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The Water-Energy-Agriculture nexus in Jordan – A case study on As-Samra wastewater treatment plant in the Lower Jordan River Basin

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Preface

This document constitutes the thesis of the dual master's program in Sustainable Energy Engineering at the Royal Institute of Technology (KTH) and the Polytechnic University of Valencia (UPV). The thesis was performed at the Unit of Energy Systems Analysis (KTH-dESA), and was written to support the FAO project "Implementing the 2030 Agenda for water efficiency/ productivity and water sustainability in NENA countries (2017-2020)". The supervisor of the thesis was Caroline Sundin, and the examiner was Francesco Fuso-Nerini.

Disclaimer: This document presents the view of the author and may therefore not reflect views from, or be supported by, the parties who are related to or involved in the project that this report is supporting.

Abstract

Historically, water, energy and agricultural resources have been naturally scarce in Jordan, but current economic, demographic, geopolitical and environmental conditions are aggravating the situation. The influxes of refugees are increasing the already high natural population growth; better economic conditions and living standards are changing consumption and production patterns; surrounding conflicts affect the supply of resources; and negative effects associated to climate change can be noticed already. Therefore, nexus thinking as a basis for integrated and cross-sectorial natural resources management is essential to achieve water, energy and food security, and eventually to move towards a sustainable development of the country. To that end, understanding the existing nexus interlinkages is crucial. This document constitutes a first nexus approach focused on water, energy and agriculture (WEA) sectors in Jordan. The research has adopted a case study method based on literature review to consider different contextual factors, and three levels of study were regarded: national level, Lower Jordan River Basin within Jordanian borders level, and As-Samra WWTP level, which has constituted the case study. Based on an extensive literature review that has resulted in an updated analysis of the current Jordanian context, the main WEA nexus interlinkages have been identified at every level of study. Thirteen future alternative pathways have been proposed, their potential impacts on WEA nexus sectors have been investigated, and related indicators to evaluate these impacts have been suggested. Additionally, three combined pathways have been analyzed in detail. In general, results show that interdependencies between WEA sectors at all levels are strong and projected to intensify in the future, and highlight the critical situation of Jordan in terms of resource management. Inefficiencies and unsustainable uses of natural resources stand out as decisive problems that urge to be solved, and future pathways appear to be potentially harmful for the Jordanian system unless they are included in an integrated nexus-based planning.

Keywords: Water-energy-agriculture nexus, Jordan, Lower Jordan River Basin, As-Samra Wastewater Treatment Plant

Sammanfattning

Historiskt sett har vatten-, energi- och jordbruksresurser varit naturligt begränsade i Jordanien, men de nuvarande ekonomiska, demografiska, geopolitiska och miljöbetingade förhållandena förvärrar situationen. Inkommande flyktningar ökar den redan höga populationsökningen; bättre ekonomiska förutsättningar och levnadsstandarder ändrar konsumtion- och produktionsmönster; kringliggande konflikter påverkar utbudet av resurser; och negativa effekter associerade med klimatförändringar är redan tydliga. På denna grund så är Nexus en god grund för integrerad och tvärsektoriell förvaltning av naturresurs och vital för att säkerställa resurser för vatten, energi och mat och eventuellt gå mot en hållbar utveckling inom landet. För att åstadkomma det ovannämnda så är förståelse för nuvarande nexus samband avgörande. Denna studie utgör ett tillvägagångssätt för en nexus studie med fokus på vatten, energi och jordbruk (WEA) sektorerna i Jordanien. Arbetet utgår från en fallstudie och baseras på en litteraturstudie som är gjord på tre olika nivåer: nationell, Lower Jordan River Basin inom gränserna av Jordanien och As-Samra vattenreningsverk, sistnämnda utgör fallstudien. Baserat på en omfattande litteraturstudie som resulterat i en uppdaterad analys av Jordaniens situation, så har de huvudsakliga WEA nexus sambanden identifierats för varje nivå. Tretton framtida alternativa utfall har föreslagits, deras potentiella påverkan på WEA sektorerna har undersökts och relaterade indikatorer har föreslagits för att utvärdera deras påverkan. Vidare, tre kombinerade utfall har utvärderats i detalj. Överlag så visar resultaten på starkt ömsesidigt beroende mellan WEA sektorerna på alla nivåer och är beräknad att intensifieras i framtiden, vilket betonar den kritiska situationen Jordanien befinner sig i med avseende på naturresurshantering. Ineffektivt och ohållbart utnyttjande av naturresurser står ut som ett stort problem som kräver en lösning, och framtida utfall tycks vara potentiellt skadliga för Jordanien om de inte inkluderas i en integrerad planering baserat på ett nexus tillvägagångssätt.

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Any potential errors expressed in this report are entirely my own. However, this project would not have been possible without the help and support of many. First, I want to express my gratitude to KTH Royal Institute of Technology for having accepted me during last academic year. Thanks to KTH-dESA, and in particular to Francesco Fuso-Nerini for offering me the possibility of taking part of this project. Thanks also to Georgios Avgerinopoulos and Constantinos Taliotis for your help and your time to solve my questions and make my work easier. And especially, thanks to Caroline Sundin. Thank you for your help, your time and your infinite patience with me, for calming me down when I was stressed or lost and for encouraging me to give my best. I really appreciate it and hope the result makes it worthwhile.

Moreover, I would not be involved in this adventure without the faith and help of my family. Thank you for letting me enroll in this programme and for supporting me in the distance. Finally, thanks Andrea for cheering me up every day and for sharing with me so many memories during last year. It would not have been the same without you.

And thanks dad. I know you would be proud of me.

List of abbreviations and acronyms

a.g.l.	above ground (sea) level
b.g.l	below ground (sea) level
BCM	Billion Cubic Meter (10^9 m^3)
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
BOD (BOD_5)	Biochemical or Biological Oxygen Demand
COD	Chemical Oxygen Demand
CSP	Concentrated Solar Power
DAF	Dissolved Air Flotation
DGWIS	Decentralized Green Water-Infrastructure System
DO	Dissolved Oxygen
DOS	(Jordanian) Department of Statistics
EBRD	European Bank for Reconstruction and Development
ESCWA	Economic and Social Commission for Western Asia
FAO	Food and Agriculture Organization of the United Nations
FTA	Farm Turnout Assembly
GDP	Gross Domestic Product
GoJ	Government of Jordan
GWh	Giga Watt Hour
H_2S	Hydrogen Sulfide
ha	hectare (1 ha = 10 000 m^2 = 0.1 dunum)
HDI	Human Development Index
HRT	hydraulic residence time
JAEC	Jordan Atomic Energy Commission
JD	Jordan Dinar (1 JD = 1.40 USD (DOS, 2017a))
JISM	Jordan Institute for Standards and Metrology
JSMO	Jordan Standards and Metrology Organization
JRTR	Jordan Research and Training Reactor
JUST	Jordan University for Science and Technology
JV	Jordan Valley
JVA	Jordan Valley Authority
KAC	King Abdullah Canal
kWh	kilowatt hour
KTR	King Talal Reservoir
LJRB	Lower Jordan River Basin
m^3	cubic meter
MCM	Million Cubic Meter (10^6 m^3)
MEMR	(Jordanian) Ministry of Energy and Mineral Resources
MSF	Multi-Stage Flash distillation
MW	megawatt
MWt	thermal megawatt
MWI	(Jordanian) Ministry of Water and Irrigation
NENA	Near East and North Africa
NEPCO	(Jordanian) National Electric Power Company
O&M	Operation and Maintenance
PS	Pumping Station
RO	Reverse Osmosis
RSDSP	Red Sea-Dead Sea Water Conveyance Project
SCADA	Supervisory Control and Data Acquisition
SDG	Sustainable Development Goal
SPC	Samra Wastewater Treatment Plant Co.
TN	total nitrogen
toe	ton of oil equivalent
TP	total phosphorus
TSS (SS)	Total Suspended Solids

UNDP	United Nations Development Program
UNICEF	United Nations International Children's Emergency Fund
UN-ESCWA	United Nations Economic and Social Commission for Western Asia
USAID	United States Agency for International Development
USD	United States Dollar
VSS	Volatile Suspended Solids
WAJ	Water Authority of Jordan
WEA	water-energy-agriculture
WEF	water-energy-food
WHO	World Healt Organizaton
WSP	Wastewater Stabilization Ponds
WWTP	Wastewater Treatment Plant

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1 Introduction

1.1 Context and statement of the research motivation

This master thesis has been performed to support the FAO project ”Implementing the 2030 Agenda for water efficiency/ productivity and water sustainability in NENA countries (2017-2020)”.

Jordan has very limited water, energy, agriculture and land resources, and the situation is being worsened by the current context. Demographic growth, influxes of refugees, urbanization expansion, climate change, tendency to increase food self-sufficiency through local agriculture and socio-economic development are some of the drivers that put more stress on natural resources. Jordan has become a resource-dependent country to cover its demand, and the situation is especially difficult in the water sector, with the fast-widening gap between water demand and supply, and the great over-exploitation and degradation of surface water and groundwater resources. Far from lessen these effects, next decades are set to accelerate and intensify the situation with the expected development of the country and the impacts of climate change.

With natural resources becoming scarcer and degraded, traditional sectoral plans that did not consider cross-sectoral trade-offs must be substituted by an integrated management of water, energy and agriculture resources. To this end, it is crucial to understand the current system and explore how the main sectors are interrelated, which can be done by using the nexus approach. The nexus approach constitutes an alternative to explore interlinkages between sectors and identify synergies, challenges and opportunities to set the framework of Jordanian strategic plan for implementing the 2030 Agenda and the Sustainable Development Goals (SDGs). Understanding the current use of natural resources and the potential implications of future alternatives is essential to set the basis for Jordanian stakeholders to reallocate and optimize resources, design water, energy and food security policies, and ultimately work towards a sustainable, socially equitable and human-rights based development.

1.2 Research questions and objectives

The main aim of this research is constituting the first step of a human-rights based water-energy-agriculture (WEA) nexus assessment in Jordan by analysing the existing and potential connections between these three sectors in the country, and in particular in the context of the As-Samra wastewater treatment plant (WWTP).

Hence, the primary research question to answer is “How are the water, energy and agriculture sectors interconnected in Jordan, both at a national scale but also in As-Samra WWTP?” To complement this central question and complete the study, two more research questions are proposed:

- What can be the implications of performing planned strategies for each of these sectors?
- How can these implications be evaluated and quantified?

Based on the research questions, the primary objective of this work is to identify water-energy-agriculture nexus interlinkages in the Jordanian context, as a first step of integrated thinking towards achieving WEA security. Several complementary objectives are as follows:

- To understand the current system for each of the nexus sectors (i.e. water, energy and agriculture) at the three levels of study (i.e. Jordan, Lower Jordan River Basin within Jordanian borders and As-Samra WWTP).
- To analyze future pathways in the three considered nexus sectors, including the identification of possible pathways, the study of potential impacts of these pathways on each sector, and the proposal of indicators to evaluate the identified impacts.

1.3 Outline of the report

The thesis is structured in five main sections and four appendices. Section 1 provides insights into the relevance of the research topic, and states the research questions and objectives. Section 2 presents the research methodology and the system boundaries, gathers the main documents from the literature review, and includes an extensive explanation of the current context in Jordan by levels and nexus sectors. Section 3 expounds and discusses the main research findings. Section 4 presents the conclusion of the study, and section 5 provides recommendations from the author on areas of future research, and a possible option to complete the nexus analysis that has been outlined in this document.

The appendices provide complementary information to the main sections. Appendix A constitutes a glossary of relevant terms. Appendix B presents extra information on As-Samra WWTP. Appendix C includes additional tables and figures that support the explanation from the main sections, and appendix D gathers the different sources that have been used to create and adapt the maps included in this study.

2 Methodology

This section presents the methodological aspects underlying this master thesis. First, the research methodology that has been followed during the development of the thesis is presented, followed by the system boundaries. Second, the main results of the literature review focused on previous nexus analysis in Jordan and As-Samra WWTP are expounded. Lastly, the background subsection contains relevant information to understand the Jordanian system and provides the basis for further analysis.

2.1 Research methodology

Along the development of this project mainly literature research has been used as working method, based on peer-reviewed articles from reliable journals, reports from international and governmental institutions (e.g. FAO, World Bank), policy acts and regulatory documents. In order to offer updated results, latest reports, online open databases and statistical resources from official governmental resources have been employed, as well as other qualitative and quantitative secondary data from historical registers and surveys.

This research has adopted a descriptive and explanatory case study method to investigate the main research question in As-Samra WWTP. In order to offer a more complete outline of the current Jordanian scenario in terms of WEA nexus, the research has taken into consideration two additional contextual approaches within the country: Lower Jordan River Basin (LJRB), and Jordan at a national level.

The research process has consisted of four main phases. First, the research was focused on understanding the system at all levels and sectors. To do so, an extensive literature review was performed, combining historical information to analyze the evolution in every sector, and latest data to set the current situation.

Second, based on this background information, WEA nexus interlinkages were identified for the current system. The considered interlinkages have been direct or first-degree interlinkages, with the exception of those ultimately addressing agriculture, which also included second-degree interlinkages (see Table 1).

Table 1 – List of the nexus interlinkages considered in the analysis. Source: Own elaboration based on nomenclature from (Laspidou, et al., 2017)

		Direct		Indirect
		1st degree		2nd degree
Water to energy	=	WE		
Water to agriculture	=	WA	+	WEA
Energy to water	=	EW		
Energy to agriculture	=	EA	+	EWA
Agriculture to Energy	=	AE		
Agriculture to water	=	AW		

Third, based on the current scenario, different alternative pathways for the future were proposed. Initially, fifteen changes or pathways were listed, but eventually only thirteen were evaluated because two of the initial proposals were discarded (i.e. rainwater-harvesting systems and shifting to less-water consuming and higher-value crops). The main reasons to leave aside these pathways were related to time constraints and lack of formal training on the topic. Next, every pathway was evaluated in terms of potential impacts on WEA nexus sectors, and associated indicators were proposed to evaluate the impacts.

Lately, three of the proposed pathways were selected and analyzed in more detail, including numerical estimations when possible. The selection of these pathways aimed at covering all WEA nexus sectors and all the different levels of study, and were combined in pairs by complementarity reasos.

It is worth noting again that all the research relies on secondary data, which in many cases is susceptible of being inaccurate or incomplete. Despite all the sources have been obtained from publications from international organizations or peer-reviewed papers, most numerical data has been extracted from official reports from Jordanian institutions, which have historically reported information that was non-standardized, incomplete, scattered, and greatly differed from alternative reliable source (Hadadin, 2015). Along the document, footnotes and explanatory comments report every abnormal value or illogical statement.

2.2 System boundaries

In general, despite an integral approach for nexus analysis is defended, due to lack or inconsistent data and time constraints, the analysis do not constitute a complete study of the system, and different aspects have not been tackled. Thus, economic and geopolitical aspects, institutional and policy frameworks, and their implications in the nexus analysis have not been included in this analysis. Nevertheless, along the presentation of the different levels some comments have been occasionally added to offer a more complete outline of the system.

As stated previously, the analysis of the Jordanian context has been divided into three different levels of study, from the broadest to the narrowest: national level, LJRB level, and As-Samra WWTP level.

The national level is limited by international borders surrounding Jordanian territory. However, as an exception, transboundary water resources, grid international interconnections and virtual trade of energy and water (through agricultural imports and exports), have been considered occasionally within the national level to better understand the system.

The intermediate level of study is constituted by the portion of the LJRB located on the Jordanian side, running from the northwest corner of Jordan to the Dead Sea. In the majority of the cases, sources do not differentiate specific values for the LJRB within Jordan, but only for the Jordan Valley (JV) or by governorate (provinces). For that reason, when data was available by governorate only (e.g. water wells information or agricultural statistics), some governorates that extend their territory beyond the basin limits have been assumed to be entirely inside the basin. The governorates that have been considered within the LJRB are: Irbid, Ajloun, Jarash, Balqa, Mafraq, Zarqa and Amman[1]. Despite this assumption can induce certain error, the natural resources and population within these governorates are mainly concentrated within the basin, hence this approximation can be acceptable.

Finally, the case study level has been limited by the influent and effluent wastewater from As-Samra WWTP. Thus, besides As-Samra WWTP facilities, it has been considered inside the third level of analysis: the stations that collect wastewater for As-Samra, the Zarqa basin where effluents are discharged, and the King Talal Reservoir (KTR) and irrigation fields in the JV, where treated wastewater are finally stored and reused, respectively.

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[1] Mafraq, Zarqa and Amman extend their administrative boundaries beyond the LJRB.

2.3 Literature review

Jordan and its limited natural resources have been subject of different publications, which have evaluated environmental challenges and have presented proposals to improve this situation. Howari & Ghrefat (2011) perform an environmental inventory of natural resources in Jordan, highlighting groundwater and soil pollution due to anthropogenic sources. Hadadin & Tarawneh (2007) present environmental problems in Jordan and their evolution during last decades, and propose recommendations with emphasis in monitoring and analysis strategies, comprehensive environmental studies and water-energy integrated solutions.

There are relatively few historical studies focused on As-Samra WWTP. Mrayyan (2005) and Howari & Ghrefat (2011) highlight the negative effects on water resources, soil, and crops associated to the historical operation of the plant. Myszograj & Qteishat (2011), Al-Omari, et al. (2013), El-Rawy, et al. (2016) and Bajjali, et al. (2017) analyze the effects of As-Samra WWTP on surrounding water resources, soil and irrigation since its first upgrade in 2008, stating positive effects in general terms. SPC (2014), SUEZ (2017) or Degrémont – SUEZ (n.d.(a,b)) present the features of the new WWTP and its potential effects on energy and agriculture sectors, but do not include empirical information.

For some time now, the volume of published studies focused on nexus analysis has increased exponentially, both theoretical and case study-based applied on specific systems and regions. Endo, et al. (2015) present a collection of methods to analyze the water-energy-food (WEF) nexus, which also classify and discuss. Similarly, Dai, et al. (2018) summarize a range of existing methods and tools for water-energy nexus analysis based on 35 WEF studies, and discuss the different approaches based on their main purposes. The World Energy Outlook (IEA, 2016) includes an excerpt focused on the water-energy nexus, where an inventory of interlinkages at global level is presented and specific cases emphasize water-energy nexus challenges and opportunities. Lee & Younos (2018) analyze sustainable strategies at the water-energy nexus, namely the effects associated to the integration of renewable energy and decentralized water-infrastructures. Ahmad & Khan (2017), perform an analysis of the water–energy nexus of irrigation modernization by presenting a case study in the Murray-Darling Basin, emphasizing the positive effects of modern irrigation systems for water and agricultural productivity at the expense of higher energy requirements.

In recent years, there has been an increasing amount of literature on nexus analysis with the Arab region and the Middle East as the object of study. Mehyar, et al. (2014) explore the creation of a water-renewable energy community based on interdependence in the Middle East to compensate the uneven distribution of resources and contribute to the peace in the region. Siddiqi & Diaz Anadon (2011) perform a quantitative water-energy nexus assessment at country level in the MENA region, emphasize the strong dependence of water abstraction and production systems on energy, and suggest considering energy implications in water-intensive food imports and restructuring the water demand in future policies. ESCWA (2015) summarizes the main variations that have emerged in terms of WEF-nexus approach through a critical review of the conceptual WEF-nexus frameworks. Then, the study is focused on the Arab region, identifying nexus interlinkages and giving specific cases of success and failure that can be used as a reference for Jordan due to their similarities. Keulertz & Woertz (2015) address funding sustainable strategies in the Arab world based on nexus thinking for demand and supply-side management. The study identifies five alternative pathways to finance WEF nexus projects, and emphasizes the role of the state and a proper regulatory framework.

