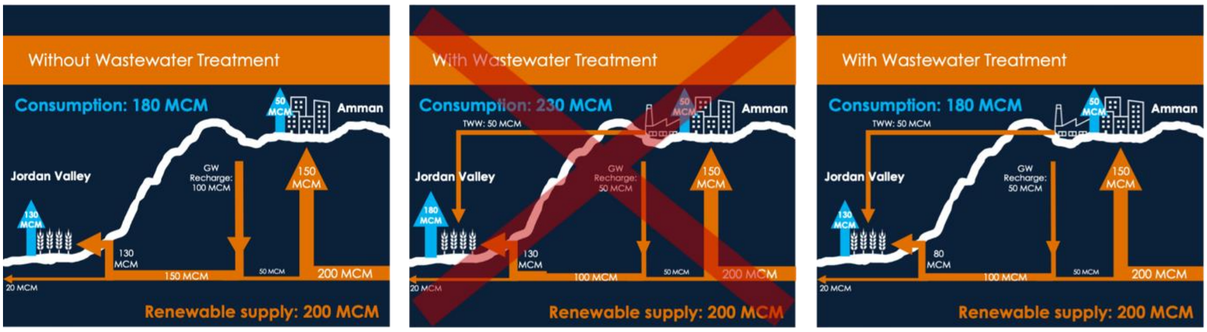


Figure 7: Example with and without wastewater treatment, with the central figure depicting the common misconception in closed basins; treated wastewater augmenting consumption

From a baseline scenario as presented in the Water Allocation Game (WAG), however, treatment of wastewater originating from renewable supply does allow for a satisfaction of demands higher than the renewable supply, as participants do not have to account for current consumptions but can start dreaming as they build their water allocation overview from scratch. This allows for an assumed recapture of wastewater in domestic and industrial sites of 80 and 70 % respectively. Wastewater recapture in agriculture is assumed to be 0, as agricultural water efficiency in Jordan is already very high and for reasons of simplification of the WAG.

It is assumed that both the assumed renewable surface- and groundwater supply do not account for regenerative flows of untreated wastewater, and thus allow for a full consumption of the calculated amount. Therefore, renewably supplied water can be used consecutively by multiple demand sites, albeit in decreasing numbers as water is partly lost to consumption, mostly in the form of evapo-(transpi)ration. This allows wastewater treatment to be regarded as a supply augmentation option, but not a consumption augmentation option.

If demands are fully satisfied, a single reuse of domestic and industrial use is assumed:

$$Assumed\ maximum\ TWW\ from\ domestic\ origin = 808 \times 0.80 = \ 646\ MCM$$

$$Assumed\ maximum\ TWW\ from\ industrial\ origin = 220 \times 0.70 = \ 154\ MCM$$

$$Total\ maximum\ TWW = 646 + 154 = 800\ MCM$$

The costs for wastewater treatment with agricultural purpose in Jordan are shown in Table 3.

Table 3: Costs of wastewater treatment for agricultural purposes per type (Ali Kashani, et al., 2021)

Type	Excl. O&M	Incl. O&M	Incl. Capital costs
Costs in US$/m^3	0.036	0.882	1.82

As these costs only represent treatment for agricultural purposes, which is often characterised by lower quality standards, the treatment for either industrial or domestic reuse will be even more expensive. Thus, the capital and running costs of upgrading the current wastewater treatment from 30 to 80 % of the total domestic and industrial supply is a substantial challenge. Furthermore, despite being capable of producing about 80 % of their own energy needs, Jordan's wastewater treatment plants still require substantial amounts of energy, which can be quite a challenge in energy resources-poor Jordan (MCC, 2018). Nevertheless, it is already a vital source of water in the zero-sum game for Jordan, that is only expected to increase in the future.

3.2 Rainwater Harvesting

Within the closed water basin of the lower Jordan River, Jordan is forced to play a zero-sum game regarding its water resources, as long as no extra water is freed-up by upstream countries. Harvesting or abstracting one source at a certain location means that it cannot be used at another location anymore (Venot, Molle, & Courcier, 2008). As shown in Figure 8, implementation of rainwater harvesting measures could lead to a local increase in groundwater recharge, however, the surface water and hence potentially also the groundwater recharge downstream of the area will be inevitably reduced. In the case of Jordan, this would mean depriving the Dead Sea of even more water, further contributing to its demise. This expresses the difficulties that arise when searching for additional supplies, many of them are not net supply augmentation options, but merely a reallocation of water.