Finally, a small but growing body of literature has applied nexus approaches in Jordan. Hoff (2011) include in their paper for the Bonn 2011 Conference a brief case study on the opportunities for demand management and green solutions in Jordan. The case study summarizes WEF context in the country, emphasizes the potential of energy and water-efficiency strategies and small-scale and decentralized infrastructures, and remarks the importance of interlinked institutions. Østergaard, et al. (2014) investigates the impact of two desalination technologies (i.e. reverse osmosis and multi stage flash distillation) on the energy sector in Jordan, concluding that both technologies are similar in fuel use. Perković, et al. (2016) study the integration of desalination and renewable in Jordan, including brine storage as a form of energy storage. Al-Zu'bi (2017) uses a WEF nexus approach to propose an integrated climate policy framework for Greater Amman Municipality, and highlights the main factors affecting Arab cities from advancing the WEF nexus approach, and the discrepancies in WEF priorities between policy-makers and citizens. Lastly, it is worth noting the existence of a specific section on the WEF nexus in Jordan's National Water Strategy 2016-2025 (MWI, 2016d). Despite its shortness, the document highlights the importance of the WEF nexus for the economic development of the country. It claims the willingness to understand better the WEF nexus to use it as a basis for the formulation of policies without compromising sustainability. Water is stated as the center of their WEF nexus, and climate change is presented as a relevant driver, but not a core sector. Lately, specific nexus-related strategies and tools are stated, such as energy-efficiency programs, or incentives for the use of wastewater biosolids from treatment plants to produce renewable energy.

2.4 Background

The present section sets the Jordanian context at all levels of study, being essential for the understanding of the current system, the subsequent analysis and the proposal of future pathways. The section starts with a brief introduction on the nexus approach and its relation with the SDGs, and follows with an extensive explanation of the three levels of study considered in this research. Within every level, an introduction precedes the detailed analysis of each of the three nexus sectors. It is worth noting that, due to the amount of relevance information, there have been included specific subsections in the different WEA sectors focused on their use of water and energy (i.e. energy in the water sector, water in the energy sector, and water and energy in the agriculture sector). In other cases (i.e. relations of agriculture with water and energy sectors), the information has been integrated in the main text and will be highlighted in the results section.

2.4.1 The nexus approach

This work presents a particular nexus approach that has not been specifically found in any previous publication, although uses as a basis the extensively investigated WEF nexus approach. Thus, this nexus approach is focused on the agriculture sector instead of the food sector. It is then, a water-energy-agriculture (WEA) nexus approach. This variation does not differ in essence, but implies a narrower focus on crops, irrigation and land use, leaving aside other aspects typically considered in a WEF nexus analysis such as livestock and fishery, food processing or transport of food.

As stated previously, the interest of applying a nexus methodology to the Jordanian context resides in the scarcity of natural resources in the country and the intrinsic connections between energy, water and food security, economic development and wellbeing (MWI, 2016d; IEA, 2016). Water and energy are reciprocally linked, and dependencies are set to intensify rapidly in both directions. The water industry is energy-intensive, consuming energy for extraction, distribution, desalination or treatment of water. The energy sector is also water-intensive, being essential for all phases of energy production, from fossil fuels to biofuels and electricity production. The agriculture and food sectors, in turn, use energy and water as inputs, and changes in any of the sectors can affect the others. Without adequate access to any of them, public wellbeing, economic and social development cannot take place (ESCWA, 2015; IEA, 2016; Kantor, et al., 2017).

For this reason, and with water, energy and food needs set to increase, understanding the linkages between these sectors is crucial for the sustainable development and the stability of Jordan. A nexus conceptual framework can help to recognize these existing interdependencies with the aim of achieving integrated natural resources management across the sectors. The utilization of this analytical framework contributes to a better comprehension of the sustainable development challenges of a system, as well as its vulnerabilities to climate change. Moreover, the nexus approach makes it possible to look at synergies and issues such as population growth, changes in production and consumption patterns, or changes in the use of technologies (Hoff, 2011; ESCWA, 2015; Kantor, et al., 2017).

However, the nexus approach is not new, but has existed under various forms such as green economy principles or integrated water resources management (IWRM), which are based on a nexus concept. Traditionally, nexus approaches were focused on two-way relationships (e.g. energy and water), but recently, more complex nexus approaches implying at least three sectors have arisen. In particular, the WEF nexus as a concept in development appeared in 2008 in the World Economic Forum. The global financial, energy and food crises, together with a higher concern about climate change, brought forth the significance of connecting WEF security and integrated resources management (Keulertz & Woertz, 2015; ESCWA, 2015). Last years, different nexus variants have emerged with distinct goals, scopes and valuation of the drivers affecting the core sectors. A selection of nexus conceptual frameworks is presented in Figure 1.

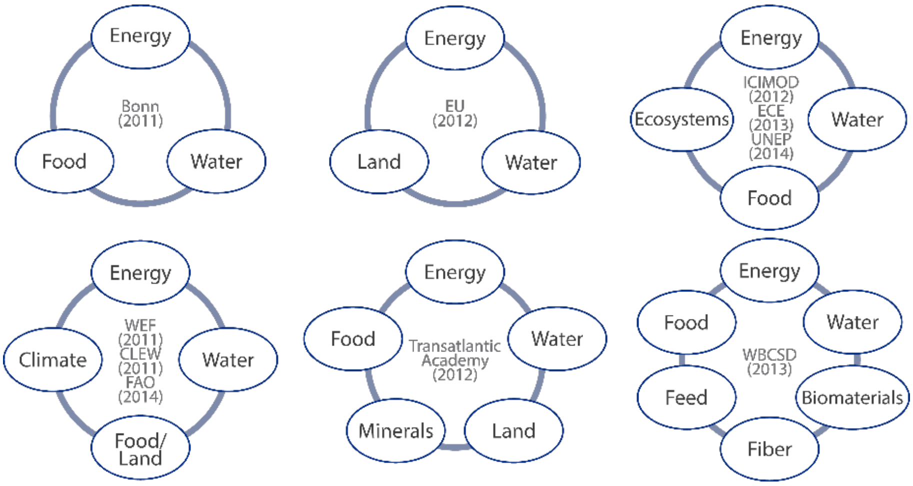

Figure 1 – Selected conceptual frameworks for illustrating the natural resource nexus. Source: Adapted from (ESCWA, 2015)

Following a similar conception to the one underlying the proposal from ESCWA (2015), this particular nexus approach is based on the consideration of food, water, sanitation, and energy as inalienable rights. This approach aims at achieving resource optimization at all three WEA nexus sectors (i.e. water, energy and agriculture), prioritizing security at every WEA nexus sector and considering each of the sectors as equally important. Therefore, technical or economic efficiencies are considered secondary and maybe will not be achieved, although are also sought. Moreover, the versatility of the nexus analytical framework allows applying it at various scales of study (e.g. national, regional and local), but an integrated thinking is required to achieve WEA security at all levels.

Finally, in addition to a technocratic conceptualization, a nexus approach should ideally consider governance and political perspectives across sectors and scales to develop integrated strategies, infrastructures and policies aiming at achieving WEA security (Hoff, 2011). Otherwise, the development of one sector can have unintended consequences for other sectors and WEA security can be threatened. In the particular case of Jordan and the Arab States, intergovernmental and cross-sectoral collaboration are crucial to develop consistent, coordinated strategies under a nexus framework due to the existence of transboundary water resources and a high dependence on external agricultural products and energy resources. Similarly, climate change should also be considered in a nexus analysis to study how the ability to achieve WEA security is affected (Keulertz & Woertz, 2015; ESCWA, 2015). Nevertheless, as stated previously, due to time constraints the present nexus approach has been limited, and governance, political or climatic implications have not been taken into consideration.

2.4.1.1 WEA nexus and SDGs

On September 25th 2015, all countries adopted the United Nations' Sustainable Development Goals (SDGs); "a set of goals to end poverty, protect the planet and ensure prosperity for all as part of a new sustainable development agenda" (UN, n.d.). These 17 goals condense the major challenges faced by human society, the core of which are the basic human needs of water, food and energy (Bieber, et al., 2018).

A nexus analytical framework can assist sustainable development and ensure the human right to water, sanitation, food, and energy, working towards the achievement of the 2030 Agenda for Sustainable Development. Despite the project this work is supporting (i.e. "Implementing the 2030 Agenda for water efficiency/ productivity and water sustainability in NENA countries (2017-2020)") is mainly focused on the SDG 6, this WEA nexus approach addresses others SDGs, both directly and indirectly.

Specifically, a WEA or WEF security nexus directly address the following three SDGs, which revolve around the core nexus sectors:

- SDG 2, which seeks to "end hunger, achieve food security and improved nutrition and promote sustainable agriculture".
- SDG 6, which pursues to "ensure availability and sustainable management of water and sanitation for all".
- SDG 7, which seeks to "ensure access to affordable, reliable, sustainable and modern energy for all" (UN, n.d.).

Furthermore, a WEA or WEF security nexus approach indirectly addresses at least seven additional SDGs, which range from good jobs and economic growth (SDG 8) or responsible consumption (SDG 12), to climate action (SDG 13) or life below water and life on land (SDG 14 & 15, respectively). Figure 2 includes the main SDGs that a WEA or WEF security nexus addresses.

Figure 2 – Addressed SDGs numbered by respective category. Source: (Bieber, et al., 2018)

2.4.2 Jordan

2.4.2.1 Introduction

Jordan (officially the Hashemite Kingdom of Jordan) is a country located in the Middle East, which borders Syria to the north, Saudi Arabia to the east and south-east, the West Bank and Israel to the west and Iraq to the north-east (see Figure 42 in Appendix 0). It is a constitutional monarchy with a representative government, and is divided into twelve governorates (OCHA, 2012).

Jordan is categorized as an "upper-middle-income" country, with a HDI (Human Development Index) value of 0.745 (out of 1) in 2015. Despite it is above the average for countries in the *high human development* category (0.744), and significantly higher than the average for Arab States (0.686), there is still room for improvement (UNDP, 2016). Jordan faces major economic challenges due to its great dependence for energy, its structural unemployment, and a lack of any economic or integrated land management policy to create jobs, stop urban spread and protect its countryside. Nevertheless, thanks to its political stability compared to its neighbouring countries, Jordan is one of the first countries in the world in terms of development aid per capita. Its economy is driven by foreign aid from the European Union, United States and Saudi Arabia, by remittances from its thousands expatriate workers in the Gulf, and by revenues from tourism (Ababsa, et al., 2014). Consequently, the country has experienced a significant increase in its Gross Domestic Product (GDP) during last decades, reaching 38.6 billion current US$ in 2016 (4 088 current US$ per capita, see Figure 3).

Jordanian population is increasing at a steady pace, with 4.7% average growth in the period 2006-2016 (Figure 3). 9.5 million inhabitants lived in Jordan in 2016 (World Bank, 2018). Specifically, 63% of the total population inhabited the four central governorates: Amman, Zarqa, Balqa, and Madaba, taking up 16.2% of the country's total area. 28% lived in the northern governorates: Irbid, Mafraq, Ajloun and Jarash, representing 32.6% of the country surface. And only 9% of Jordan's population lived in the southern governorates: Karak, Tafila, Ma'an and Aqaba, which constitute 51.2% of Jordan's area (UNDP, 2016). Therefore, the population is unevenly distributed across the territory. 90 % of the population lives around 10 % of the country's area in the northwest corner of the kingdom (see Figure 56 in Appendix 0), which also corresponds to the arable land in the country (OCHA, 2012; Ababsa, et al., 2014). This is partly result of a rapid urbanization since the 1970s driven by the diversification of jobs in construction and services, and the economic boom of oil-producing Arab countries. In turn, this particular context has led to a continuously decrease of rural population, with 16% of the population living in rural areas in 2016 (see Figure 3) (Ababsa, et al., 2014; Figueroa, et al., 2018).

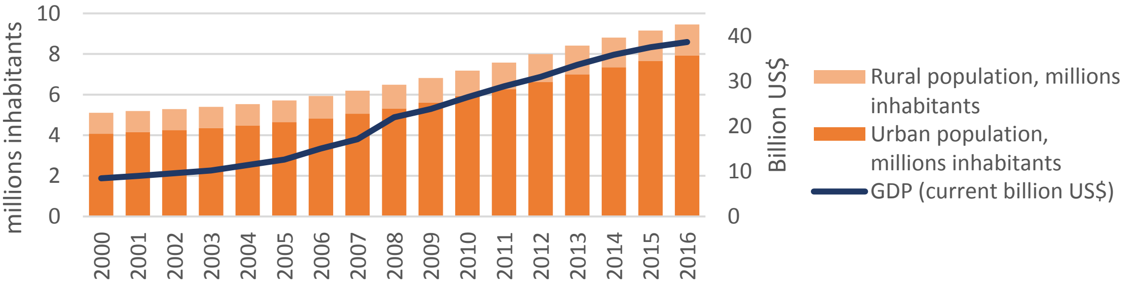

Figure 3 – Population (urban and rural) and GDP in Jordan, 2000-2016. Source: Own elaboration based on (World Bank, 2018)

As a result of prolonged conflict in the Middle East, Jordan has hosted several waves of refugees and displaced people, with a especially high influx of Syrian refugees last years (UNDP, 2016). This has had a large impact on the population growth rate, leading to pressure on natural resources, growing income disparities and increase in poverty (OCHA, 2012; Figueroa, et al., 2018). According to UNICEF (United Nations International Children's Emergency Fund), Jordan now hosts 2.7 million refugees, the highest number in the world. This includes 655 000 registered Syrian refugees (51.6 % children), 60 000 Iraqi refugees (33.6 % children) and more than 2.1 million registered Palestinian refugees (UNICEF, 2017).

Table 2 – Jordan's physiographic regions, 2015. Source: (DOS, 2017b; DOS, 2018a)

Indicator	**Area (km^2)**	**% of total**
Total Area of the Kingdom	89 318	100
Land Area	88 778	99.4
Heights	550	0.6
Plains	10 000	11.2
Rift Valley	8 228	9.2
Desert	70 000	78.4
Aquatic Area	540	0.6

Jordan has a total land area of 88 778 km^2, with very limited natural resources and huge altitude differences and gradients between the Dead Sea area and plateaus (i.e. 423 m below sea level and 1 000 m above sea level respectively). These differences create four main physiographic areas: desert, which covers three quarters of the country, plains, heights and the rift valley (Table 2, Figure 42) (Ababsa, et al., 2014). The climate ranges from semi-arid in the northwest to arid desert in the east and south (Hadadin, 2015), with temperatures that can reach 45 °C in the long summers and a few degrees above zero in the short, rainy winters (Howari & Ghrefat, 2011; Myszograj & Qteishat, 2011).

2.4.2.2 Water sector in Jordan

Water resources

Jordan is a chronically water scarce country, and is considered one of the fourth most water stressed countries in the world. In 1946, 3 600 m^3 per capita of water resources were available annually, and currently there are less than 105 m^3/year per capita, far below the threshold of severe water scarcity of 500 m^3 (MEMR, 2017; Hadadin, 2015; JAEC/Worley Parsons, 2011; MWI, 2016d).

Precipitation in Jordan ranges between 50 to 500 mm yearly depending on the location and topography, but over 90% of the country receives less than 200 mm/year (see Table 3) (Ababsa, et al., 2014; MWI, 2016d). Rainfall decreases from north to south, from west to east and from higher to lower altitudes (see Figure 43 in Appendix 0). The country suffers periodic droughts and very irregular thunderstorms in terms of duration and intensity that provide most rainfall along the year. This precipitation regime, together with degraded land, causes soil erosion and the decrease of groundwater recharge (Howari & Ghrefat, 2011; Hadadin, 2015).

Table 3 – Rainfall distribution in Jordan. Source (Jaloudy 2006 as cited in Ababsa, et al., 2014)

Rainfall range (mm)	Area (ha)	% of total area
< 50	3 679 670	41.26
50–100	2 325 260	26.07
100–200	1 986 630	22.28
200–300	435 700	4.89
300–400	216 210	2.42
400–500	118 030	1.32
> 500	104 520	1.17
Dead Sea	52 990	0.59
Total	8 919 010[2]	100

The climate conditions also affect the potential of evaporation, which ranges from 1600 mm/year in the northwest to more than 4 000 mm/year in Aqaba and Azraq regions (Howari & Ghrefat, 2011). According to long-term average values, around 92% of the total rainfall volume is lost through evaporation, while 3% flows into rivers and other catchments as winter floodwater and 5% contributes to groundwater recharge (see Figure 4).

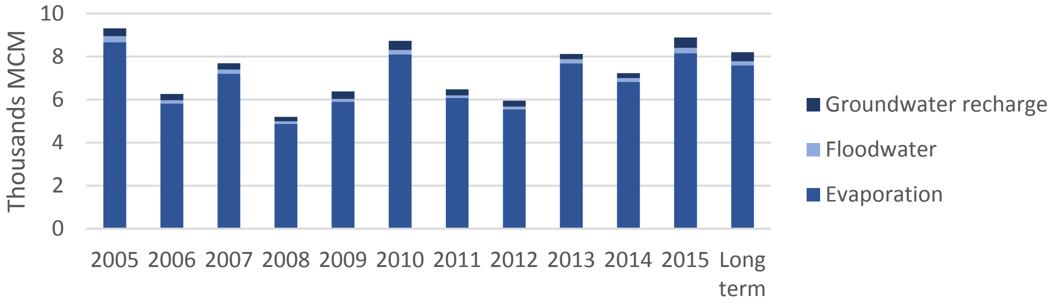

Figure 4 – Water budget in Jordan: Distribution of rainfall. Source: Own elaboration based on data from (MWI, 2016b)

The scarcity and an uneven distribution of precipitation result in very limited water resources for the different activity sectors. Moreover, the situation has been worsened because Jordan shares most of its natural water resources with neighboring countries (i.e. Israel, Syria, Palestine and Saudi Arabia), and over last decades these countries have partially deprived Jordan of most of the water share that naturally corresponds to the country. In addition, climate change is reducing the rainfall volumes and increasing evapotranspiration, among other adverse effects in the environment. These alterations have led to a

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[2] Total area differs between sources, namely from 89 190 km^2 (Ababsa, et al., 2014) and 89 318 km^2 (DOS, 2018a).

substantial decrease of the water resources over the past years in terms of quantity and quality. The situation of severe water scarcity has been also aggravated by an increase in the water demand. Main drivers of this increase are a high rate of natural population growth, massive influxes of refugees, increased urbanization, gradual industrialization, agricultural development and new standards of living (Hadadin & Tarawneh, 2007; Howari & Ghrefat, 2011; Hadadin, 2015; El-Naser, et al., 2014).

Consequently, Jordan is already using more water than the country can provide in a sustainable manner. Water sources are being drained, dried and polluted, and water scarcity has become the major challenge for the country to face. The Jordanian Ministry of Water and Irrigation (MWI) is considering new solutions to overcome the lack of resources, which include additional water resources (e.g. rainwater harvesting, import of water or desalination of seawater and brackish water), and the efficient management of water resources (e.g. managed aquifer recharge (MAR) and reduction of system losses) (Howari & Ghrefat, 2011; El-Rawy, et al., 2016; Hadadin, 2015).

Currently, the main water resources in Jordan are groundwater (61%), surface water (28%) and treated wastewater (11%), but the supply is far from being sustainable (see Table 5). The renewable water resources cannot cover the present use, and the deficit is being supplied by overexploited renewable aquifers and fossil aquifers (i.e. non-renewable), resulting in lowered water tables and water quality. In addition, the declining resources have been historically polluted. Some main factors include inadequate location of industrial plants upstream of potable supplies, release of untreated or poorly treated industrial and municipal wastewater, and overuse and misuse of fertilizers, fungicides, insecticides and pesticides that eventually reach water resources. Despite some WWTPs have been upgraded and more strict water quality standards have been implemented, there is still need for improvement (Howari & Ghrefat, 2011; Hadadin & Tarawneh, 2007).

Surface Water

In Jordan, the surface internal water is estimated at 680 to 850 MCM (million cubic meters) annually, and is unevenly distributed among fifteen surface water basins, being more abundant in the north and west, and scarce in the south and east (see Table 15 and Figure 44 in Appendix 0). The three main surface water resources in the country are the Jordan, Yarmouk and Zarqa rivers. Additionally, 6-10 small rivers or side *wadis* flow from the mountains to the JV. However, these resources are highly unreliable due to upstream diversion by other riparian countries (i.e. Israel and Syria) in the case of the Jordan and Yarmouk Rivers, and due to water pollution in the case of the Zarqa River (Howari & Ghrefat, 2011; Hadadin, 2015; Ababsa, et al., 2014). Moreover, the water flows vary greatly between season and years and the overuse of water resources and the decreased precipitation are reducing and drying out river flows and streams. At best, freshwater in surface courses is being progressively replaced by effluents of treatment plants, transforming in any case the ecological balance over time (Hadadin & Tarawneh, 2007; AQUASTAT, 2009b).

The Jordan River is a 251 km (3) stream shared by five riparian countries (see Table 16 in Appendix 0). It is originated 5 km south of the northern border in Israel from the merging of the Dan, the Banias and the Hasbani rivers. The Jordan River flows south towards the Lake Tiberias, whose outflow creates the Lower Jordan River that forms the Israel-Jordan and Israel-West Bank borders in the JV. There, the Lower Jordan River receives water from its tributaries (i.e. the Yarmouk River and several *wadis* and aquifers) until it ends in the Dead Sea. Originally, the Lower Jordan River received its main inflow from Lake Tiberias and discharged around 1 370 MCM/year into the Dead Sea, but flow rates have decreased sharply because of the construction of water infrastructures and diversion schemes by riparian countries (e.g. Syria, Israel or Jordan). Currently, the Jordan River[4] has become a pollute, saline creek not suitable for drinking or irrigation. The stream is mainly constituted by agricultural return flows, groundwater seepage, untreated sewage and brackish water from springs diverted from the Lake Tiberias area. At its end in the Dead Sea,

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[3] Some differences between sources have been identified, being 223 km according to UN-ESCWA and BGR (UN-ESCWA and BGR, 2013).

[4] In the present document, from now on and unless it is explicitly stated, the term *Jordan River* refers to the *Lower Jordan River*; i.e. the portion of the river flowing from Lake Tiberias down to the Dead Sea.

the Lower Jordan River is almost dry most of the year because water is diverted into fields, pumps and pipes along the river course to supply surrounding areas. In the past years the discharges have ranged 20-200 MCM, only due to large floods that cannot be captured by the existing facilities (AQUASTAT, 2009b; UN-ESCWA and BGR, 2013; Howari & Ghrefat, 2011).

The Yarmouk is a 57 km river, of which 10 km are within Jordanian territory. It flows along the Jordanian-Syrian border, the Jordanian-Israeli border and empties into the Lower Jordan River. Jordan takes a part of its water according to its agreement with Israel (Mustafa, et al., 2016; AQUASTAT, 2009b; DOS, 2018a). The Yarmouk River is the largest external surface water in Jordan and historically accounted for 25% of the surface water, but its average discharge has declined in recent decades due to the lack of precipitation and an increased exploitation (see Table 17 in Appendix 0). The average annual flow was about 438 MCM in 1980, but in 2016 was 80 MCM until it reached the Wehdah dam and 8 MCM until the King Abdullah Canal (KAC). In terms of quality, several factors affect the water of the Yarmouk River, such as the effluents of WWTPs that reach the watercourse during floods, and the leachates from El-Ukheider solid waste disposal sites when their liquid loads exceed evaporation and infiltration. Consequently, the catchment area of the Yarmouk River is restricted to rain fed and some irrigated agriculture. Furthermore, the concentrations of NH_4, NO_3, Cl and BOD_5 (biochemical oxygen demand) of the water from the Yarmouk River have historically increased when diverted to the KAC and mixed with water from the Zarqa River, which contained effluents from As-Samra WWTP. In spite of the pollution, after mixing the water can be used for irrigation with some restrictions (Howari & Ghrefat, 2011; Ababsa, et al., 2014).

The Zarqa River is the major local surface water resource in Jordan. The river is 70 km long and has two branches: the eastern branch (Wadi Dhuleil) drains only floodwater, and the western branch (Seel-Zarqa) drains base flows and floodwater. Until 1976, the average annual discharge was around 65 MCM/year, but the natural system was modified by different factors. Some of these factors were the import of water to the catchment area for domestic and industrial uses, the discharge of municipal, industrial and agricultural effluents, or the construction of the KTR. In fact, the Amman-Zarqa basin where the river is located gathers around 70% of Jordanian small-medium sized industries, which have historically polluted the Zarqa River. The untreated waste raised contents of chemicals and metals, making the water unsuitable for irrigation or domestic uses. Only during floodwater periods the water quality traditionally improved. Nonetheless, higher quality and quantity of the effluents from As-Samra WWTP has amended this situation lately (see 2.4.4.2) (DOS, 2018a; Howari & Ghrefat, 2011; Hadadin & Tarawneh, 2007).

Groundwater resources

Jordan has twelve aquifers or groundwater basins. The largest basin is the Amman-Zarqa Basin, which supplies around 30% of the Jordanian wells (DOS, 2018a). Currently, groundwater resources are considered the major water resource in the country accounting for 61% of total used water in 2015. Nevertheless, the groundwater resources are being largely over-exploited, with abstraction rates greatly exceeding the safe yield volumes in most of groundwater basins (see Figure 5, and Figure 45 in Appendix 0). The total amount of safe yield extraction from underground aquifers is estimated at 419 MCM/year, while actual abstraction reached 624 MCM in 2015 (MWI, 2016b). This results in an average over-abstraction rate of 149%, with only three groundwater basins having an abstraction rate lower than the safe yield (i.e. JV, and Hammad and Sirhan in the eastern Jordan). Direct consequences of this great over-exploitation are increased salinity and intrusion of pollutants in many watercourses (MWI, 2016d). The situation is especially difficult in areas where groundwater resources are the only available water (Howari & Ghrefat, 2011).

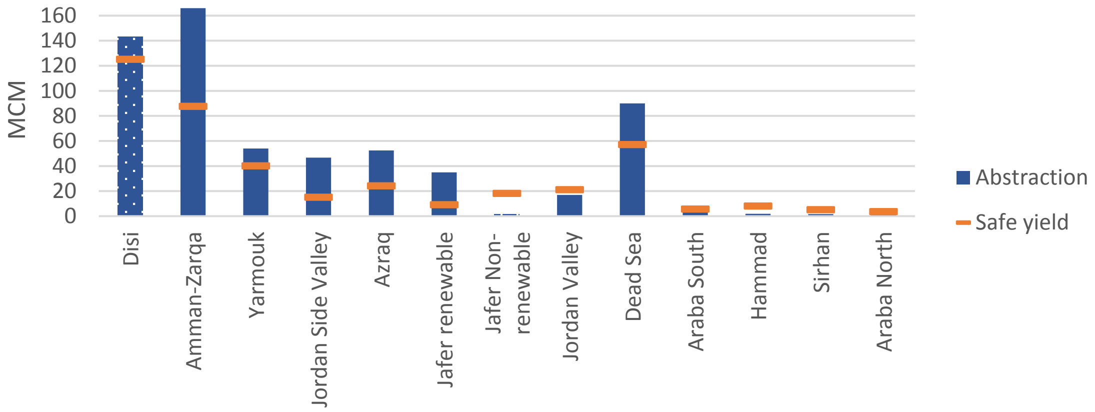

Figure 5 – Groundwater abstraction in 2015. Source: Own elaboration based on (MWI, 2016b)

Among the Jordanian groundwater resources, there are two fossil aquifers: Disi and Jafer, which are estimated at 118 MCM over a period of 100 years (Ababsa, et al., 2014). The Disi aquifer, also known as the Ram Group, supplied 23% of the total abstracted groundwater in Jordan in 2015, and stands out due to its particular exploitation.

The Disi aquifer is a groundwater basin that extends over a distance of around 308 000 km² from northern Saudi Arabia into Jordan. The reserves are estimated at 65 billion cubic meters (BCM), 4-10 BCM of which can be found under Jordanian territory. Jordan first exploited the Disi aquifer in 1977 for various uses (5.4 MCM/year), and 70-80 MCM/year were abstracted since the 2000s for agricultural (55 MCM) and municipal uses (15 MCM). Since 2013, 100 MCM/year are extracted to supply the Disi-Amman Water Conveyance Project. The Disi project was developed to increase the water resources in the country and supply the Greater Amman area with fresh, drinking water for at least 25 years. The system consists of a pipeline that conveys water from the Disi aquifer to Amman over 325 km and lifts it 800 m, after being extracted from 65 wells, 500 m deep. The whole process requires around 2% of Jordan's annual energy consumption (Ababsa, et al., 2014; ESCWA, 2015).

The project was initially conceived as an interim alternative for 20-100 years to relieve the upland aquifers from over-use until the Red Sea-Dead Sea water conveyance project (RSDSP) was totally completed. Additionally, some indirect positive effects were expected from the project, such as a higher quality of wastewater, and in turn a higher quality of water for irrigation. However, the Disi aquifer is not replenished, and the abstraction rates are depleting the resource to an alarming point. The groundwater levels have dropped at an average rate of 2.3-10.5 m/year, and the energy demand is constantly increasing to pump the water from deeper levels. If a similar extraction rate continues, in 25 years further abstraction will be economically unfeasible (Hadadin & Tarawneh, 2007; Ababsa, et al., 2014; ESCWA, 2015).

Despite this project supplies a large additional volume of fresh water, it has been stated that the required water volume would be much lower with an effective limitation of private wells, removal of illegal wells and elimination of unmonitored extractions (Ababsa, et al., 2014; Østergaard, et al., 2014). Thus, according to the MWI 2 998 wells were identified in Jordan in 2015[5], of which 1580 (67%) were working legally, 479 (16%) were working in violence and 514 (17%) were illegal wells but not working (MWI, 2016a). Regarding the working wells (i.e. 2 519 wells in total), the illegal wells represented 20% of the total, and extracted 16 MCM. The largest sector was agriculture with 1 580 wells (63% of working wells), which extracted 215 MCM representing 78% of the total abstracted volume. Because of a poor control of private-well drilling and abstraction rates, the over-exploitation of groundwater resources is being aggravated, water tables are declining, and pumping costs and salinity levels are increasing (Qtaishat, et al., 2017).

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[5] Some differences can be found depending on the publication, all of them from the MWI.

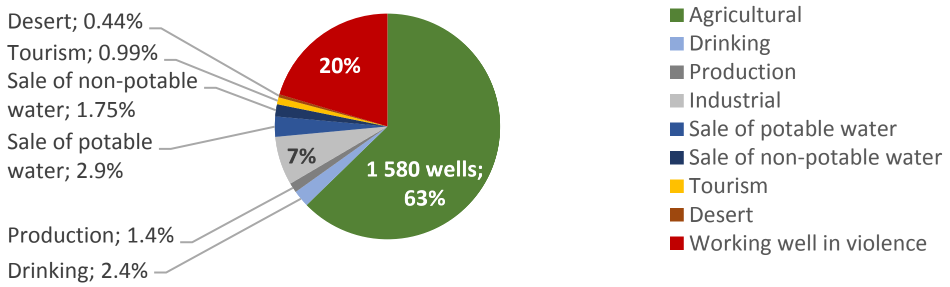

Figure 6 – Number of working wells in Jordan by sector, 2015. Source: Own elaboration based on data from (MWI, 2016a).

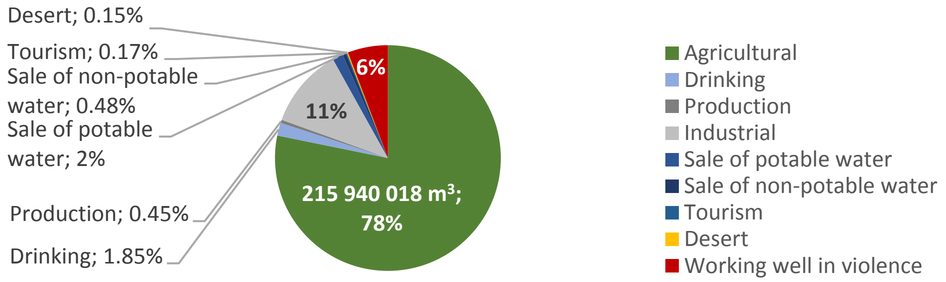

Figure 7 – Extracted amount from wells in Jordan by sector, 2015. Source: Own elaboration based on data from (MWI, 2016a).

Wastewater

In Jordan, 93% of population had access to safe sanitation in 2015; 30% used on-site sanitation methods such as septic tanks or and cesspits, and 63% had access to a sewerage system. According to the MWI, the sewer systems users amounted 5.8 million people and generated 140 MCM, but 152 MCM of wastewater entered the Jordanian WWTPs according to the same source. The difference between both volumes (i.e. 12 MCM) has been assumed as industrial wastewater[6]. (MWI, 2016a; MWI, 2016d).

In 2016, 33 WWTPs were operating in Jordan, which treated 98% of collected wastewater and amounted 159 MCM (MWI, n.d.). Most of them use the activated sludge system as standard treatment, but trickling filters and waste stabilization ponds are applied in some cases (see specific information on Jordanian WWTPs[7] in Table 27, in Appendix 0). All of the WWTPs are relatively small except for As-Samra, which in 2016 accounted for 61% of the total wastewater treatment capacity in Jordanian WWTPs and almost 70% of actual treated flow (see section 2.4.4). The total volume of wastewater is increasing at a steady pace due to the population growth, the increase of water use, a higher access to sewerage systems and the expansion of WWTPs. At the same time, the volumes of treated wastewater and re-used treated wastewater are also rising (Figure 8), and last years (i.e. 2010-2016) accounted respectively for 96% and 88% of influent wastewater in Jordanian WWTPs on average. In Jordan, treated wastewater is essential due to environmental and sanitary reasons, and because constitutes an additional water resource of increasing importance. Currently, treated wastewater is the main non-conventional water resource in the country, accounting for 11% of total water uses in 2015 (MWI, 2016b; MWI, 2017; MWI, n.d.; Howari & Ghrefat, 2011; MWI, 2016d). Over 91% of this treated wastewater is used in agriculture, either directly from WWTPs or after being discharged into watercourses (see Table 5 on page 17). The early establishment of national standards for treated wastewater has contributed to the acceptance of its use in the country. Other uses for treated wastewater include industrial cooling or aquifer recharge, depending on the level of treatment and the location of the WWTPs (ESCWA, 2015).

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[6] Specific information to confirm or refute this hypothesis has not been found.

[7] Information about the WWTP Azraq Refugee Camp was not available, hence was not included in Table 28.

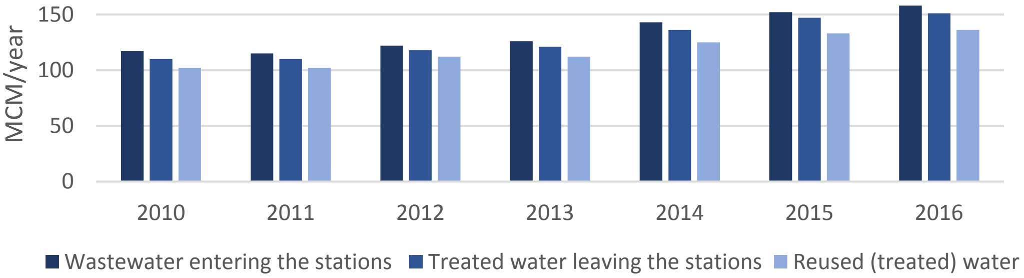

Figure 8 – Treated wastewater, effluents from WWTPs and reused water in Jordan, 2010-2016. Source: Own elaboration based on data from (MWI, 2016a)

Despite the considerable development of a regulatory framework on treated effluents, a strict quality enforcement is still required. Infiltration of wastewater into groundwater remains a challenge in Jordan, constituting the main source of groundwater pollution (especially in urban areas), and being responsible for the high nitrate concentration that has been identified in groundwater resources (Howari & Ghrefat, 2011; ESCWA, 2015). According to the MWI, another critical challenge is the quality of operation and maintenance (O&M) in Jordanian WWTPs to accomplish the wastewater reuse strategy, hence many facilities require urgent rehabilitation and extension. Thus, different improvements are often necessary, such as more professional expertise and a higher level of process control to achieve a proper introduction of anaerobic sludge stabilization. This improvement in sludge management can reduce CO_2 emissions and increase operational efficiency, as successfully completed in As-Samra WWTP (MWI, n.d.; MWI, 2016d).

Lastly, the energy associated to the wastewater collection, distribution and treatment needs to be considered as a relevant requirement that can limit the sustainable development of the sector if not properly managed. Specific data on the energy use in Jordanian WWTPs has not been found, but values from different countries and technologies can be used as a reference. Only in the case of As-Samra the energy intensity has been estimated based on published information. In this case, Chile and USA have arisen from literature as illustrative examples of high and low energy intensities respectively, to set a range of typical values in wastewater treatment (see Figure 9). These values are indicative only, and actual energy demands in Jordanian WWTPs can differ.

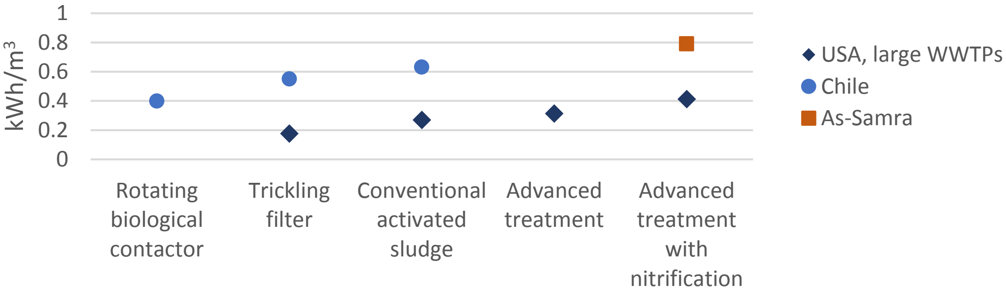

Figure 9 – Energy intensities for different wastewater-treatment technologies. Source: Own elaboration based on data from (Liu, et al., 2012; SUEZ, 2017; Molinos-Senante, et al., 2018)

As can be seen in Figure 9, the energy intensities typically increase with the complexity of the treatment. Within the wastewater-treatment process, wastewater aeration, pumping, and solids processing are the steps that typically constitute most of the electricity needs. Other aspects that affect the energy intensity in WWTPs and explain the differences within a same treatment technology include climate conditions, inlet and outlet parameters of the treated wastewater, the size and age of the system, or specific design and operation characteristics of the facility (ESCWA, 2015; Copeland & Carter, 2017).

In general, there is a large potential for energy savings in wastewater treatment. Energy efficiency measures applied to wastewater facilities can offset the energy demand, and the selection of an appropriate technology to match local climate conditions can reduce the energy needs. For instance, anaerobic processes can be more energy-efficient because require less energy for aeration. In the case of Jordan, anaerobic digestion is especially suited due to the warm climate, and additionally allows for extracting part of the embedded energy in wastewater from the digesters in form of biogas. This bioenergy from recovered off-gas and other on-site renewable technologies need to be considered because decrease the external energy supply, but do not reduce the actual energy demand (ESCWA, 2015; IEA, 2016; Copeland & Carter, 2017).