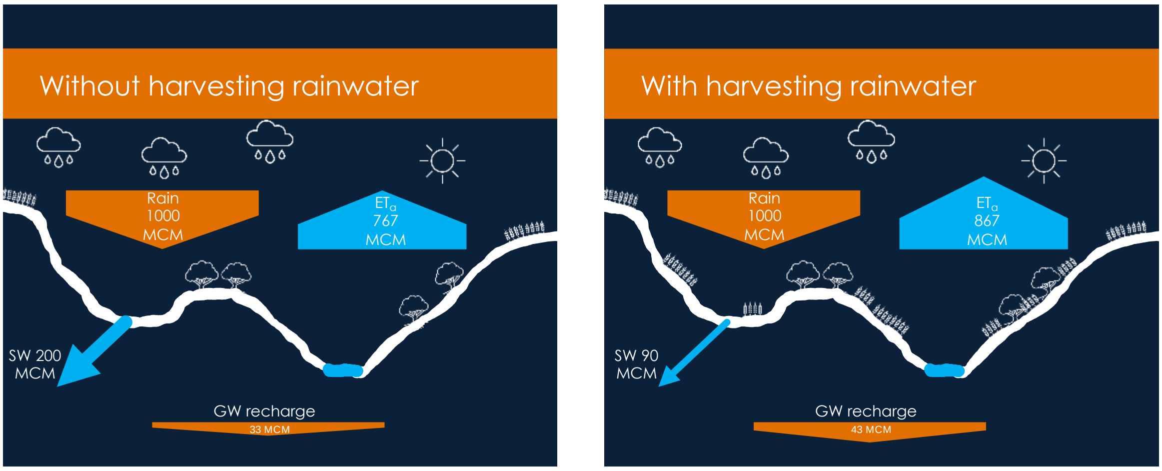
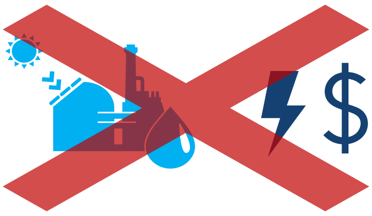


Figure 8: Water balance (left) without harvesting rainwater and (right) with harvesting rainwater

3.3 Brackish Groundwater Desalination



With a total non-renewable, stagnant amount of 24 BCM and a maximum non-renewable, flowing amount of 300 MCM/yr of brackish or saline groundwater resources available, brackish groundwater desalination seems an appealing option to contribute to closing the supply-demand gap in Jordan (JICA, 1995). However, these resources are non-renewable and extracting them would thus lead to reducing future resources and postponing the inevitable. Moreover, any extraction from the deep brackish to saline aquifers will cause downward percolation of fresh shallow aquifers' groundwater into the deep aquifers' sandstone system due to the interconnectedness between the Upper Cretaceous calcareous rocks and the underlying sandstone aquifer series of Lower Cretaceous to Cambrian ages, as shown in Figure 9. Thus, extracting deep brackish to saline groundwater does not mean accessing new water resources, but depleting the groundwater already used for drinking, irrigation, industry, and other uses (Salameh E. , 2021). The relatively small amount of 60 MCM of renewable brackish groundwater is assumed to be part of the 275 MCM of actual renewable groundwater supply and is therefore also not considered as a supply augmentation option (JICA, 1995).

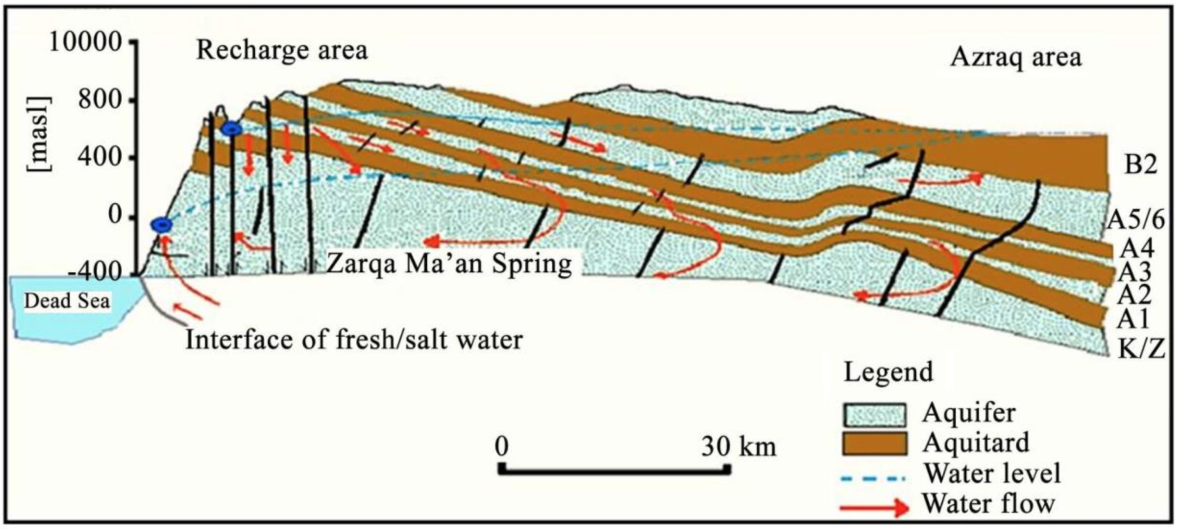


Figure 9: Schematic hydrogeological cross section from the Dead Sea in the west to Azraq area in the east (Salameh & Udluft, The Hydrodynamic Pattern of the Central Part of Jordan , 1985) modified in (Salameh, Shteiwi, & Al Raggad, 2018)

3.4 Red Sea Desalination (National Water Carrier, NWC)

Another option is desalination of Red Sea water and subsequent conveyance to the demand sites in the north of Jordan. The latest plan is to produce 300 MCM of desalinated water and convey it to the Amman region. The design would amount to a total of 2.5 billion US$ (JT, 2022 January) of investment costs. The desalination costs are estimated to be about 0.79 US$/m^3 (Advisan, N.D.). With a distance of 450 km (JT, 2022 March) and a minimum elevation of 900 m to be bridged, the minimal conveyance costs, which are 0.05 US$/100(k)m/m^3 (Zhou and Tol, 2005) will be the following:

$$Minimal\ Conveyance\ costs = (0.05 \times 4.5) + (0.06 \times 9) = 0.77\ US\$/m^3$$