Water storage - dams and desert dams

In Jordan, most of the water from rivers and *wadis* that empty water towards the Dead Sea basin is used or stored. Thus, ten large dams[8] have been built in the last fifty years with a total storage capacity of 325 MCM and a catchment area of 13 980 km^2 (see Table 26 in Appendix 0 for specific details of the main dams). To complement these dams, there are numerous desert dams, ponds and desert excavations (see Figure 46 in Appendix 0), which mainly aim at storing water for artificial groundwater recharge and animal uses. In addition, several water-harvesting projects have been developed to store rainfall (Hadadin, 2015; Howari & Ghrefat, 2011).

The main existing dams are used to store base flows and floodwater, regulate water and release it for agricultural use, being the KTR on the Zarqa River the most important dam in the country with a total storage capacity of 86 MCM[9]. Meanwhile, the desert dams, excavations and ponds in desert areas had been historically used for grazing only, but during last years they have been used to provide local population with permanent water resources for irrigation, watering livestock and recharge purposes (Hadadin & Tarawneh, 2007; Hadadin, 2015). According to the MWI, in 2015 there were 61 desert dams with a capacity of 88 MCM, 65 ponds with a storage capacity of 0.3 MCM, and 192 desert excavations amounting 2 MCM. In total, water storage capacity in Jordanian dams in 2015 was estimated at 415.3 MCM (see Table 4).

Table 4 – Summary of water storage capacity in dams and reservoirs. Source: Own elaboration based on data from (MWI, 2016b; MWI, 2016d)

Category	Number	Capacity (MCM)
Existing dams	10	325
Desert dams	61	88
Ponds	65	0.3
Desert excavations	192	2
Planned dams	11 (10)	21.35
Planned water harvesting systems	-	15
Total in 2015		**415.3**
Expected total in 2025		451.65

However, storage systems in Jordan are threatened by several factors such as pollution of water and sediments. This pollution is mainly due to agriculture practices, mining or untreated wastewater from WWTPs or factories, which raise salinity and levels of metals and chemicals. Consequently, Jordanian reservoirs have been reported to be highly eutrophic. Moreover, sediment accumulation reduces the storage capacity in dams, especially in KTR, Walah, Mujib, Kafrein, Sultani and Bowedah dams, and even though sediment removal strategies have been tried, the results have been costly and not very effective (Hadadin & Tarawneh, 2007; Hadadin, 2015).

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[8] The Karamah Dam is the only large, existing dam not built on side rivers and *wadis* with their outlets to the JV.

[9] The Unity Dam on the Yarmouk River, also known as Al Wihdeh or Al Wehdah, is larger than the KTR with 110 MCM, but it is shared between Syria and Jordan, corresponding three quarters of the water stored to Jordan.

[10] In some cases, planned projects consist of the extension of existent dams, therefore the total number of dams will not result the addition of the existent and the future projects.

Desalination

There are two major sources for desalination in the Kingdom: seawater from the Red Sea at the Gulf of Aqaba, and brackish water, which is available throughout the country. However, desalination has not been traditionally used in Jordan, although an increasing deployment of desalinated water use is expected to cover the growing water demand in a medium and long-term future (Qtaishat, et al., 2017).

Before the proposal of the RSDSP, seawater desalination was considered economically infeasible for domestic uses, because the sea shoreline in Aqaba is far from the consumption centers, in the north-west region of the country. Only tourist and industrial uses constituted a viable option due to higher associated revenues per volume of water. On the contrary, desalination of brackish water and in particular by means of reverse osmosis (RO), has been considered a realistic option in Jordan to contribute in bridging the water gap (Abu Qdais & Batayneh, 2002). The potential of brackish aquifers after desalination has been estimated differently, ranging from 55 MCM/year after desalination (Myszograj & Qteishat, 2011), to about 100 MCM/year, including 60 MCM/year from South Ghor, and 10 MCM/year from saline springs in the sides of the JV (Hadadin et al., 2010 as cited in Qtaishat, et al., 2017).

Regarding current use of desalination in Jordan, sources greatly differ. According to the water budget from the MWI, the total use of brackish water in 2015 was 6 MCM, and entirely used in the domestic sector (see Table 5). Meanwhile, Qtaishat et al. state that the Water Authority of Jordan (WAJ) runs 20 public desalination plants out of 44 water treatment plants, which produce about 70 MCM of desalinated water annually for drinking-water supply. The Zara Ma'in plant alone is said to produce 36-50 MCM/year, supplying 30% of total water used in Amman city (Yassina & Ghandour, 2014). Additionally, some small to mid-size water-desalination plants already produce up to 10 MCM/year, including Karamah Dam (1 MCM/year), Faisal nursery wells (2.3 MCM/year) or Bereen wells (1.8 MCM/year), and there are at least 6 plants under construction that will desalinate about 10 MCM/year (Qtaishat, et al., 2017).

It has been also reported that some RO units are installed in industries for treatment process water (e.g. Arab Potash Company and Jordan Petroleum Refinery), and private desalination plants are used by farmers in the JV to treat brackish groundwater for irrigation. According to Qtaishat et al., in 2010 there were over 50 plants ranging from 360 to 2 400 m^3/day of capacity, amounting around 14 MCM/year in total. All the plants use RO as desalination technology and are powered by the electric-power grid. These plants typically operate 24 h/day in summer and 12 h/day in winter, and in 2010 treated 11.7 MCM, which resulted in 7.7 MCM of desalinated water. After being diluted in fresh water, desalinated water is used to irrigate high-value crops such as bananas, strawberry or dates, which provide higher revenues than the costs of desalination (Ababsa, et al., 2014; Qtaishat, et al., 2017; Abu Qdais & Batayneh, 2002).

Nonetheless, the potential of brackish-water resources is difficult to exploit due to several reasons, including the topography in Jordan, the need for special treatments to eliminate chemicals (e.g. manganese, iron, sulfates or hydrogen sulfide), the scattered location of the resources and the disposal of brine. Moreover, brackish-water desalination is still a costly option. Desalinated water can double or triple the production cost of fresh water, although is becoming more competitive for certain uses (e.g. urban uses) due to declining desalination costs and increasing costs for surface water and groundwater (Qtaishat, et al., 2017).

Finally, an important issue to consider is the energy required during the desalination process. RO and multi-stage flash distillation (MSF) are two of the most used desalination technologies, and both are high energy-intensive (Diná Afonso, et al., 2004). RO is dependent on a pressure difference that is typically applied by means of electricity, and MSFT often uses electricity, but primarily requires heat that can be obtained from boilers, solar collectors or low-grade excess heat from thermal power plants (CHP). In RO desalination plants, the electricity demand ranges from 0.5-2.5 kWh/m^3 (kilowatt-hour per cubic meter) for brackish water and 5-9 kWh/m^3 for seawater. In MSF systems, the energy demand includes 1.2-5 kWh/m^3 of electricity and 25-120 kWh/m^3 of heat demand[11]. Therefore, a large deployment of desalination plants in Jordan will have a direct impact on the TPES, although according to Østergaard, et al. the impact will be similar for MSF and for RO in the Jordanian system (Østergaard, et al., 2014; ESCWA, 2015). In other countries, the required energy in desalination systems is supplied by renewable energy (see examples in Table 20, in Appendix 0), which can be suitable for Jordan, specifically for the scattered brackish-water resources in rural off-grid areas. In particular, solar desalination can be a viable solution because water shortages are common in summer, when solar radiation is maximum. Similarly, hydropower has been proposed to take advantage of the reservoir that desalination systems require for residual brine, using brine as a medium for pumped storage (Perković, et al., 2016; Qtaishat, et al., 2017; Lee & Younos, 2018).

Water demand and supply

In 2015, the total water use in Jordan raised to 985 MCM, with agriculture (including livestock) consuming the largest portion. However, despite the total volume of water is increasing, the distribution by sectors has changed during last years. In 2000, the agriculture[12] and domestic sectors accounted for nearly 70% and 30% of the total water use, while in 2015 both sectors had a similar consumption, amounting 50% of total water use in the case of agriculture and 46% in the case of the domestic sector (Figure 10).

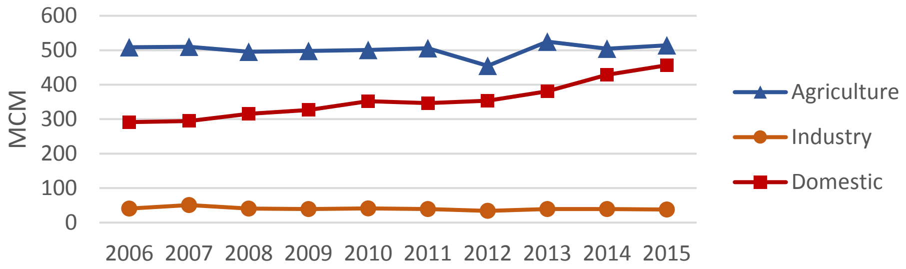

Figure 10 – Water uses by sector in Jordan, 2006-2015. Source: Own elaboration based on data from (MWI, 2016b)

In terms of water resources by origin, 61% of the water was extracted from groundwater systems, 28% from surface sources and 11% was constituted by treated wastewater (see Table 5) (MWI, 2015a; MWI, 2016b; DOS, 2018a). It is also remarkable that the water dependency ratio was 27.21% in 2014, meaning that over a quarter of the water resources used in Jordan were originated outside the country (FAO Aquastat, 2017b).

Table 5 – Water use in Jordan by sector and source in 2015[13]. Source: (MWI as cited in DOS, 2018a)

Source	Livestock		Irrigation		Industrial		Municipal		Total	
	MCM	**%**	**MCM**	**%**	**MCM**	**%**	**MCM**	**%**	**MCM**	**%**
Surface Water	7	97%	139	29%	4.0	11%	124	27%	274	28%
JV (Zai station)	0		69		4		104		177	
Springs	0		25		0		19		44	
Base & floodwater	7		45		0		1		53	
Groundwater	0.2	3%	237.4	49%	31.7	85%	332.5	73%	601.8	61%
Renewable	0.2		211.6		30		209		450.8	
Non-renewable	0		25.8		1.7		117.5		145	
Brackish water	0		0		0		6		6	
Treated Wastewater	0	0%	107.5	22%	1.7	5%	0	0%	109.2	11%
Total	7.2	1%	483.9	49%	37.4	4%	456.5	46%	985.0	100%

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[11] The energy use in desalination depends on variables such as salt content, desired salinity, size of the plant or operation of the plant, so the actual values can range between wide spans, and a close monitoring process is needed to analyze specific consumptions in a desalination system and propose retrofitting strategies accordingly (ESCWA, 2015).

[12] In this case, it is assumed that *Agriculture* includes irrigation and livestock uses, despite any clarification in the source.

[13] Different values for the water use distribution in 2015 in Jordan can be found from the MWI. For this report, the latest publication was selected when there was conflicting data.

However, the current water demand in Jordan already exceeds the available resources, and the gap between water demand and supply is widening through the years. According to the MWI, the water demand in Jordan in 2015 was around 1 400 MCM, hence the gap between water supply and the water demand was over 400 MCM (MWI, 2016b). Consequently, there is a severe competition among socioeconomic sectors, which is being aggravated by the rise in water demand and the associated decrease in the quality of water resources. The water balance in Jordan is therefore posing serious sustainability challenges, and water shortages are threatening both the development and the health of Jordanian population (Hadadin & Tarawneh, 2007; Howari & Ghrefat, 2011; Van den Berg & Agha Al Nimer, 2016; Qtaishat, et al., 2017).

Despite the highest priority of the MWI is "to ensure that all citizens have access to sufficient, safe and affordable water for personal and domestic uses" (i.e. 120, 100 and 80 l/day per capita for major urban centers, small towns and rural areas respectively), domestic water supply constitutes a particularly critical challenge in the water system. Over 94% of Jordanian population has already access to improved water supply via network and 99.3% of water-quality tests fulfil the required microbiological parameters[14], but the service is still deficient (MWI, 2016d). The government is implementing a strict water-rationing program, and Jordanians living in big cities receive water once per week for some hours. Meanwhile, other areas receive water every other or every two weeks. Since the Disi project became operational the continuity of supply has increased, but the water supply remains intermittent. Rooftop tanks constitute an integral part of the supply system to store water for the weekly needs, and population that does not own tanks or is not connected to formal water networks consumes less water (El-Naser, et al., 2014; MWI, 2016d). Moreover, an intermittent water supply regime brings about complications. For instance, the required maintenance in the water system is higher due to variations in pressure and the alternative presence of air and water. This also leads to higher pipe burst and corrosion that result in leakages, and in turn causes water and energy losses. Additionally, irregular water supply can result in the intrusion of pollutants to the network or the tanks, hence compromising the quality of the water (ESCWA, 2015)

Other major aspect of the deficient domestic water supply is the non-revenue water (NRW). NRW consists of water sent into the distribution system that is not billed, also referred to as physical and administrative losses (i.e. leakages and illegal uses). According to the MWI, NRW can be due to old, damaged equipment and pipes, inadequate maintenance, non-working meters or unauthorized connections. In 2014, NRW accounted for 52% of the water supply in the domestic sector, so instead of 126 l/day per capita, the average supply was 61 l/day per capita[15] (MWI, 2016d).

Energy use in the water sector

A key aspect of the water supply in Jordan is the associated energy use, most of which consists of electricity consumption. The water sector involves an energy-intensive operation by deploying large water pumping, transport, distribution, irrigation systems, treatment of water (including desalination) and wastewater (ESCWA, 2015; Copeland & Carter, 2017). The electricity consumption associated to the water and agriculture sector has fluctuated between 14% and 15% of the total electricity consumption during last decade (Figure 11), and in particular amounted 14.9% in 2016 (MEMR, 2018; MWI, 2016d).

The MWI estimated an average energy consumption per volume of water of 4.43 kWh/m^3 in 2015, but the specific energy-water ratios for WAJ and JVA (Jordan Valley Authority) differed a lot, ranging from 8.01 kWh/m^3 to 0.17 kWh/m^3 respectively (MWI, 2016b). These differences can be partly due to large pumping needs to deliver water over long distances and at different altitudes, as well as other factors such as the water source (surface water pumping typically requires less energy than groundwater pumping), different treatments, intended end-use, topography or amount of water loss in the system (Copeland & Carter, 2017).

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[14] Drinking water quality in Jordan is governed by Jordanian Standard 286 (JS286) which is adapted based on the World Health Organization (WHO) guidelines (MWI, 2016d)

[15] In informal settlements, the per capita consumption is estimated at 25-50 liters/day (MWI, 2016d).

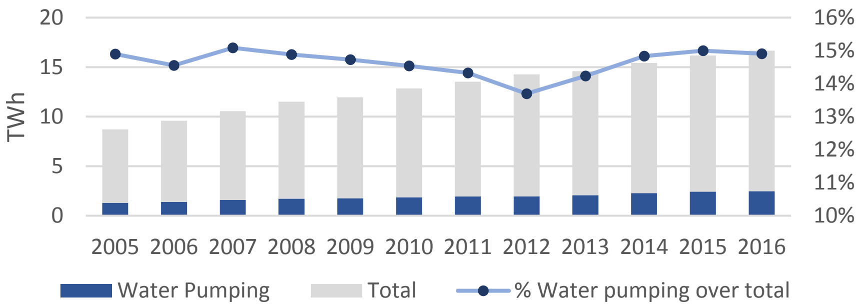

Figure 11 – Electricity consumption for water pumping in Jordan, 2005-2016. Source: Own elaboration based on data from (MEMR, 2015a; MEMR, 2018)

For that reason, the optimization of the energy use in the water sector can reduce the conventional energy requirements through the increase of efficiencies and the reduction of losses. These changes are to be applied to both the energy systems within the water sector and the water inefficiencies and losses, because any positive change in the water system will affect positively the required energy. Some improvement options include improving O&M, optimizing system processes by means of monitoring and control systems (i.e. SCADA), and replacing, rehabilitating or upgrading equipment in treatment and distribution systems by more efficient and right-sized machinery. Other options comprise reducing long-distance pumping through integrating decentralized water infrastructures that use rainwater or other local water sources. Moreover, decentralized systems can reduce service interruptions and can be coupled with user-scale energy systems to cover the energy requirements of treating water onsite (MWI, 2016d; Lee & Younos, 2018; Copeland & Carter, 2017).

Additionally, continued reliance on imported fuel to power Jordan's water sector exposes water prices to volatilities in the oil and gas markets, which have impacts on the country's energy demands, and in turn on Jordanian economy and overall development (Al-Zu'bi, 2017). Same trends in the energy supply can repress industrial growth and affect food security, hence tapping alternative energy sources (i.e. renewable energy technologies) is an option that the MWI has started to deploy (JAEC/Worley Parsons, 2011; MWI, 2016d). The inclusion of renewable energy in on-site systems in water utilities can provide low carbon water production, and off-grid energy production could promote rural electrification, water pumping, irrigation and low carbon food production (Keulertz & Woertz, 2015). In the case of reservoirs, ponds, irrigation water tanks and other water bodies, the integration of floating photovoltaic covers has reported numerous benefits, although the deployment of this technique is still marginal. Some of these benefits include up to 90% decrease in evaporation losses, reduction of photosynthesis and weed growth, which improves water quality, and increase of the electricity output of the solar panels by up to 25% thanks to the cooling effect of the water surface (Redón Santafé, et al., 2014; Taboada, et al., 2017; Motta Silvério, et al., 2018).

Prospects in the water sector

Projections of water resources show that there will be persistent shortage in the future, driven by the natural water scarcity together with a growing population and an expanding economy. Water demand in the domestic sector is expected to increase 50-60% by 2050, while industrial and commercial sectors are projected to use, in ten years, 300% and 200% of their current water demand, respectively. Furthermore, the stress on water resources will be worsen by the effects of climate change. Models predict 15% decrease in rainfall, 3% increase in evapotranspiration, or 18% higher irrigation-water demand in the next 20 years (Howari & Ghrefat, 2011; El-Naser, et al., 2014; MWI, 2016d). Consequently, water availability will be 30% lower, and Jordan will require alternative water resources and efficiency strategies (Qtaishat, et al., 2017).

The Jordanian government presented in 2016 their 'National Water Strategy 2016-2025', based on Integrated Water Resources Management (IWRM) to promote the coordinated management of land, water and related resources in order to maximize the resulting gains in an equitable and sustainable manner. The strategy aims at achieving a balance between supply and demand without hindering development. The main proposed lines of work are: (i) improving efficiency in sourcing, distribution and conservation of resources; (ii) increasing wastewater treatment; and (iii) developing new water source options through rainwater harvesting, storage of water runoff, artificial recharge, desalination, and share of transboundary resources. The strategy includes special attention to the protection of water resources (i.e. pollution, quality degradation and depletion) and the adaptation to climate change (Hadadin, 2015; MWI, 2016d).

Some specific measures to be achieved by 2025 include 25% reduction of NRW, the decrease of technical losses below 15%, and the construction of new dams to enlarge their capacity up to 400 MCM (see Table 21 in Appendix 0). In terms of sanitation, all municipalities with over 5 000 inhabitants are expected to have access to a sewage system, accounting for 80% of total population and generating 240 MCM (versus 140 MCM produced in 2015). Additionally, some energy targets are considered for public water facilities, such as reaching 10% share of renewable energy and reducing 15% the total energy consumption (MWI, 2016d).

Even if these measures are implemented, according to projections from the MWI the gap between supply and demand in the water sector will not be solved by 2025, although will be reduced from 409 MCM in 2015 to 88 MCM in 2025 (Figure 12).

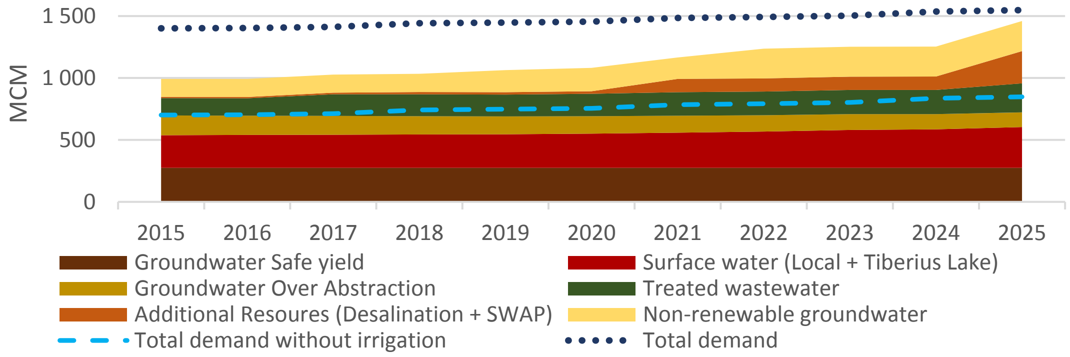

Figure 12 – Prospects on Jordan's water supply and demand (2015-2025). Source: Own elaboration based on data from (MWI, 2016d)

Nonetheless, the achievement of larger water resources will be subjected to the deployment of desalination. As a central part of the national strategy, different desalination projects will be promoted to meet shortfalls in freshwater availability. For instance, there are plans to increase by 1 MCM/year the desalination capacity in the period 2015-2020 through small and mid-size plants, and a plant in Aqaba will provide 10 MCM/year, but the main desalination project and largest water-related project in Jordan will be the RSDSP. According to the MWI, without the RSDSP the gap between demand and available water resources will reach over 26%, instead of 6% if it is eventually developed (MWI, 2016d; Qtaishat, et al., 2017).

The RSDSP

The main objectives of the RSDSP are to provide an affordable and secure water supply for Jordan, to save the Dead Sea from disappearance, and to provide a regional water supply for Jordan, Palestinian Authority and Israel while promoting regional cooperation among them. Despite the final features of the system can vary, the project will include the extraction and conveyance of 190-300 MCM/year of seawater from the Red Sea to a desalination plant north of Aqaba, where 65-85 MCM/year of desalinated water will be produced by RO. In its phase I, expected to come on stream in 2021, 30-35 MCM/year will be sent back to Aqaba, and 35-50 MCM/year will be supplied to Israel in the south. In exchange, Israel will supply about 30 MCM from the Lake Tiberias to the northern regions in Jordan at a previously agreed price[16]. This transfer will alleviate water shortages, and 20 MCM/year will be used for irrigation purposes. The remaining brine and seawater (i.e. about 110-220 MCM/year) will be pumped 180 km and discharged to south of the Dead Sea. Phase II is not defined yet, but will increase the desalinated water by around 150 MCM/year with a new plant (235 MCM/year in total), to be delivered to Amman (Ababsa, et al., 2014; MWI, 2016d; Rabadi, 2016). A diagram of the complete system is included in Figure 48, in Appendix 0.

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[16] In literature, this transfer agreement is also referred to as SWAP.

The RSDSP will also include a hydropower station along the conveyance system, although the power capacity is unknown. According to different studios, around 400-800 MW (megawatts) could be extracted from the 400 meters difference of altitude between the two seas. In principle, the produced electricity could be used to cover the energy requirements associated to the pumping and desalination systems, and any electricity surplus could be sent to the national electric grid (Ababsa, et al., 2014; Rabadi, 2016; Rahim, 2015).

Apart from the main positive impacts, numerous additional effects are expected from the project, including the revitalization of tourism and the industry around the Dead Sea or the restoration of flora and fauna. However, from an environmental perspective, there are negative changes potentially associated to the RSDSP. For instance, the water with a lower rate of salinity could lead to deposits of gypsum, algal, blooms and microorganisms in the Dead Sea. Furthermore, the pipeline could disrupt natural ecosystems, and since will pass through an active fault, seismic activity could cause leakages and groundwater contamination in the Wadi Araba (Ababsa, et al., 2014).

2.4.2.3 Energy sector in Jordan

Energy resources

Mineral energy resources

In Jordan, mineral energy resources at national level are very limited in terms of oil and gas, but different strategies are being followed to search and develop new unexploited resources. Hamza oil field constitutes the main national oil source, with a production of 500 ton in 2015. Hamza had 90 million barrels in 2010, of which 10 million are thought to be recoverable. Natural gas reserves were 6 031 billion m^3 in 2010, with a production of 121.8 million m^3 in 2015. Most of this production corresponded to Risha gas field (in the Eastern desert near Iraq), with 340 000 m^3/day (MEMR, 2017; Ababsa, et al., 2014).

However, Jordan has deposits of non-conventional oil (see Figure 49 in Appendix 0), being the fourth largest in the world. Thus, there are large reserves of oil shale with an average organic content of 9% to 13% and great quantities of deep crude reserves ten times higher than the surface oil shale (MEMR, 2017). According to different studies, 70 billion tons containing more than 7 billion tons of oil cover 60% of the country, which could satisfy all Jordan's energy needs for several hundred years (Al-Zubari, 2017). The largest deposit is in Yarmouk, with approximately 300 m thick. Moreover, in the Wadi Isal area approximately 35 million tons of tar sands have been discovered, with about 10% oil by weight (Ababsa, et al., 2014).

Finally, the uranium resources in Jordan are present in more than one horizon in north and central Jordan, at different depths (Howari & Ghrefat, 2011). Three general areas with uranium reserves have been identified: central Jordan, Al Hasa, and south Jordan (Rahim, 2015). Overall estimations differ between 40 000 and 60 000 tons of uranium reserves. The production from this deposits is expected to be of 1 ton of yellow cake per 10 000 tons of uranium ore (MEMR, 2017), and the rate of production of uranium from the mines is expected to be about 2 000 tons annually (Rahim, 2015). According to the Jordan Atomic Energy Commission (JAEC), 100 000 tons of additional uranium can be found in phosphates (JAEC/Worley Parsons, 2011).

Renewable energy resources

Jordan has a great potential for renewable energy production, namely in terms of solar and wind resources. In terms of wind energy potential, several hundreds of megawatts could be installed according to the Jordan's wind atlas. Wind speeds reach 7 to 9 m/s at 50 m a.g.l (above ground level) in certain areas across the territory, especially in the north and west with wind speeds of up to 11.5 m/s (see Figure 50 in Appendix 0). These conditions allow payback periods to be 6 years in some cases (Perković, et al., 2016).

The country is located in the earth-sun belt area, which leads to average direct solar radiation ranging from 5 to 7 kWh/m2 (see Figure 51 in Appendix 0). These values are among the highest in the world, and combined with relatively moderate temperatures, low humidity, low dust levels and around 330 days of sunshine provide Jordan a high solar energy potential, both for solar thermal production and for power production. Several studies have estimated the payback period for solar power projects as low as 2.3 years in some cases (Rahim, 2015; MEMR, 2017; Perković, et al., 2016).

Apart from solar and wind energy, Jordan has potential to deploy additional renewable energy resources. Thus, there is potential to use biogas from solid waste for electricity production, and Jordan is already using methane generated from landfills to produce electricity. Despite natural water resources are very limited for hydropower production, there can be a moderate potential if a proper management of man-made water systems is developed or the RSDSP is eventually completed. There are also medium and low geothermal waters ranging from 20ºC to 60ºC along the Dead Sea rift valley have been found. Finally, the potential of biomass resources has been estimated at 6.6 PJ including collection losses, but organic industrial, human and animal residues can also be used in waste-to-energy technologies for secondary sources of energy while reduce the quantities of waste that require final disposal (Rahim, 2015; ESCWA, 2015; Østergaard, et al., 2014).

Energy balance in Jordan

Jordan is very dependent on imports to cover its primary energy needs. In 2015, 97% of the energy resources were imported. Fossil fuels accounted for over 97% of the total primary energy supply (TPES) mainly including crude oil, oil derivatives and natural gas. Renewable production principally consisted of solar and wind and contributed to 2% of the TPES, but due to the overall low production with national energy resources, renewable technologies accounted for 64% of the total local production (IEA/OECD, 2018).

In the past, around 80% of gas needs for electricity production were covered by low-priced natural gas from Egypt, but the regular supply was sharply disrupted in 2011 by attacks targeting the gas pipeline. Consequently, the Jordanian government purchased oil at high costs to cover a 64% drop in the gas supply, resulting in a large increase of the public debt, higher energy costs and a decline in food security between 2012 and 2015, particularly in terms of food availability. Currently, the majority of the oil is imported from Saudi Arabia, Iraq and the Gulf States, with some processing of crude oil being done at the only Jordanian oil refinery located in Zarqa. Moreover, in order to increase the security of supply Jordan has become a LNG importing country, with large import volumes and the construction of a regasification terminal in Aqaba. In 2017, 88% of the electricity in Jordan was produced using natural gas from this terminal (IEA, 2017; Ababsa, et al., 2014; Al-Zu'bi, 2017; Figueroa, et al., 2018; MEMR, 2018).

In terms of final energy consumption, transportation sector accounted for almost half of the total in 2015, and its share is expected to increase (Al-Zu'bi, 2017). The next largest-consumer sectors were residential with 23% and industry with 15% (Figure 13).

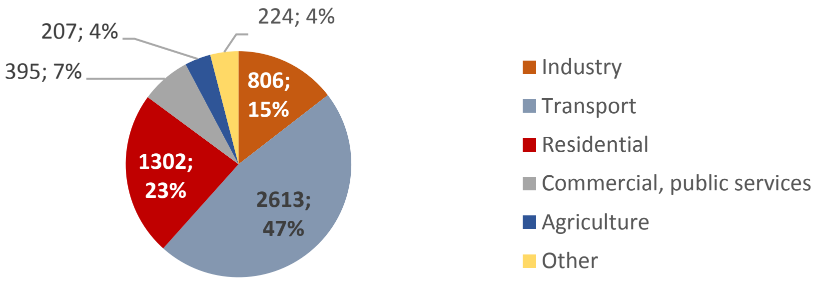

Figure 13 – Final energy consumption by sector in Jordan, 2015 (thousands toe, %). Source: Own elaboration based on (IEA/OECD, 2018).

Electricity installed capacity, production and consumption

Regarding the installed electricity-producing capacity in Jordan, during last years there have been fluctuations due to plants being decommissioned but also entering the system (see Figure 52 in Appendix 0). Among these variations, several changes are especially noticeable, such as the consecutive reductions and increases in capacity of steam and gas turbines since 2012, new fuel oil and diesel systems in 2014 to compensate the disruption in the Egypt-Jordan gas pipeline, or the incorporation to the fleet of around 480 MW of wind and solar systems in 2015 and 2016.

Total electricity-producing capacity reached a maximum of 4.6 GW in 2016, including industries and the electricity sector (see Table 22 in Appendix 0). Within the total capacity of 4.4 GW in the electricity sector, fossil fuels accounted 89%, and combined cycle alone constituted 49% (see Figure 14). Renewable technologies (11%) were dominated by solar (6%) followed by wind (4.5%), with 100 MW of capacity corresponding to small-scale renewable systems (MEMR, 2018).

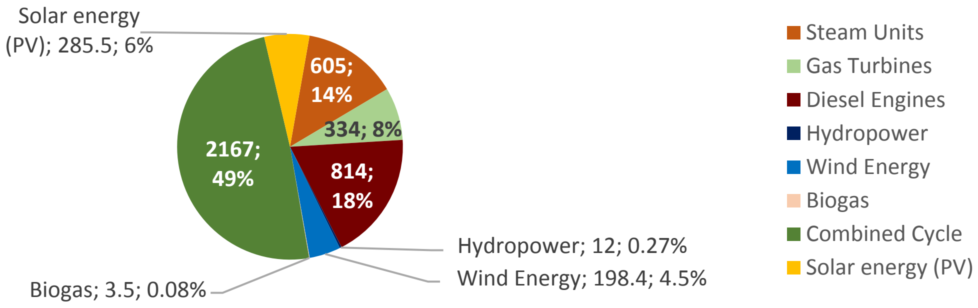

Figure 14 – Installed capacity by type of production in the electricity sector (MW). Jordan, 2016. Source: Own elaboration based on data from (NEPCO, 2017)

Overall electricity production in Jordan has been increasing at a steady pace last decades, reaching 19 730 GWh (Giga Watt Hour) in 2016 (see Table 22 in Appendix 0). In this case, 95% of the production corresponded to fossil fuels, with combined cycle accounting for 77% (see Figure 53 in Appendix 0).

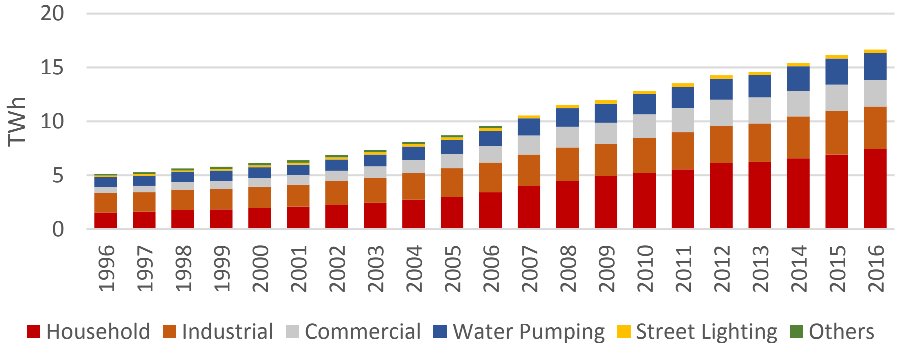

Figure 15 – Electricity consumption by sector in Jordan, 1996-2016. Source: Own elaboration based on data from (MEMR, 2015a; MEMR, 2018)

Meanwhile, the total electricity consumption has followed a similar increasing trend (see Figure 15) and amounted 16 843 GWh in 2016, in comparison with 11 509 GWh in 2008 (Al-Zu'bi, 2017). By sectors, the main electricity consumer in Jordan is the domestic sector, which in 2016 accounted for 45% of the total consumption, followed by the industrial sector with 24%.

National grid and connectivity

The national electric system in Jordan is constituted by 132 kV and 400 kV transmission lines that interconnect the main power generating stations with the final loads across the territory. According to NEPCO, projects to construct new transmission lines (i.e. 132 kV and 400 kV) were implemented in 2016, but the total length of the transmission lines remained the same in 2015 and 2016 (i.e. 924 km-circuit for 400 kV lines and 3 573 km-circuit for 132 kV lines). Last registers state an availability of the transmission system of 99.82% and 99.91% in 2015 and 2016 respectively. Despite a slight increase in 2015, over last years the electrical losses have decreased at every level within the electricity sector (i.e. production, transmission and distribution, see Table 24 in Appendix 0). The national electric grid also includes the distribution system and international connections: a 400 kV tie line with Syria in the North and a 400 kV submarine line with Egypt in the Southwest (see Figure 54). In 2016, the imported electricity from Egypt via the tie line amounted 333.8 GWh, and the exported electricity to Jericho region (Al-Quds Electricity Company) and Tree Beil (Iraqi Border Centre) amounted 45.4 GWh. (NEPCO, 2017).

However, the capacity limitations have characterized the national grid. In 2013, the Jordanian Government cancelled several projects to build new power plants due to the inability of the grid to accept new loads. In 2014, a significant grid expansion was carried out, increasing the grid capacity from 3 186 MW in 2013 to 4 000 MW (NEPCO, 2015). Subsequently the grid capacity has been further enlarged (see Table 23 in Appendix 0). Therefore, managing the proper expansion of the national grid is a key issue for Jordan to implement effectively its national strategy (Rahim, 2015).

According to the World Bank, Jordan reached 100% of electrification in 2014 (World Bank, 2018), but the latest information from the MEMR (Ministry of Energy and Mineral Resources) states that the percentage of population supplied with electricity was 99.9% in 2016, staying invariable from 2009 (i.e. first accessible data from the MEMR) (MEMR, 2015b; MEMR, 2018). The MEMR announced that the electrification of remote villages, rural communities and poor families had continued in 2016, with 2 362 recorded requests for electrification and 1 722 new electrified houses (MEMR, 2017).

Water use in the energy sector

The energy sector has associated a large use of water, including water uses for mining, extraction and processing of energy resources and water requirements for electricity production. The use of water is divided into consumption, being the water lost to evaporation, and withdrawal. The water withdrawal is the extraction-release component of the water use, and although not lost, has important implications on the environment such as stress on aquifers, reduction of environmental flows in rivers, lakes and seas, warming of the aquatic environment (thermal pollution) or effects on fauna and flora (ESCWA, 2015). Within the energy sector, the power sector is the largest source of water withdrawals, although primary energy production is larger in terms of consumption (IEA, 2016).

Water for cooling constitutes a major part of the water use in electricity production, especially in Jordan where most of the energy resources are imported. There are three main types of cooling technologies: once-through, wet-tower and dry cooling. Each technology presents benefits and drawbacks in terms of impact on water quality, energy penalties or water withdrawals versus consumption. Once-through technologies are generally the most efficient and with the lowest capital costs, but the withdrawal rate is the highest; wet-tower systems withdraw a smaller volume, but the consumption is higher; dry cooling uses very little water, but is costly and has the lowest efficiency. Hybrid alternatives (i.e. a combination of dry and wet cooling systems), are projected to be extensively deployed together with dry options, due to their flexibility and more competition for water and strict regulation. When comparing the same cooling technologies, combined-cycle gas turbines (CCGT) usually present the lowest rates of water use among thermal power plants, while nuclear power plants on average withdraw more water per unit of energy (IEA, 2016).

Specific values for Jordan have not been found, and instead, generic values could be assumed. In terms of operational water use, as can be seen in Table 25 (Appendix 0) the average needs do not necessarily depend on the fuel or energy source, but on the applied cooling technology. For instance, despite concentrated solar power plants (CSP) are considered a promising renewable option for areas with high insolation like Jordan, the water use for cooling and cleaning of mirrors and lenses can be comparable to conventional thermoelectric plants depending on the cooling system. Consequently, dry or hybrid cooling systems are the most preferable options, and in some water-scarce regions CSP is never suitable (ESCWA, 2015; IEA, 2016).

The technologies with a lowest water demand are wind turbines and photovoltaic[17] (PV), being zero for wind and 22.7 liters/MWh for PV, which is mainly associated to cleaning. Therefore, these technologies can be considered the most suitable for Jordan in terms of water use. In any case, the water use associated to electricity production is of special relevance in Jordan due to the limited water resources, because if not properly managed, a lower carbon energy pathway can intensify water stress or be limited by it (IEA, 2016).

Additionally, the extraction and refining of fossil fuels require large quantities of water, although is minor in Jordan. For crude oil refining, 200 to 800 liters of water are used per ton of crude oil. Much of the water is recaptured along with the produced oil, but generates a large waste stream to be treated and disposed. Gas extraction is generally less water intense but site-specific, depending on geological formations, and can be different even within the same well field. (ESCWA, 2015)

Another main use of water in the energy sector is hydropower production, but in Jordan its potential is reduced due to the water scarcity and the great seasonal fluctuations. According to NEPCO, in 2016 only around 12 MW of hydropower capacity were installed in the Jordanian electricity sector, accounting for 4.5% of total electricity-producing capacity (NEPCO, 2017). Hydropower turbines at the outlet of the cooling system in Aqaba Power Station provide 6 MW, and the KTR includes 6.4 MW of installed hydropower capacity, being the only dam in Jordan used for hydroelectric production[18]. Moreover, As-Samra WWTP covers part of its energy needs with hydropower turbines at the inlet and the outlet of the facilities, with 4.2 MW in total (see section 2.4.4.3).

Energy prospects

Jordan's vision is to reduce the use of fossil fuels and increase the energy independence. Moreover, Jordanian electricity-production fleet is relatively old, and most of the existing power plants are planned to be decommissioned by 2020. Meanwhile, electricity consumption is expected to grow at a rate of 6% to 7.4% annually by 2020, and 15 GW of electricity production capacity will be needed by 2040. Therefore, a consistent strategy is required to avoid widening the gap between electricity demand and available production capacity (JAEC/Worley Parsons, 2011; Perković, et al., 2016; Al-Zu'bi, 2017; Al-Zubari, 2017).