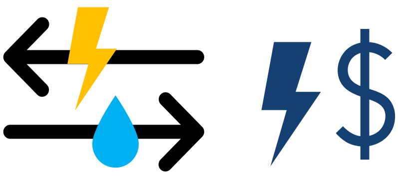
$$Minimal\ O\&M\ costs = 0.79 + 0.77 = 1.56\ US\$/m^3$$

Furthermore, pumping water over a minimal difference in height of 900 m requires approximately 3.3 kWh/m^3 (Richart Díaz, 2022). As the energy requirements for reversed osmosis are 2.98 kWh/m^3 (Pinto, 2020), the minimal energy requirements amount to:

$$Minimal\ energy\ requirements = 300\ \times 10^6 \times (3.3 + 2.98) = 1.89 \times 10^9\ kWh$$

This substantial number does not even consider the vast distance of 450 km that still has to be bridged. Thus, the total amount of energy that is needed is immense, heavily burdening an already stressed energy grid that is mostly reliant on foreign gas resources.

3.5 Bilateral Agreements (Water for Energy Deal, WFED)



As Jordan shares various rivers and groundwater basins with neighbouring countries, bilateral agreements on water management could free up water for Jordan. However, as the climate in the Mediterranean is changing disproportionally fast, water becomes ever scarcer in neighbouring countries, thereby making it increasingly difficult to negotiate extra water supply to Jordan. Nonetheless, last November, Jordan and Israel signed a letter of intent to conduct a feasibility study for receiving a maximum of 200 MCM/yr while providing Israel with 600 MW/yr (JT, 2021). The investment costs of the solar power plant are to be covered by the Emirates Development Bank and construction is to be executed by an Emirati Firm, as the deal was brokered by the United Arab Emirates. Still, the Israeli water has a price, albeit unclear which exactly and what price Jordan will receive for solar energy. Furthermore, the term of the deal is only set to a maximum of 5 years. Thus, much remains unclear and uncertain, making the option an unreliable option for 2050, albeit worth the effort trying to negotiate any extra water supply considering the state Jordan's water balance finds itself in.

Satisfying one demand while increasing another – Water-Energy Nexus

It should be stressed that the three most viable supply augmentation options for Jordan, TWW, NWC, and the WFED, share a tremendous need for energy. Jordan's huge solar power potential is, for the most part, still unharnessed, as disparity between production and peek use continue to prevent a large-scale implementation. Solutions involving the energy water nexus could focus on temporarily storing energy and water while considering their temporal demands. In other words, in times of solar surplus, water could be pumped up to reservoirs while being released again once demands are high, producing hydropower by making use of the gravitational head, recouping 70-80% of the energy used (Rehman, Al-Hadhrami, & Alam, 2015).

The total energy requirements for TWW, desalinisation of the NWC and WFED, and transport height of the NWC are estimated between 2121 and 4405 GW per year. This is between 10 and 25 % of total current production (IRENA, 2021). This energy requirement is built up as follows:

TWW requires 0.3 – 2.41 kwh/m^3 of treatment (Capodaglio A.G., 2019). With 800 MCM this amounts to 240 – 1928 GW per year. Desalination requires 2.98 kwh/m^3. So with the NWC at 300 MCM and the WFED at 200 MCM the energy requirements lie between 849 – 1490 GW per year. The water for the NWC has to be transported over a 900 m height difference, requiring substantial pumping cost. For a similar water transfer in Spain, 2.85 kwh/m^3 is needed, amounting to 987 GW per year for the NWC.

4. Water Allocation Game (WAG)

The projected demands for 2050 in Table 2 formed the baseline of the lay-out of the WAG, as shown in Figure 10. The demands were distinguished for the Jordan Valley and Highlands based upon their current proportional divisions, assuming a proportional growth in demands up to 2050. The WAG was designed to let workshop participants try to close the gap between demand and renewable supply while only making use of feasible supply augmentation options: NWC, WFED and TWW.

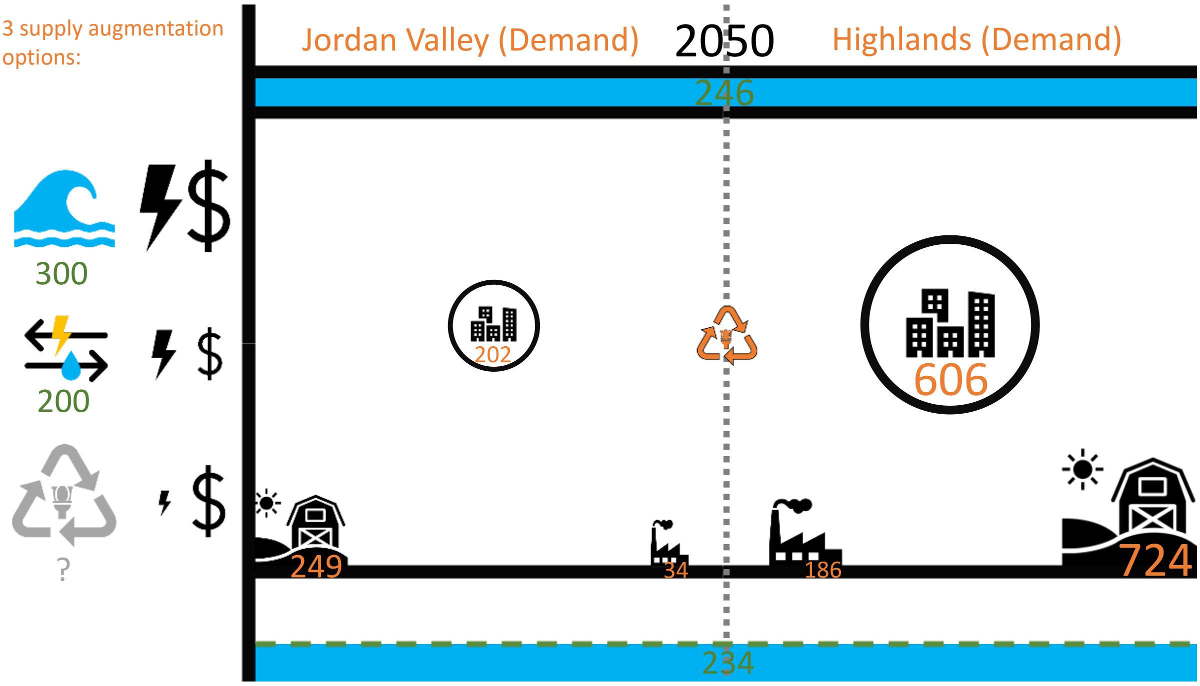


Figure 10: 2050 demands per sector, distinguished for JV and HL

5. Food Security

Before the game could be played it was vital to discuss the role of food security, as food security is an essential strategic development goal of Jordan and has significant implications for water allocations. Recently, the Action plan 2022-2024 of the National Food Security Strategy 2021-2030 has been developed. The plan is set to 'safeguard Jordan's population against food insecurity and ensuring access to safe, stable, affordable and nutritious supply of food at all times', aligning with FAO's definition that 'food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life' (p 1. ESA, 2006).

The plan recognises the inconsistent understandings and interpretations of food security at institutional level. There are different ways to achieve food security; namely international food aid, land grabbing (obtaining land in foreign countries for production of domestic food needs), domestic production and food imports (Kumaraswamy & Singh, 2018). Despite this acknowledgement, the plan fails to specify which understanding is adapted for the case of Jordan at national level.

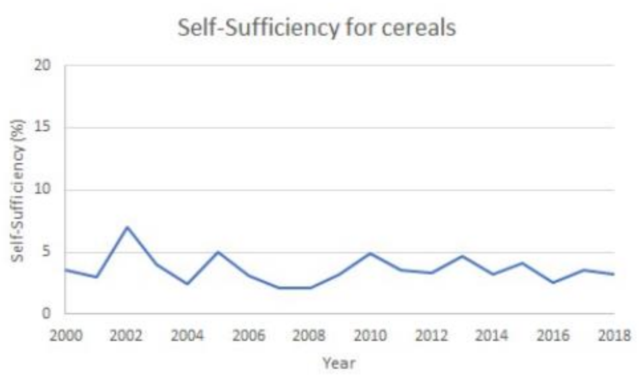


Figure 11: Self-Sufficiency ratio (domestic production divided by domestic consumption) for cereals in Jordan between 2000-2018 (WUR team's analysis, scientific paper under review in Food Security Journal, data source: FAOSTAT)

Based on research conducted by the WUR team (scientific paper currently under review in Food Security Journal), in line with the recent food security plan, Jordan has been importing most of its cereal crops (around 95%) for the last decade (Figure 11). By doing so, it has been successful in externalising 3000 MCM of water use through cereal imports[6]. Considering Jordan's limited water resources, this strategy is sensible. Even though Jordan's high dependency on imports is mentioned in the plan, the role of trade in creating food security is not specified.

The WUR team's analysis showed that Jordan's agricultural trade balance has been decreasing in the last decade, thereby progressively increasing the dependency on the wider economy for importing essential foods (Figure 12). With increasing population growth and subsequent food demands, this dependency will only continue to grow under a business-as-usual scenario. Adding to this, international food price crises, like the 2008 world food crisis, will also affect food accessibility for Jordan. As food becomes more expensive, food imports and accessibility will be threatened, further burdening the wider economy. The opportunity for agriculture, considering the limited water resources, is thus to increase its economic contribution to finance food imports that Jordan itself cannot produce sustainably.

[6] Assuming cereal imports of around 3 million tonnes and an average water consumption of 1m3/kg.

Agriculture does not need to provide physical food to meet food security goals but can maximise economic value creation through the agricultural sector and thus enhance Jordan's economic capacity to import and buy food with minimum impact on water resources.