Jordan's National Energy Strategy (2007-2020) includes as main goals: diversifying energy resources, increasing the use of local resources, reducing the dependency on imported oil, and enhancing environmental protection (Al-Zu'bi, 2017). Among the main strategies towards greater energy security, Jordan has planned to expand renewable energy projects, produce and use shale oil for electricity production, install nuclear power and promote electrical interconnections with neighboring countries. Additionally, there are plans to expand the use of natural gas for power production, and refurbish decommissioned thermal power plants such as Hussein Thermal Power, with 485 MW, expected to be operating in the second half of 2018 (GoJ, 2014; MEMR, 2018). Table 6 summarizes the prospects from the MEMR for the primary energy mix by 2020 and 2025.

Table 6 – Primary energy supply prospects in 2020 and 2025 in Jordan. Source: (MEMR, 2018)

	Crude oil and products	Coal and coke	Renewable energy	Natural gas	Electricity imports	Oil shale	Nuclear
2020	51%	4%	5%	30%	0%	5%	-
2025	50%	4%	10%	8%	0%	10%	22%

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[17] Some variants of PV such as solar concentrated photovoltaic (CPV) or high concentrated photovoltaic (HCPV) have a higher water demand associated with cooling (ESCWA, 2015).

[18] Al Wehdah dam (also called Unity dam), includes 240 MW of hydropower capacity (3 Francis turbines, 80 MW each), but according to the agreement between Jordan and Syria, the electric production belongs to Syria (AQUASTAT, 2009b). Wadi Arab dam is also prepared for hydropower production according to literature (see AQUASTAT, 2009b; Hadadin, 2015), but information about the installed capacity is scarce and old. The only data found states that 375 kW were installed in Wadi Arab dam, including a hydro-pumping system for energy storage (Murakami, 1995).

Aside from energy production measures, Jordan is implementing energy-efficiency strategies, such as the Jordan Renewable Energy and Energy Efficiency Fund (JREEEF) or the National Energy and the National Energy Efficiency Action Plan (NEEAP) to reduce the overall energy demand (MEMR, 2018). The untapped potential of energy-efficiency gains across all sector can reduce over 25% of the primary energy consumption by 2030. These energy savings can be considered as the most cost-effective source of energy supply, and bring about many positive impacts such as water savings in the energy production, and environmental, social or economic benefits (ESCWA, 2015).

Oil shale

Jordan is planning the exploitation of oil shale from national reserves, and the MEMR projects that will cover 5% and 10% of total primary energy supply by 2020 and 2025 respectively (ESCWA, 2015). The construction of 470 MW of direct combustion with oil shale has started, and is expected to be concluded in following years (MEMR, 2018). However, the reliance on domestic oil shale will imply a great use of water resources, potential groundwater pollution and an extensive use of land. Apart from the cooling water required during its use in power plants (see Table 25 in Appendix 0), additional water will be necessary for drilling wells, hydraulic fracturing, well completion and treatment to secondary recovery, among other stages of oil shale extraction and processing. (ESCWA, 2015).

Over 23 shale oil fields have been studied in Jordan, most in the central regions. In the shale oil deposits in El Lajjun and Attarat, it has been estimated that 1.8 barrels of water are required to process one barrel of oil shale, which will be extracted from a local aquifer in the Attarat area. There are also plans to use *in situ* processing in Azraq and Al Jafr, which will require large amounts of fossil water from the Ram group, and can be harmful to groundwater (ESCWA, 2015). In other cases, the MWI has planned to use brackish deep aquifers to cover the water needs for shale oil extraction (MWI, 2016d). Furthermore, it takes 2.6-4 barrels of water to produce one barrel of oil from oil shale, and 2.3-5.8 barrels of water for one barrel of oil from oil sands (ESCWA, 2015).

Nuclear power

The first nuclear reactor in Jordan has completed its hot commissioning testing and is awaiting the issuance of its operation license. The Jordan Research and Training Reactor (JRTR), located on the Jordan University of Science and Technology (JUST) campus, consists of an open-tank-in-pool multi-purpose research reactor with a maximum rated power of 5 MWt (thermal megawatts), upgradable to 10 MWt. It will provide different services, including education and training, neutron activation analysis, radioisotope production or material irradiation (Suaifan, et al., 2017).

However, the largest nuclear project planned in Jordan consists of installing 2 GW of nuclear power, estimated to cover 22% of total primary energy supply by 2025. The location of the plant has changed several times, in part due to seismic characteristics of the different proposals. The latest site is placed in Qasr-Amra, about 70 km southeast of Amman, in Al-Azraq province (World Nuclear Association, 2018).

Nuclear power can offer numerous benefits to the Jordanian context, but there are also very relevant concerns to consider. On the one hand, nuclear power is a commercially proven and carbon-free electricity supply. It is geographically constrained, with the lowest use of land per installed capacity: a minimum area of 0.3 km^2/GW is required, and additional 0.1 km^2 if a cooling tower is used (ESCWA, 2015). According to the JAEC, the construction of 2 GW of nuclear power in Jordan will have an additional impact across economic sectors of USD 10 161 million, in particular USD 155 million in the electricity and water sectors, and USD 108 million in the agriculture sector. Similarly, it will have an effect on employment rates with 7 726 jobs, including 189 new jobs in the electricity and water sectors, and 168 new jobs in the agriculture sector (JAEC/Worley Parsons, 2011). Furthermore, it is reliable for baseload power needs with an annual working period of 7 500-8 000 hours, increases Jordanian energy independence and contributes to getting rid of the price volatility associated to fossil fuel prices (JAEC/Worley Parsons, 2011).

On the other hand, nuclear power presents security and environmental constraints, such as radioactive waste storage or potential contamination of water sources (i.e. thermal or/and radioactive pollution). Moreover, nuclear power production is very water intensive (Lee & Younos, 2018), being mainly required for cooling and for liquid waste dilution. As said previously, nuclear power is generally the power-producing technology that withdraw the highest amount of water per unit of energy, in part because has large cooling needs and cannot discharge heat directly into the atmosphere (IEA, 2016). In Jordan, treated wastewater from As-Samra WWTP will be the main source for the nuclear power plant, and even though the required water volumes greatly vary with the cooling technology, any option will have a great impact in the national water budget. The less negative option would be a dry-cooling system, but there is no specific example for a large nuclear plant (ESCWA, 2015). According to projections from the MWI in 2012, cooling water for nuclear power will amount 100 MCM/year, although the latest prospects in the National Water Strategy 2016-2025 reduces this value down to 70 MCM, including oil shale-associated water demand (MWI, 2016d). Part of that water will not be lost but will be warmer when discharged to the environment[19], which can involve additional environmental effects.

Furthermore, despite Jordan does not plan to enrich its own fuel in the near term (JAEC/Worley Parsons, 2011), there are plans to start mining uranium. This process will imply potential natural radioactive pollution from uranium deposits nearby phosphate-bearing horizons, and great water uses estimated at around 60 MCM/year according to JAEC (Howari & Ghrefat, 2011; ESCWA, 2015).

Renewable energy technologies

Jordan has targeted 1.8 GW of renewable electricity production by 2020, including 56% of the renewable capacity covered with solar energy (IEA, 2017). In 2015, the total capacity of renewable energy systems (i.e. solar PV and wind) being constructed, under constructed or under development amounted 1.35 GW (MEMR, 2018). These alternatives can increase the energy independence, but also constitute a challenge due to the intermittency of the sources and their physical land requirements (i.e. solar plants require around 30 times more land than nuclear power plants) (ESCWA, 2015).

However, upscaling the deployment of renewable technologies requires structural changes in the system, especially in the case of intermittent sources such as solar or wind that usually have a low number of working hours (e.g. 2 000 equivalent hours per year for solar plants). In the case of centralized systems, it is crucial to develop smart grids to stabilize the intermittent energy inputs into the grid[20], and robust interconnecting networks between countries together with power exchange agreements to manage effectively the surplus of energy production. In the case of decentralized systems and particularly those coupled with water-pumping systems (see *Energy for agriculture* in section 2.4.2.4), net metering schemes or similar strategies to monitor and regulate are advisable (ESCWA, 2015).

2.4.2.4 Agriculture sector in Jordan

Jordan is a food-deficit country, importing 87% of the food due to limited natural resources for agricultural production (JAEC/Worley Parsons, 2011; MWI, 2016d). Field crops constitute 91% of imported agricultural products, while fruits and vegetables are exported and account for one quarter of total agricultural exports (Figueroa, et al., 2018). The contribution of the agricultural sector to GDP has

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[19] There is not Jordanian standard for thermal effluents from a nuclear power plant, and regulations from other countries greatly differ, when do exist. In some cases there is a maximum limit in the temperature difference: 1ºC from ambient in Canada, South Africa, Norway or Denmark, 2-10ºC in the discharge and mixing zones in the Netherlands, 3ºC in the discharge zone in Spain, 7-10ºC in the discharge zone in Germany, or 11ºC between inlet and outlet in France. In other cases, there is an absolute maximum, either used as the only requirement or to complement a temperature difference: 25-30ºC in the Netherlands, 30ºC in France and Germany, or 32ºC in many states in the U.S. (BEEMS, 2011; Madden, et al., 2013)

[20] There is not an only, generally accepted parameter or method to evaluate power grid stability. Some proposals include frequency, voltage and rotor angle stability (Čonka, et al., 2014; Musau, et al., 2017), or "basin stability" (Menck, et al., 2014).

experienced a reduction during last decades, but since 2000, it has almost doubled (see Figure 16). While in 1970 agriculture constituted 11.6% of GDP, in 2000 there was a minimum of 2.3%. Driven by an increasing domestic demand, in 2016 the agricultural contribution to GDP reached 4.3%, of which around one third corresponded to vegetables (Figueroa, et al., 2018). Despite the low direct contribution of agriculture to GDP, due to strong downstream and upstream linkages a large share of GDP is considered as agriculture-dependent in Jordan (JAEC/Worley Parsons, 2011).

In terms of total employment, the share associated to the agricultural sector has decrease during last two decades from 6.6% in 1991 to 2% in 2016, and has remained around this value for last years (Figure 16). Parallel to this reduction, services and industry sectors have increased their relative importance. However, even though the share of Jordanian population employed in agriculture has been reduced, many refugees constitute the majority of labor in the sector (Figueroa, et al., 2018).

The lower importance of agriculture in current Jordanian economy compared to how it was several decades ago shows a process of structural transformation, with the growth of the industry sector parallel to the decrease in value of agriculture (Figueroa, et al., 2018).

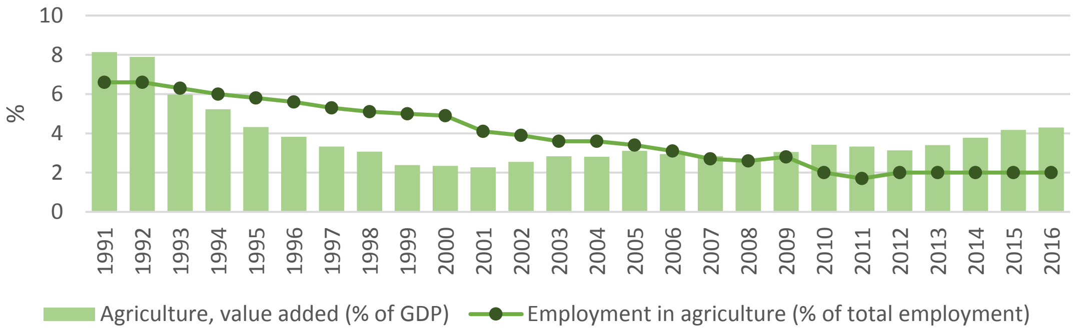

Figure 16 – Agriculture in Jordan: value added (as percentage of GDP) and employment (% of total), 1991-2016. Source: Own elaboration based on data from (World Bank, 2018)

Scarce water resources and cultivable land limit the deployment of agriculture in Jordan, and consequently the country's food self-sufficiency. Increasing water scarcity, land degradation and growing demand make Jordan unable to meet its food needs at national or regional levels. In particular, grain self-sufficiency is economically very costly for Jordan, and local production only covers 3% of their use for food and feed (OCHA, 2012), although cereals account for almost one third of the total harvested area. Moreover, investments aiming at enhancing food self-sufficiency can increase agricultural productivity, but can also outstrip water, energy and agricultural costs. Since the 1960s, subsidies in the sector encouraged domestic production to the detriment of land and water resources. However, natural resource constraints, anticipated negative impacts of climate change, increasing population, and changing production and consumption patterns call for alternative measures to satisfy national food needs. Currently, food security in Jordan is achieved through a more open economic approach where international trade covers food deficits, which can be a cheap option if world commodity prices remain stable but entails potential risks. Moreover, importing food also supposes a water-harnessing strategy for water-scarce countries like Jordan, since virtual water (and energy) embedded in the food are also imported. Between 1995 and 1999, net virtual water imports per capita in Jordan associated to crops and livestock trading were 957 m^3/year, while total renewable water resources per capita were 129 m^3/year. Following the same principle, by trading local agricultural products like vegetables and fruits, Jordan exports part of its water resources, which should be evaluated due to the water-scarcity situation in the country (Keulertz & Woertz, 2015; ESCWA, 2015).

Agricultural land

According to satellite images, fields, pastureland and forests cover less than 9% of the land in Jordan (Ababsa, et al., 2014), but only around 5-10% is considered arable (JAEC/Worley Parsons, 2011; Figueroa, et al., 2018). Most of the agricultural fields are concentrated in the LJRB, where the JV and the Highlands are located. Other cultivated areas include the Disi-Mudawwara region, where agriculture is water-inefficient but artificially held by the existence of the Disi aquifer, and *Badia*, where scattered cultivations rely on groundwater irrigation (Figueroa, et al., 2018). The total harvested area experienced an overall decrease led by the reduction of wheat-planted area since the 1960s to the 2000s, followed by a stable period with a slightly increasing trend driven by olives and vegetables (see Figure 61 in Appendix 0). In 2016, 2 700 km² were cultivated (3% of Jordanian territory), but the harvested area accounted for only 54% of the cultivated area, with 1 470 km² (DOS, 2018b). This difference entails water and energy that are not effectively used.

Even if irrigation water is available, in some cases the type of soil is not suitable for cultivation (Ababsa, et al., 2014). This is partly due to land degradation in Jordanian territory, which has impaired agricultural soil. Besides the decreasing precipitation driven by climate change, human activities are aggravating land degradation, including deforestation, overgrazing (i.e. grazing land no longer left fallow), and the conversion of rangelands to croplands in areas where rainfall is not enough to support cropping in the long term. This makes the soil highly susceptible to wind and water erosion, which contributes to desertification. Additionally, uncontrolled urbanization, improper farming practices such as over-cultivating the land, over use of herbicides or pesticides and failure to use contour ploughing also constitute threats to cultivable soil (and water) (Hadadin & Tarawneh, 2007; Howari & Ghrefat, 2011).

Main crops and yield in Jordan

Despite the modernization of agriculture in Jordan and a high increase of the overall agricultural production (see Figure 62), cropping patterns have slightly changed over last three decades. In terms of cultivated area, the main crops are olives with one third of the total, barley and wheat, followed by tomatoes and potatoes. Other vegetables and fruits mainly constitute the remaining quarter of the overall distribution (see Figure 17). In contrast, the distribution of main crops by production is led by tomatoes accounting for around one third of total production, followed by cucumbers, potatoes and olives (see Figure 18). Other fruits and vegetables amount 42% of total production, with a great variety of crops but with minor individual contributions to the overall production. It is worth noting that the particular expansion of bananas is due to artificially high prices because of import restraints (Van den Berg & Agha Al Nimer, 2016).

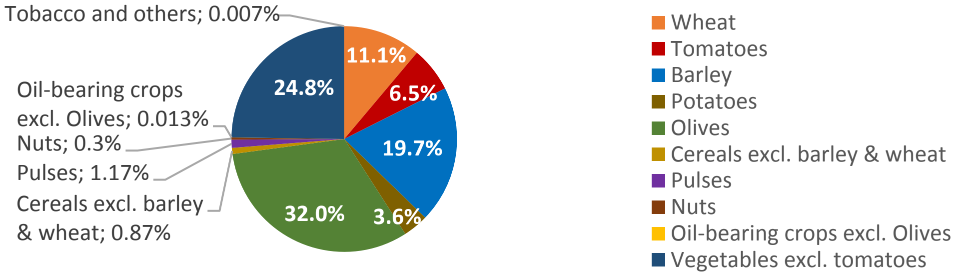

Figure 17 – Area harvested in Jordan in 2015. Source: Own elaboration based on data from (FAOSTAT, 2017a)

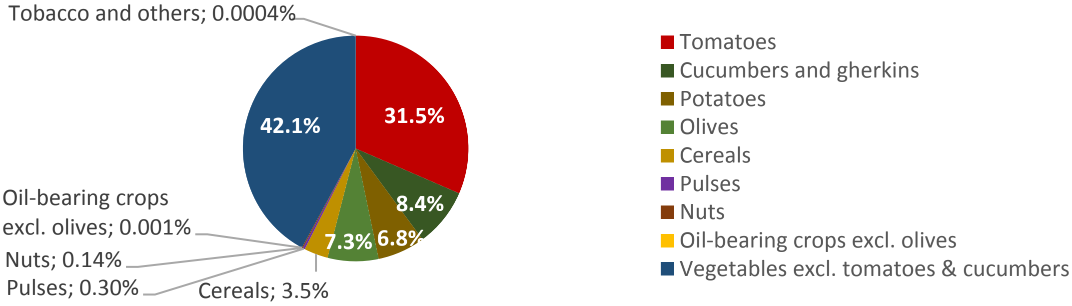

Figure 18 – Crops production in Jordan in 2015. Source: Own elaboration based on data from (FAOSTAT, 2017a)

Main cultivated crops in Jordan have a larger yield compared to average Western Asia and World values, except for cereals (i.e. barley and wheat), whose yield is lower (see Figure 55 in Appendix 0). In the last three decades, agricultural productivity in Jordan has increased despite the existent water-resource constraints, mainly due to the deployment of new farming and irrigation technologies. Some of these systems include greenhouses, drip-irrigation technologies, high-yielding crop varieties and agrochemicals like pesticides and fertilizers (Van den Berg & Agha Al Nimer, 2016). The high use of fertilizers in Jordan is especially remarkable, being one of the largest consumers per unit of treated area in the world. In the future, fertilizers will be necessary to enhance agricultural production and keep pace of the growing population, but the negative environmental effects associated to their use (and especially misuse and overuse) must be taken into consideration. Some of these effects include pollution and acidification of land and water resources by water run-off and infiltration, and the increased growth of aquatic plants that can reduce oxygen levels and affect aquatic life (ESCWA, 2015).

Water use in agriculture

Water resources for irrigation in Jordan

The agriculture sector is the largest water-user sector in Jordan, but presents a challenging situation. Firstly, this sector required around 700 MCM annually in 2015, but only 484 MCM were used once the basic water needs were met (MWI, 2016d). Jordanian farmers are experiencing a reduction in the volume of fresh water for their activity because of the competition between socio-economic sectors and the water scarcity. The 5-year moving average of surface water diverted for irrigation decreased from 155 to 144 MCM between 2003 and 2013-2014 (JVA, 2015 as cited in Qtaishat, et al., 2017). Thus, the government has given higher priority to the domestic sector followed by the sectors that provide the highest economic return per volume of water used, and the agriculture sector is far below the rest (see Table 18 in Appendix 0). However, water for agriculture is still a priority to maintain rural areas and ensure food security (ESCWA, 2015). Within the national water budget, irrigation was responsible for 49% of the total water use in 2015: 28% corresponded to surface water, 26% to treated wastewater and 46% to groundwater (see Table 5 in section 2.4.2.2). The volume of treated wastewater is mostly applied in irrigated agriculture in the JV is increasing, but the overall water quality has been reduced (Van den Berg & Agha Al Nimer, 2016; MWI, 2016d).