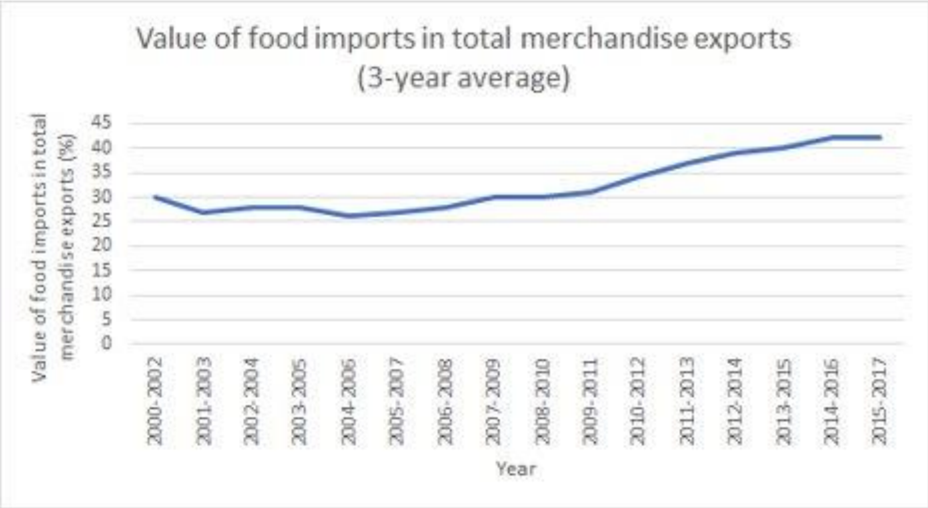


*Figure 12: Value of food imports over total merchandising exports in Jordan between 2000-2017, indicating an increasing dependency of food imports on the wider economy (WUR team's analysis, scientific paper under review in Food Security Journal, data source: FAOSTAT)***.**

Other than creating economic value at farm level, agricultural water use also generates value at societal level (poverty alleviation, employment generation, rural development, environmental sustainability etc). Something that is indispensable under the extreme water scarcity projected for 2050 where all water using sectors will need to use water with the highest socio-economic returns for society.

As there are limited options to increasing physical, agricultural production in Jordan, opportunities for agricultural socio-economic and financial value creation lay in investing in agri-processing and agri-businesses that add value to domestic production and increase market opportunities. Other options include the establishment of niche markets in products that Jordan has comparative advantages in, as well as agri-tourism opportunities.

6. Economic Value of Water

When discussing the feasibility of desalination or treated wastewater, it is important to make a distinction between the price, costs, and value of irrigation water. The costs of irrigation water are often higher than the price paid by farmers, which implies that there is no full cost recovery by the farmer and that irrigation water is subsidised. Globally the establishment, and sometimes even the operation and maintenance of many irrigation schemes have by-and-large been subsidised by governments, development banks and donor agencies. The feasibility of desalination or treated wastewater depends on the costs of provision of water and the value of the water. It is, however, not always so straightforward what costs and values to compare.

It is important to make a distinction between the financial returns on water for the farmer and the socio-economic value of water for society as a whole. It is important to study the latter as well, as the desired impacts on society are the usual rationale for imposing subsidies in the first place (while the negative social and environmental impacts have become the rationale for reforming subsidies).

Desalination costs can be higher than the value of water for irrigating staple crops. However, farmers do often not cover all water treatment costs, which can make irrigation with treated wastewater feasible. Jordan water valuing studies present data on the societal value for water, and they don't look into farm-level economics and the economic value of water whereas farmers are the ones who have to pay for increasing water prices. Often studies look at the societal value of water for the agricultural sector, see (FAO, 2018) & (WRG (McKinsey), 2011), from which seemingly high values emerge. For instance, the FAO (2018) study reports for maize a value of 0.8 USD/m^3 or cucumber 5.8 - 9.2 USD/m^3 (winter and summer values) and the McKinsey (2011) study reports for tomatoes a value of over 2 USD/m^3 (in Valley and Highlands). These values mistakenly suggest that increases in water prices are easily paid in the agricultural sector. Farmers' revenues (and margins) are much smaller when compared to the agricultural sector (including traders and retailers). A study by USAID (2012) did look at farm-gate prices and costs when determining the economic value of water, across the Jordan Valley, Highlands, and in summer and winter season (USAID, 2012). By looking at farm-gate revenues and costs, the study subsequently presented lower water values than the FAO (2018) and McKinsey (2011) studies, for maize (0.26 JD/m^3 or 0.37 USD/ m^3), cucumber (1.69-4.61 JD/m^3 or 2.38 – 6.50 USD/ m^3) and tomatoes (0.34-0.54 JD/m^3 or 0.48– 0.76 USD/ m^3).

7. Recommendations drawn from the WAG outcome

As both the role of food security and economic value in water allocation strategies had been discussed, and all participants realised that the gap was unbridgeable with current and even future water supply augmentation options, reducing demand and TWW substitution of freshwater supplies to agriculture and industry became imperative in the challenge of closing the gap. Once this awareness was rooted in all participants, the agricultural recommendations sprouted up (see recommendations report). In this chapter, the technical background and the feasibility of these recommendations are described.