The reuse of treated wastewater in agriculture brings about numerous benefits, but also drawbacks to consider. On the one hand, using treated wastewater for irrigation allows for the reallocation of freshwater resources that would have been employed in irrigated crops to other sectors without greatly affecting the available irrigation water (ESCWA, 2015). Moreover, a proper management of treated wastewater in agriculture can reduce or even eliminate the use of synthetic fertilizers due to the nutrients content of treated wastewater (Mrayyan, 2005; Bajjali, et al., 2017). On the other hand, in the absence of a comprehensive management system with careful monitoring procedures and regulations, treated wastewater can have impacts on human health and the environment that offset its benefits. These effects include soil damage due to alkalinity and salinity, changes in composition and rates of groundwater recharge, alterations of aquifer geochemistry, crop toxicity, and decrease of crop yield due to pathogens and heavy metals contained in wastewater. Furthermore, there are potential risks to public health such as risks of infection with the bacteria "Giardia", which have been associated with wastewater reuse, and have been reported in the JV (Mrayyan, 2005; MWI, 2016d; Bajjali, et al., 2017).

Regarding irrigated areas, mainly two areas concentrate the bulk of irrigation in Jordan: the JV and the Highlands, both within the LJRB. Around 60% of cultivated land relies on rainwater (i.e. is not irrigated), with 46% corresponding to non-irrigated field crops (see Figure 19). The remaining 40% of cultivated area is used for irrigated crops (mainly fruit trees and vegetables), and produces 90% of total agricultural yield. Moreover, irrigated agriculture provides the higher percentage of direct agricultural jobs and complementary jobs in support services (MWI, 2016d).

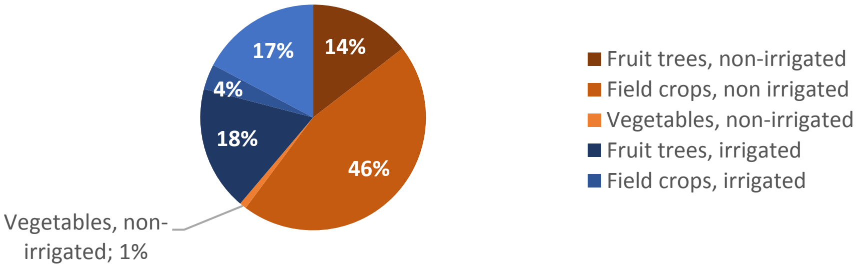

Figure 19 – Irrigated and non-irrigated area by type of crop in 2015. Source: Own elaboration based on data from (DOS, 2016)

Despite cropping patterns have remained mainly the same, in the last two decades the pattern of water use in irrigation has changed. Currently, 65% of groundwater-irrigated crops is concentrated in the Highlands, which irrigate water-intensive and low-value crops that occupy around two thirds of irrigated agricultural fields. In contrast, the JV now uses most surface and treated wastewater, and even though consumes half of the irrigation water used in the Highlands, produces double the volume of products (MWI, 2016d).

The Disi-Mudawwara region, in the south-west of Jordan, constitutes an exception in irrigated agriculture in the country due to its proximity to the Ram Group (i.e. the Disi aquifer) and its high irrigation needs. There are 11 676 hectares (ha) irrigated with groundwater resources, but the water requirements are much higher than anywhere in the country. For instance, on average, one kilogram of wheat produced in this region under irrigated condition requires 3.5 times more water than in other Jordanian regions (ESCWA, 2015).

Under general conditions, two factors determine the amount of water that is required: the growing periods and the water demands of particular crops. Crops such as olives, grapes or citrus fruits have a lower water demand than others like bananas, rice or sugarcane; and green beans, spinach or radish require less water than those with longer growing periods such as cotton or alfalfa. Therefore, a proper selection of crops should consider climatic conditions to enhance water-use efficiency. In the case of Jordan and the Arab region, the selection of crops has not been optimal, resulting in an average water-use efficiency for irrigation of around 50-60%. Instead of cultivating vegetables and fruits, Jordan has traditionally favored less efficient options, like raising cereals and other field crops or using agricultural fields as pasture (ESCWA, 2015).

Besides a correct choice of crops, improved agricultural practices can also contribute to increasing water-use efficiency. The use of agroforestry, ploughing perpendicularly to the slope, terracing, appropriate scheduling[21] for water-supply systems, or the burying of crop residues, can improve the water retention through lower evapotranspiration and reduced water run-off and percolation (ESCWA, 2015). Another necessary measure for further efficiency gains is the reduction of water losses in the distribution system for irrigation (Figueroa, et al., 2018).

According to the MWI, these water losses attributed to seepage, leakage and operational losses accounted for 12% in 2015: 181 MCM were eventually used for irrigation, out of 206 MCM of water that were released (MWI, 2016b; Ahmad & Khan, 2017). Despite the share of losses is much lower than the NRW from the domestic water supply (see *Water demand and supply* in section 2.4.2.2), the volume of water lost amounts 25 MCM/year. This amount of water constitutes over two thirds of the water use in the industrial sector, which has a financial return per volume of water over 100 times higher than the agricultural sector (see Table 18 in Appendix 0).

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[21] In Egypt, a computer-based irrigation scheduling resulted in water savings of 100, 128 and 140 MCM on corn, groundnut and wheat crops, respectively, and over 20% of water savings in drip irrigation of tomatoes (ESCWA, 2015).

Irrigation systems

Traditionally, gravity-based irrigation systems like furrow irrigation and open channel supply were the majority options and almost the only alternatives, but over last decades, Jordanian agriculture has started to adopt pressurized irrigation systems like sprinkler or drip irrigation. Consequently, water efficiency has improved and productivity has increased, especially in the JV (Van den Berg & Agha Al Nimer, 2016). Thus, minimum water losses make pressurized irrigation systems more water-efficient than surface and flood irrigation systems. Sprinkler irrigation systems are more water-use efficient than surface systems, but less than drip systems, which uses around 25% less water. Variants of the drip irrigation such as burying pipes and using a waterproof tarp or the buried diffuser can save up to 20-33% of water used in regular drip irrigation and up to 70% of energy. Table 30 in Appendix 0 presents typical water-efficiency values for a broad selection of irrigation systems. In contrast, pressurized irrigation systems require a higher energy input and have a larger environmental footprint. Moreover, the initial cost of these systems and the energy costs for their operation make them prohibitive for small and poor farmers, limiting their complete adoption (ESCWA, 2015; Ahmad & Khan, 2017).

As a consequence of this transformation in the agricultural sector[22], 87% of the cultivated area with vegetables in Jordan uses drip systems in Jordan, while only 2% uses sprinklers, 6% uses surface irrigation and 5% is not irrigated (see Figure 20). Meanwhile, in the case of field crops only 7% of the cultivated area is irrigated: 5% with surface irrigation, 1% with sprinklers and 1% with other systems (see Figure 21). Therefore, there is still room for improvement, especially in field crops, where water losses by evapotranspiration are usually higher than for fruits and vegetables, due to the use of less efficient systems like sprinkler and surface irrigation (ESCWA, 2015).

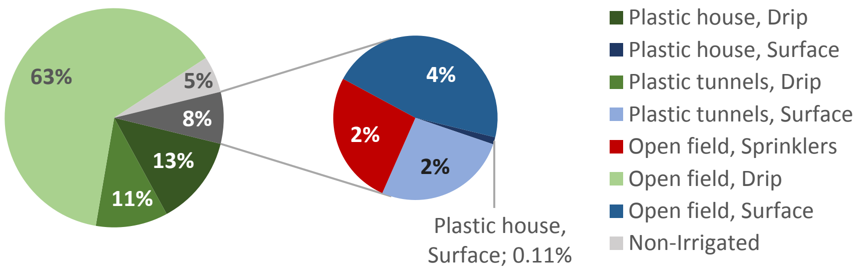

Figure 20 – Cultivated area with vegetables by type of irrigation in Jordan, 2015. Source: Own elaboration based on data from (DOS, 2016)

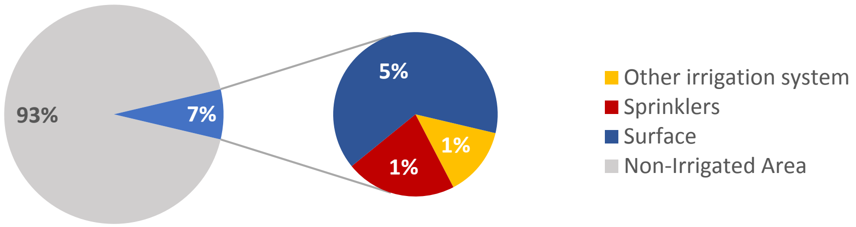

Figure 21 – Cultivated area with field crops by type of irrigation in Jordan, 2015. Source: Own elaboration based on data from (DOS, 2016)

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[22] Data for irrigation systems in fruit trees fields was not found.

Energy use in agriculture

The agricultural sector is a great energy consumer. The direct and indirect energy dependence of agriculture is strong, and any aspect in the energy sector (e.g. dependence on fuel imports or electricity service intermittency) can affect the capacity to deliver reliable water services and ensure food safety (ESCWA, 2015). According to the MEMR, Jordanian agricultural sector consumed 207 ktoe in 2015, most of which was electricity for the operation of pumps[23] (see *Energy balance in Jordan* in section 2.4.2.3). In the future, the energy consumption associated to this sector is expected to increase with the adoption of new technologies. Thus, energy input in agriculture is directly linked to the level of technology adoption and the level of production. Therefore, the agricultural modernization in Jordan, although essential for providing food for the growing population because contributes to higher productivity and water efficiency, will require increasing amounts of energy, which can have long-term impacts on climate change (Ahmad & Khan, 2017).

The energy use in agriculture can be divided into direct and indirect uses. Direct uses include energy associated to actual agricultural activities, and indirect uses encompass the energy used in agricultural inputs such as pesticides and fertilizers. In middle-income countries like Jordan, the total energy is generally divided into 60% and for direct and indirect uses respectively. Along the whole production process, energy is consumed both directly and indirectly. Before farming, the production and distribution of fertilizers, chemicals and other inputs require energy. Energy inputs during farming depend on the particular crop, but usually include high power-consuming (but also laborsaving) machines used in direct agricultural activities such as tilling, planting, pruning, thinning, harvesting and electricity for irrigation pumping. The energy from the sun is also an essential input, but since is not purchased is usually not considered. After farming, transportation, storage (usually dry or cool storage), processing and retailing entail energy consumption. Therefore, an inappropriate supply chain management of agricultural products can result in high food losses, including water and energy embedded into the products or waste. Embedded-energy losses associated to food losses can reach up to 38% of the total energy consumption during the farming process (ESCWA, 2015; Ahmad & Khan, 2017). Some main indicators to evaluate the energy performance of an agricultural production system include energy productivity, water-energy productivity and energy efficiency in the agricultural system (see *Glossary* in Appendix A).

Finally, agricultural systems and in particular water-pumping systems can be coupled with renewable energy technologies, and lower costs of these energy-efficient systems have caused an extensive proliferation. However, their uncontrolled use has become a threat for water resources management in the Arab region. In many cases, farmers use the renewable water-pumping systems as soon as the source is available (i.e. sun or wind), increasing the groundwater extraction and over-irrigating crops. A possible solution to regulate over-abstraction of water is monitoring and limiting the energy consumption, but in the case of privately-owned renewable water-pumping systems the control can be very complicated (ESCWA, 2015; Hartung & Pluschke, 2018).

Prospects in Jordanian agriculture

The evolution of the agricultural sector during last decade shows a similar increasing trend in production and electricity consumption for water pumping[24]. Meanwhile, the total water use in irrigation and the total harvested area have remained mainly constant (see Figure 22). These results indicate that using the same land and water resources the production can be increased, but implies a higher electricity consumption associated to agricultural activities. This can be partly due to the deployment of water-efficient irrigation systems that save water but require more energy. Moreover, energy needs associated to water pumping can be higher because of lower energy and water efficiencies in the water system, and the increasing depths to abstract groundwater associated to the depletion of aquifers and the decrease of water tables.

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[23] For that reason, in national publications the energy use associated to agriculture is usually considered within the water pumping energy consumption.

[24] Data for electrical consumption associated to water pumping does not specify whether include activities exclusively related to the agricultural sector or also from other sectors (e.g. water distribution and water treatment).

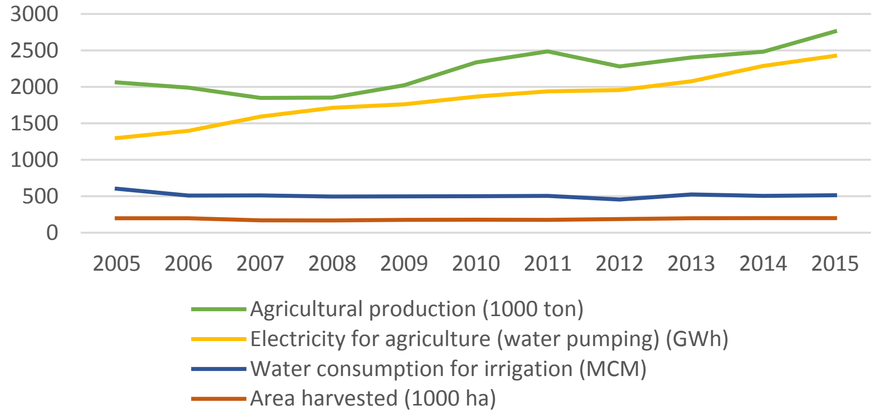


Figure 22 – Agriculture in Jordan: production, electricity consumption, water usage and harvested area (2005-2015). Source: Own elaboration based on (World Bank, 2018; FAOSTAT, 2017a; MWI, 2015a; MWI, 2016b)

Fresh water scarcity, land degradation, population growth and changing diets have proven that Jordan and other Arab countries cannot achieve food security through food self-sufficiency alone. If current trends continue, international trading will be essential to complete the food supply. Consequently, the virtual imports of water embedded in the food from international markets will increase. The water that otherwise would have been used to produce food locally will be reallocated, and part of the energy consumption associated to the agricultural production will be avoided (ESCWA, 2015). Meanwhile, different strategies will seek to promote rural transformation for economic development and job creation, conserve local water resources, and expand the agricultural sector (i.e. 10% growth targeted in the contribution of agriculture to GDP, starting from 2018) (Figueroa, et al., 2018).

Agricultural systems and particularly rain-fed agriculture are especially vulnerable to potential effects of climate change due to their high demand of water and energy. Climate change is expected to lead to changes in farming systems, and to put pressure on rural communities to adapt to new conditions (Figueroa, et al., 2018). Therefore, climate-smart systems will ease that adaptation, and will help managing more efficiently while promoting a low carbon food economy (ESCWA, 2015).

The National Water Strategy stablishes different plans pursuing a water-efficient agriculture. The efficiency of bulk irrigation-water distribution and on-farm irrigation systems will be improved (i.e. lower losses), and the agricultural activities that negatively affect the drinking water supply will be reduced (MWI, 2016d). Improved agricultural practices will be applied, such as shifting cropping patterns towards water-efficient and higher-value crops (e.g. medicinal herbs and aromatic plants), expanding greenhouse production and using new technologies to increase agricultural productivity (in particular of fruits), or deploying agro-processing production (JAEC/Worley Parsons, 2011; ESCWA, 2015; Figueroa, et al., 2018). Moreover, saline irrigation will be replaced where possible by desalinated water, which is expected to increase yields and to drastically decrease the amounts of water that are used to leach salts from the root zone (Qtaishat, et al., 2017).

In terms of water resources for agriculture, Jordanian government aims at keeping agricultural water use at 700 MCM in the future, so a better resources management will be necessary to generate the highest possible value (Qtaishat, et al., 2017). However, population growth and the impact of climate change is expected to increase the use of water for irrigation. The reallocation policy will be essential, which plans to cap and eventually reduce fresh water used for irrigation in the Highlands. Groundwater use in this area will be reduced to reach safe yield levels, and will be replaced by treated wastewater. Wherever treated wastewater is available, irrigated agriculture will be expanded, and in the case of the JV, irrigated water will be also increased through reclaiming NRW and reduced water losses. Additionally, the RSDSP, the SWAP agreement in the JV, desalinated water, rainwater harvesting, larger volumes of treated wastewater or the introduction of technologies for direct use of brackish water in irrigation will provide new resources for the agricultural sector (MWI, 2016d).

2.4.3 The Lower Jordan River Basin

As will be apparent on next pages, the LJRB level constitutes the most important region within Jordan. This area concentrates most of the resources, population, economy, production or consumption, and many facts at this level and at national level barely differ. For that reason, this subsection mainly includes, when available, additional explanations that help to better understand the situation in the region, and particular data to specify the difference between the LJRB and the national level. For the same reason, there is not a specific section for *energy in the LJRB*, since information centered on the LJRB was scarce and out-of-date.

2.4.3.1 Introduction to the LJRB

The Jordan River Basin is a transboundary basin with a total area of approximately 18 500 km^2, being 40.4% of the basin located in Jordan. The average annual precipitation in the basin is estimated at 380 mm, but greatly varies with the location; namely, in the southern LJRB precipitation can be less than 100 mm, in the most fertile area of the basin (i.e. the JV) is less than 350 mm, and it reaches 1 400 mm in the upper basin. Ecosystems are very diverse, changing across very small distances from arid to sub-humid Mediterranean climates. However, climate change is endangering these ecosystems, and projections estimate severe aridification in the region (AQUASTAT, 2009b).

As stated previously, this analysis is focused on the LJRB within the Jordanian borders, i.e. the part of the Jordan River Basin located inside Jordanian territory (Figure 23). From now on, the term LJRB will be referred to this particular section of the basin.