7.1 Completing the shift from freshwater to TWW

Modification of wastewater regulations and treatment process

The implied shift from freshwater resources to treated wastewater dependency for agriculture in 2050, as outlined in the 2050 scenario, has major implications for the regulation and development of TWW use in agriculture. As participants explained during workshop II (see workshop reporting), Jordan is currently enforcing the JS286-2021 law on TWW use. According to this law, crops and produce that are consumed raw, e.g., fruit and vegetables, may not be irrigated with TWW but can be irrigated with blended water (mix of fresh surface water and TWW), while TWW use is unrestricted for crops that are cooked before consumption. The same restrictions are imposed on exports of agricultural products to the Gulf region. Considering the 2050 scenario, this does impose a severe restriction on closing the water gap, as not enough fresh surface water is available to blend the TWW for agricultural re-use.

Another issue for TWW reuse in irrigation regards the quality of the treated water. As outlined in the FAO/WHO guidelines on wastewater use in agriculture, (T)WW can be applied safely in agriculture for human consumption when complying to the rules and regulations governing water quality, sanitary handling of wastewater (e.g. farmers) and sanitary handling of consumables (e.g. consumers). The water quality produced by current wastewater treatment plants is considered to be adequate, with more than 80 per cent of plants complying with the Jordanian standards on effluent water quality. However, as only a mere 30% of domestic/industrial water supply is treated, the majority of wastewater remains untreated and ends up in surface water bodies. This poses the risk of polluting the surface water bodies and thus decreasing the quality of blending water (mix of TWW and surface water). As such, issues on water quality of TWW as well as the quantity of TWW remain.

The shift to TWW does not only imply challenges though, it also provides opportunities in modernising and reshaping irrigation systems for TWW use (see text box 'Restructuring the JVA irrigation system for the transition to TWW supply; making use of new opportunities.').

Salinity management

In 2013, 63% of the cultivated soils in the Jordan Valley were classified as saline out of which 46% even moderately to strongly saline (4.5-14.1 dS/m), see Figure 13 (Ammari, et al., 2013). This is only expected to increase as most freshwater irrigation sources have to be replaced with more saline TWW by 2050. In addition, the lack of floods and decreasing precipitation prevents natural leaching of accumulated salts, further challenging sustainable salt balance management (Ammari, et al., 2013). Meanwhile, in the Highlands TWW will increasingly be substituting groundwater, while remaining groundwater resources are already in danger of salinisation due to overabstraction (Al Naber & Molle, 2017). Thus, issues with salinity and salinisation will increasingly be faced in both the Jordan Valley and the Highlands.

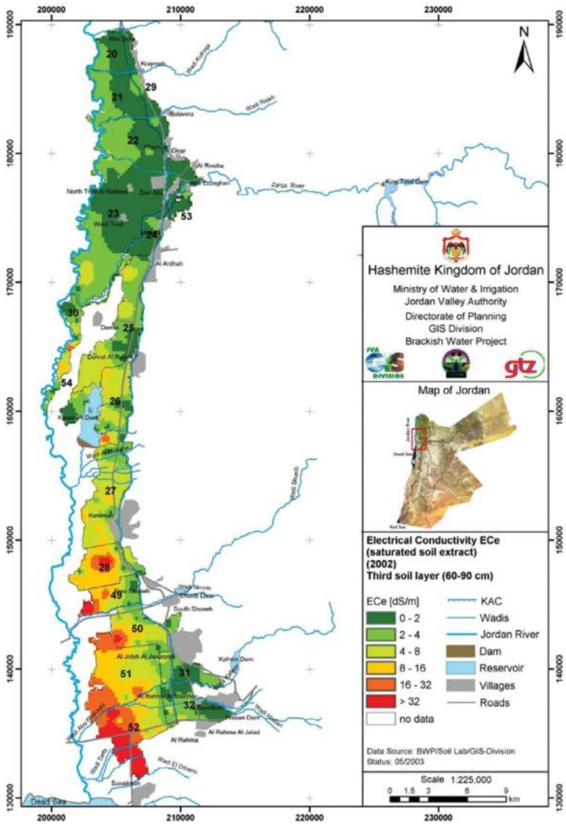


Figure 13: Soil Salinity map of the Jordan Valley (Choukr-Allah, 2021)

These issues concern two aspects: i) dealing with saline water (groundwater, blended water, TWW, although technically this should not be an issue) and ii) salt accumulation in the soil that affect plant production and soil-health. To safeguard agricultural production in the future, investments and developments in salt tolerant crops are needed. This covers two aspects: (i) selection and breeding of salt tolerant crops, preferably with high value potential; (ii) sustainable management of the salt balance in the soil to avoid excessive salinisation and sodification.

Potential crops identified as suitable for saline regions were olives, pomegranates, beet, and quinoa. To further enhance and facilitate these crops and cropping patterns a dedicated research and support facility is required that:

- can select the best salt tolerant varieties;
- enhances the variation in suitable crops for the areas and their processing;
- enhances the marketing strategies and opportunities.

To cope with saline irrigation water in a sustainable and productive way, specific management measures need to be considered that provide for adequate yields and avoid excessive salt induced water stress symptoms. Thus, irrigation water in excess of “normal” crop water requirements needs to be applied to leach out and dispose of soil accumulated salts (to saline aquifers or with drainage). Depending on crop and variety specific characteristics, and the salinity level of the irrigation water, this extra irrigation application can amount to 2 to 3 times the normal requirement to attain minimal yield loss.

Thus, previous research efforts by NARC, focused on salt tolerant crops and varieties, should be revived, and complemented by research into services and the extension sector dedicated to sustainable soil salinity management (Al-Rifaee, 2013).

Restructuring the JVA irrigation system for the transition to TWW supply; making use of new opportunities.

In the discussions of the future implications for agricultural development in the Jordan Valley, the state and functionality of the King Abdullah irrigation canal (KAC) and system came frequently to the fore. There is a consensus that the efficiency of the KAC (in terms of seepage losses, evaporation, and unregistered use) can still be improved to save water. This feeds the frequent calls to upgrade the KAC into a closed pipe system. Despite saving a substantial amount of evaporation losses, estimated to be 30 MCM by the Ministry of Water & Irrigation, elimination of seepage and unregistered losses does not free-up extra water. It only brings forth a re-allocation of current (re-)appropriation, as seepage losses are currently regained by groundwater abstractions and just like unregistered water extractions, they are at present, beneficially used for cultivating crops (Lankford, et al., 2020). Thus, when the plan of piping the canal is procured, it should account for the subsequent ‘losses’ for these users.

However, as the water balance scenarios for 2050 imply a radical shift from surface water to TWW to supply agriculture, potential improvements of irrigation infrastructure in the JV are not just limited to piping the KAC. On the contrary, the infrastructure can be rethought in a completely new context, as a shift from surface to TWW for irrigation also provides new opportunities for a modernised and pressurised irrigation system.

For the 2050 outlook of the JVA, one could consider restricting the use of fresh and blended (e.g., TWW from Irbid) irrigation water to the northern JVA area, e.g., north of the Zarqa River. This northern area could then be continued to be supplied by an upgraded and modernised KAC of lower carrying capacity. For the region south of the Zarqa river, a complete shift to TWW supplied by an expanded Amman provides new opportunities to transform the irrigation systems in a closed, centralised, and pressurised pipe system, making use of the height difference between Amman and the JV. A system that is currently applied in the Valencia region of Spain (re. Acequia Real del Jucar and Taus Irrigation system). Energy can be recuperated from the height, while still providing irrigation water under adequate pressure to distribute over the valley. Such a system would allow to distribute the water under pressure to the farm, in distribution units. In these central distribution units, the water is distributed to farm plots and can additionally be augmented with fertigation (application of fertilizer to irrigation water). The irrigation and fertigation scheduling can in these circumstances be centrally controlled and automated, permitting farmers to outsource these tasks and services to the Water Users Association. An added advantage is the monitoring of TWW on nutrient load to adjust the fertigation levels to agronomic optimum requirements.

A potential impediment for this plan is the current prohibition of irrigating crops likely to be consumed uncooked with TWW, despite WHO standards allowing TWW application after retainment in stabilisation ponds or secondary treatment. (Nazzal, Mansour, Al-Najjar, & McCornick, 2000) (World Health Organization, 2006). Furthermore, a challenge to full substitution of surface water by TWW is the high salinity of TWW, currently forcing Jordan to blend it with surface water to adhere to Jordan’s water quality standards (Myszograj, Qteishat, Sadecka, Jedrczak, & Suchowska-Kisielewicz, 2014).

This illustrates that the inevitable transition to TWW for agricultural use provides both challenges and new technological opportunities that need to be carefully considered in the upgrading and modernisation of the KAC over the next decades.

7.2 Enhancing the economic value of agriculture

The argumentation for the essence of increasing the economic value of agriculture is provided in chapter 5 Food Security. However, this has proven not to be an easy task as farmer's productions are constrained due to a decreased ability to implement innovative farming or irrigation technologies (De Groot, Haddadin, & Schurink, 2018). In addition, farmers lack – and lose – stable links to domestic and international markets, expressing the production and income risks, resulting from volatility of being highly market-dependent (De Groot, Haddadin, & Schurink, 2018). Thus, a growth in capacity of the government and especially the National Agricultural Research Centre is a prerequisite for attaining an overall higher economic value in the agricultural sector. The proposed programme should focus on a cross-value-chain approach, mainly referring to, e.g., stable, long-term contracts and potential investments between producers, transporters and (international) retailers. The programme instigated by a team of interdepartmental governmental and private sector actors, should not only focus on economic value development, but broaden the scope to include also the social and environmental development opportunities, as was also advocated for by (Vervelde, Kelder, Dasoo, Samah, & Verhulst, 2020).

7.3 Rainwater Harvesting

To enhance the effective use of limited rainfall there seems to be scope to enhance the catchment level (through construction of Hafajer dams) and in-situ (re. conservation agriculture, regenerative agriculture) capture of rainwater for agricultural use. This is seemingly an attractive option, as it provides the opportunity to harvest rainfall water and concentrate it for in-situ utilization by agriculture and/or nature regeneration. Converting in effect, more rainfall into productive (transpiration) use. As indicated in section 3.2, however, this raises concerns of the potential impact of rainwater harvesting on the overall water balance of Jordan. Increasing the effective use of rainwater for transpiration and biomass production may reduce the groundwater and surface water (renewable) recharge that depends on excess un-utilized rainwater. At present, the hydrological processes that govern the surface and groundwater recharge flows in Jordan, and how these may be affected by rainwater harvesting, are not known, or assessed. This forms a critical knowledge gap for the design, support and programming of rainwater harvesting strategies in Jordan. It is thus essential that this gap is addressed so that clear guidelines and design criteria for rainwater harvesting schemes can be set. These criteria should be centred around the safeguarding of the delimited freshwater resources in the national water balance. The criteria and design principles to comply with should, from a national water security perspective, centre around:

- Ensure the construction of Hafajer dams (catchment level rainwater harvesting) primarily optimizes managed aquifer recharge (MAR), and thus enhances the renewable freshwater availability at aquifer level, and reduces evaporation losses;
- Ensure that any increase in transpiration from agriculture and regenerative nature development around catchment level and in-situ rainwater harvesting does not result in a decrease of surface and/or aquifer recharge potential (to be accounted for at the national water balance scale);
    - Ensure that any increase in agricultural and nature consumptive use contributes to an increase in economic value per unit of water consumption (e.g. high value rainfed agricultural produce, regenerative agri/nature development and tourism).
- Explicitly accounts for the potential impact of reduced environmental flows on the dead sea and other environmental flows.

7.4 Reducing agricultural water demand

Improving water use efficiency in irrigation, targeting both main irrigation systems and on-farm irrigation applications, could potentially reduce seepage and evaporation. However, this might result in reduced groundwater sources elsewhere. Moreover, this will only contribute to closing the water gap in the water balance when any gain in efficiency is accompanied by a proportionate reduction in water supply that reduces the total (gross) water use of agriculture (see text box 'Agricultural water efficiency; a gain or a pain?').

Shifting to higher water efficient crops

Arid CAM crops[7] such as pineapple, aloe vera, red pitaya, etc, are the most water productive crops due to their highly efficient photosynthetic pathway (Mizrahi, Raveh, Yossov, Nerd, & Ben-Asher, 2007). These crops are also related to niche markets that are highly profitable. For example, aloe vera is used in cosmetic products. As such, CAM crops can provide a cropping alternative that satisfy the dual objective of increased economic profitability under reduced water consumption.

Rainfed crop breeding

The highlands contain the major rainfed agricultural areas of the Hashemite Kingdom of Jordan, situated on the high grounds with annual rainfall of over 500 mm per year. They form important agricultural areas with traditional rainfed crops as wheat, barley, olives, and peas. Climate change is posing increasing challenges on these traditional crops and cropping patterns due to: (i) erratic rainfall, (ii) cold stress and (iii) heat stress (Rahman, Gorelick, James Dennedy-Frank, Yoon, & Rajaratnam, 2015). This requires targeted agronomic adaptations. For instance, by development and selection of crop varieties with targeted genetic treats of higher stress (water, cold and heat) tolerances that enable these crops to return higher and better yields in increasingly stressed environments. For some crops, such as the traditionally rainfed onions, peas, and okra, this may require the implementation of supplementary irrigation, where rainfed crops and yields are secured by adding one or two irrigation applications in the critical yield formation growth stages of the crop.

[7] CAM crops are arid crops with a specific and highly efficient photosynthetic pathway that produce the highest water productivity in terms of biomass produced per water consumed.

Agricultural water efficiency; a gain or a pain?

While discussing demand reducing options in agriculture, water efficient technologies were mentioned manyfold as they are often promoted as the most-promising way to reduce agricultural water use. Although they are successful in bringing down water use on field level, they usually lead to an increase in overall ET_a, as farmers tend to increase their production with water that has been freed-up by using, e.g., drip irrigation technology (Perry, 2007). This happened to be the case in the Jordan Valley. The 33% increase in the average ET_a between 2009 and 2021, as recorded by 100m resolution of WaPOR (FAO, 2020), coincided with the widespread shift from surface (around 30% during 2005 (Shatanawi, Fardous, Mazahrhi, & Duqqah, 2005)) to drip irrigation in the Jordan Valley (almost exclusively since 2016 (Van den Berg & Al Nimer, 2016)). In other words, the gains in efficiency have all been used for an increased ET by agriculture, thus increasing rather than decreasing the water balance gap.

In conclusion, technological efficiency gains in agriculture are only effective in closing the water balance gap, if:

- the supply of irrigation water is proportionally diminished with the gains in efficiency;
- and/or, the cultivation area is proportionally reduced.

A potential solution that honours both requirements, is reviving the former governmental rule of financially compensating farmers to leave the land fallow in summer at the costs of 500-1000 JD per farm unit of 3 hectares. This would serve to sustain the livelihoods of agricultural labourers who are currently paid with the largely unprofitable summer harvest of vegetables such as cucumber and eggplant. By reducing cropping intensity in summer season, a substantial amount of water could be saved if the policy is accompanied by regulations that prohibit the use of the freed-up water elsewhere. Hereby, demands in agriculture do not rise, and gains in efficiency can be effectively reallocated within the water balance to close gaps elsewhere.

Deficit & supplementary irrigation

One example of successfully deficit irrigated crops in Jordan is the bell pepper, which in one research performed the highest water use efficiency and water productivity under 80 per cent irrigation of the calculated crop evapotranspiration (ET_c) (Shammout, Qtaishat, Rawabdeh, & Shatanawi, 2018). Building upon this research, irrigation water use in Jordan can be reduced without significant yield losses to help resolving the water supply gap.

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