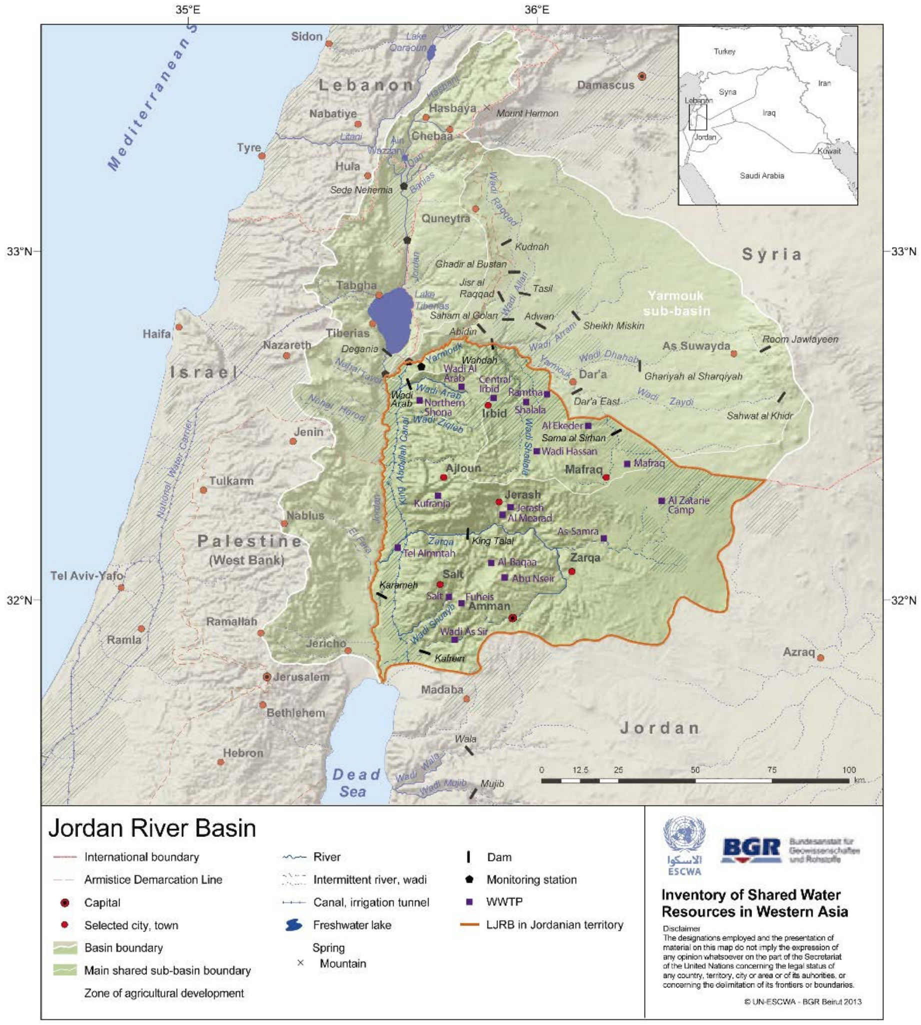
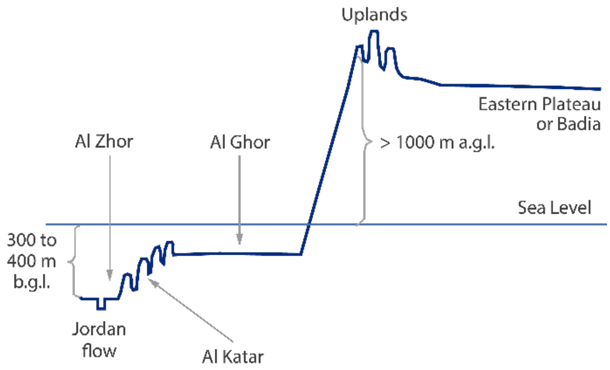


Figure 23 – Overview of the Jordan River Basin. Source: Modified from (UN-ESCWA and BGR, 2013; MWI, 2015b)

The LJRB is a region of major relevance for Jordan, although it represents 8.4% of the Jordanian territory (AQUASTAT, 2009b). This area concentrates the majority of the hydric resources, and consequently over 83% of the total population and most of the main industries in the country are also located in this area (see Figure 56 in Appendix 0). Therefore, the LJRB is considered the area with the highest potential for economic development. The region is mainly divided into two main areas: the JV with 5.7% of the national surface, and the highlands accounting for 2.9% of the total Jordanian territory (Courcier, et al., 2005; Venot, et al., 2007).

The JV is a 110 km-long, narrow area between the Yarmouk River and the Dead Sea, which corresponds to the northern part of the Jordan Rift Valley that extends from Lake Tiberias to the Red Sea. The altitudes range from 200 m in the north to 400 m b.g.l (below ground level) in the south. The western part of the JV, called Al Zhor, corresponds to a fertile plain where the Jordan River riverbed is placed, and can be flooded during heavy rains. The rest of the JV, known as Al Ghor, is also a fertile area where irrigation schemes have been implemented. The Highlands, in turn, are constituted by desert plateau or *Badia* extending easterly at an average altitude of 600 m, and a mountain range along the JV also known as Uplands (Venot, et al., 2007). Figure 24 shows a west-to-east cross-section of the LJRB, where the characteristic topography of the LJRB can be seen.



a.g.l. = above ground (sea) level   b.g.l. – below ground (sea) level

Figure 24 – Topography of the LJRB in Jordan: cross-section of the LJRB from west to east. Source: (Courcier, et al., 2005)

2.4.3.2 Water in the LJRB

The LJRB is the wettest area in Jordan. The average rainfall in the JV is 50-300 mm, and in the Highlands ranges between 400 and 580 mm. The LJRB comprises 80-90% of the national water resources in Jordan, i.e. Lower Jordan, Yarmouk and Zarqa rivers, side *wadis*, dams and sewage systems. It also includes a portion of the water from Lake Tiberias that is bought from Israel, and wells and fresh springs in the northwest of the country used by many farmers. These water resources are renewed at a rate of 705 MCM/year, of which 550 MCM/year are surface water and 155 MCM/year are groundwater (Courcier, et al., 2005; Venot, et al., 2007; Hadadin, 2015).

However, the great demographic and economic developments of last five decades, together with the quasi interruption of the flows from the Upper Jordan, have resulted in a rapid and intensive mobilization of the water resources. While around 2 700 MCM of surface water and rainfall enter this region every year, 200 MCM/year reach the Dead Sea. The rest is lost through evaporation (61%), or effectively used in irrigated fields (18%), in rain-fed crops (18%) and in industrial and municipal uses (3%). In total, it is estimated that this region accounts for 75% of the total water demand in the country. In the 2000, 585 MCM/year were withdrawn in the LJRB, including 310 MCM/year of surface water (60 MCM/year of which were treated wastewater), and 275 MCM/year of groundwater. Additionally, 30 MCM of groundwater and 45 MCM of surface water were imported yearly from other regions (Courcier, et al., 2005).

Currently, these values are estimated to be larger due to the increasing water demand and the operation of the Disi project. Nevertheless, the per capita availability of water is low and decreasing because of the growing population (Venot, et al., 2007). In 2015, the water supply per capita in the LJRB was 117.8 liters/day (versus 127.2 liters/day at national level), but the values differ depending on the governorate (see Figure 57 in Appendix 0).

At the same time, wells have been drilled in the Highlands and in the JV for domestic and irrigation purposes (AQUASTAT, 2009b), and according to estimations account for 63% of all existing wells in Jordan. As it occurs at a national level, a large portion of these wells is considered illegal. In particular, 400 wells out of 1448 (22%) are estimated to be in violence in the LJRB: 15% are working and 7% are not working. In terms of use, 66% of the wells in the LJRB are estimated to be used for agricultural purposes and responsible for extracting 81% of the total abstracted water (see Figure 58 and Figure 59 in Appendix 0).

Water management in the LJRB

The water management system in the LJRB is structured along the Jordan River, limited by the Lake Tiberias in the north and the Dead Sea in the south. The main element in the LJRB for water transportation is the KAC, initially built in 1961. Previously known as East Ghor Canal, it consists of a 110 km long and 1.6-2 m deep canal, which holds between 500 000 and 800 000 m^3. Therefore, it is simultaneously a conveyance and a storage system, prepared to open and close gates to follow the water schedules and regulate its flow more effectively. Despite water in the KAC is monitored and controlled with a SCADA system (Supervisory Control and Data Acquisition) in a control center in Deir Alla, illegal pipes to pump water are widespread along the canal. Moreover, not all of the gauges are working, so the control is not very accurate (AQUASTAT, 2009b; Mustafa, et al., 2016).

For about 65 km from its beginning to Deir Alla, the KAC holds freshwater from springs, wells, dams, the Yarmouk River and the Lake Tiberias (through a pipeline completed in 1995). At Deir Alla, the freshwater not allocated to agricultural purposes is pumped up to Amman to be used for drinking water (see Figure 25). The rest of the KAC (i.e. from Deir Alla to the Dead Sea) only transports treated wastewater from sewage systems, and at the last 15 km of the KAC water from fresh springs and Kafrein dam is directly conveyed to farmland (AQUASTAT, 2009b; Mustafa, et al., 2016). The sewage systems are connected to 19 WWTPs spread across the LJRB (see Figure 23), that in turn are linked to different streams to distribute and store treated wastewater to be used for irrigation. In 2016, the total design capacity of WWTPs in the LJRB was 196 MCM (90% of national capacity), and 142 MCM were treated (MWI, 2017).

Once the water is siphoned from the KAC to the pumping stations[25] (PS), water pumps or the gravity force distribute the water to the farms through main and lateral lines. Every farm is equipped with a Farm Turnout Assembly (FTA), including a flow regulator, a flow limiter, and sometimes a water meter. The purpose of this system is to ensure a flow of 6-12 l/s depending on the specificities of the farm, but many of these systems are broken (Mustafa, et al., 2016).

Running along the JV, there are seven out of the ten main constructed dams[26] in Jordan: Arab, Ziglab, King Talal, Karameh, Shueib, Kafrein and Al Wehdah Dam. With a total storage capacity of 271 MCM (i.e. 83.4% of total capacity of main dams), these systems help capturing winter rainwater runoff and store treated wastewater from sewage systems (Hadadin, 2015). Figure 25 summarizes schematically the water system in the LJRB.

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[25] The pumping stations are designated with numbers, corresponding to the kilometer distance from the head of the KAC (Mustafa, et al., 2016).

[26] It is known the existence of additional water-storage systems in the LJRB (e.g. desert dams, ponds or water excavations), but specific information about these systems has not been found. An approximated distribution of some of these constructions at national level is presented in Figure 46, Appendix C.

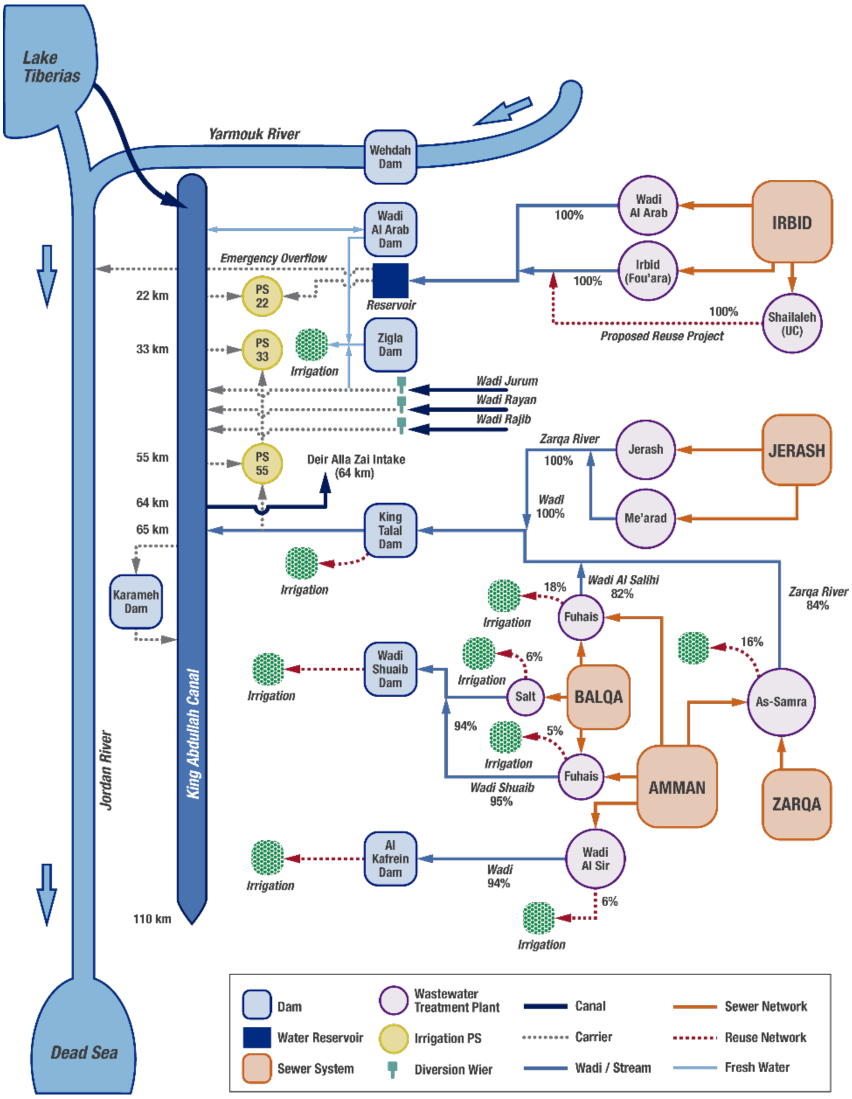

Figure 25 – Simplified schematic of the LJRB water management system. Source: Modified from (Mustafa, et al., 2016).

2.4.3.3 Agriculture in the LJRB

The soil type in the northern part of the country and in the JV are the most favorable for agriculture in Jordan (Howari & Ghrefat, 2011). The JV is considered the food basket in Jordan, and together with some dispersed locations in the Highlands, concentrates most of the irrigated areas in the LJRB with 32 000–48 000 ha equipped for irrigation (see Figure 60 in Appendix 0). In total, the LJRB constitutes around 80% of the irrigated agriculture in Jordan. (Courcier, et al., 2005).

Intensive irrigated agriculture started in the country with the construction of the KAC at the 1960s, and the subsequent development of dams and diversion of flows allowed the deployment of irrigation over a larger area. Irrigation schemes were first constructed around side *wadis* and in the JV, and new irrigation projects were built after the extension of the KAC and the development of additional water systems. Since the 1990s, the open canal irrigation schemes were converted to pressurized systems (AQUASTAT, 2009b; Van den Berg & Agha Al Nimer, 2016). In the Highlands, there was an increase in extensive rain-fed agriculture in the mid-1970s, but later declined with the growth of cities and the economic and industrial development (Courcier, et al., 2005). However, groundwater-based irrigation has been intensively deployed in the region lately, and the uncontrolled exploitation of the aquifers due to a light regulation on irrigated agriculture is resulting in the rapid depletion of groundwater resources (MWI, 2016d).

Except for some rain-fed agriculture in the uplands, the bulk of agriculture in the LJRB is irrigated, using water from surface resources, springs, wells, treated wastewater, and runoff water that is stored in dams. In the case of the JV, irrigation mainly relies on surface water and treated wastewater. Irrigated areas amount around 33 000 ha, but 6 000 more ha of arable lands remain to be irrigated north of the Dead Sea. Its unique location makes for an ideal climate that allows for year-round agriculture and production of off-season fruits and vegetables. The variations in rainfall, temperature and humidity create different agro-climatic zones in the JV, producing crops that require irrigation throughout the year, mainly: citrus, dates, vegetables and bananas (MWI, 2016d; Mustafa, et al., 2016). Consequently, agricultural production in JV is very high compared to the land and water resources that are used. According to the MWI, 70% of total agricultural products are originated in the JV, but using only 35% of the irrigation water (MWI, 2016d). In terms of area, only 16% of total harvested area in Jordan corresponded to the JV, while 39% of total production (in terms of mass) was generated in this region (see Table 28 and Table 29 in Appendix 0).

The Highlands concentrate most of the private tube-well-based irrigation, with over 14 000 ha in the region. The mountains are mainly constituted by rangelands, with some stone-fruit trees and olive trees. The plateau is mostly planted with rain-fed cereals near the mountains, where main urban areas are placed and rainfall is still enough. Eastward in the highlands, few groundwater-based irrigated agriculture can be found, and primarily nomadic Bedouin livestock farming (Venot, et al., 2007).

At region level, the LJRB accounted for 73% of total planted area in Jordan, 78% of total harvested area, and 77% of production in terms of mass (see Table 28 and Table 29 in Appendix 0). In 2015, the harvested area by main crops was dominated by olives (36%), followed by barley (17%), wheat (5%), tomatoes (5%) and potatoes (4%). Other vegetables, fruit trees and field crops complete the mix of crops in terms of harvested area with 16%, 12% and 5% respectively (Figure 26, left). In contrast, despite constituting a great portion of the harvested area, olives production only accounts for 8% of the total. The largest crop by production in 2015 were tomatoes (27%), followed by cucumber (10%), clover and olives (8% each), and potatoes (7%). Other vegetables and fruits represent 18% each, and other crop fields constitute the smallest share with 4% (Figure 26, right).

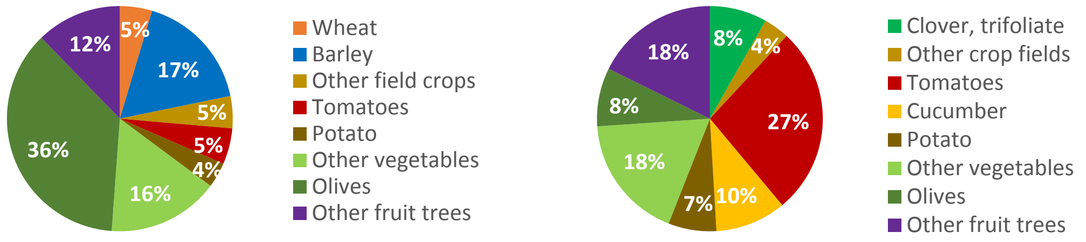

Figure 26 – Harvested area (left) and production (right) by main crops in the LJRB, 2015. Source: Own elaboration based on (DOS, 2018b)

In the period 2010-2016, the harvested area remained relatively constant at around 150 thousand ha in total, except for a drop to 130 thousand ha in 2011, and the crops mix barely change (see Figure 63 in Appendix 0). Similarly, the total production experienced a drop in 2011 and 2012 reaching around 1480 thousand tons in total. Since 2012, the overall production in the LJRB increased at a steady pace up to 2320 thousands ton in 2016, also keeping a similar distribution by crops (see Figure 64 in Appendix 0).

In terms of irrigation systems, the situation in the LJRB is mainly the same as it is at a national level[27]. In the case of field crops, only 8% of the area is irrigated (see Figure 66 in Appendix 0), divided into surface (5%), sprinklers (1%) and other systems (2%). In contrast, only 7% of the area planted with vegetables is not irrigated (see Figure 67 in Appendix 0). Within the irrigated area, 61% corresponds to drip irrigation in open field, followed by drip systems in plastic house (16%), and drip systems in plastic tunnels (8%). The

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[27] Specific information about irrigation systems for fruit trees has not been found.

remaining 8% corresponds to surface systems and a negligible portion to sprinklers (0.02%). Therefore, as it happens at national level, despite most irrigated area uses efficient irrigation systems, at least 7% of field crops and 8% of vegetables use non-efficient systems that can be upgraded.

A remarkable aspect in the agriculture in the LJRB, is the difference between the planted and the harvested area for some main crops, which imply energy and water losses (i.e. use of water and energy resources that does not produce effective results). The most relevant cases are cereals, namely wheat and barley, followed by bananas; in 2015, only 42% of the planted area with wheat and barley was eventually harvested, being 68% in the case of bananas (see Figure 65 in Appendix 0). Nevertheless, although bananas have a higher percentage of planted area that is harvested, they consume more resources since are irrigated, so proportionately higher energy and water losses can be expected.

Due to the extreme water scarcity and the priority given to the domestic sector, the future of irrigated agriculture is uncertain, especially for water-intensive and/or low-profitable crops, such as olive trees. As has been seen, they represent a big portion of the total harvested area and use significant water resources, but their production is relatively low, and are partly responsible for the depletion of aquifers, which jeopardize their use for domestic water supply, as they become saltier (Courcier, et al., 2005).

2.4.4 As-Samra WWTP

2.4.4.1 Introduction to As-Samra WWTP

Located in a desert area around 35 km northeast of the capital city Amman, As-Samra[28] Wastewater Treatment Plant (WWTP) constitutes the largest WWTP in Jordan. The Jordanian government has upgraded and extended it during last years focusing on: (I) producing treated wastewater of high quality to reduce the use of fresh water for agricultural and industrial purposes, (II) discharging effluents of high quality to the environment and (III) reducing site energy consumption through on-site renewable energy and energy recovering from sludge (Degrémont - SUEZ, n.d.(a)).

The first As-Samra WWTP was built in 1985 after a national long-term plan to treat wastewater in 1982. It consisted of Wastewater Stabilization Ponds (WSP), with a capacity of about 67 000 m^3/day, and the influent flow rate was always exceeding the plant's design capacity (Myszograj & Qteishat, 2011). Effluents from As-Samra WSP were not able to meet the Jordanian domestic wastewater discharge standards, and the Zarqa river that contained the effluents from As-Samra, drained most of its polluted water into the King Talal Reservoir (KTR), causing significant environmental and health concerns.

The WWTP was upgraded for the first time between 2003 and 2008 (phase 1) to replace the old, overloaded WSP and improve the quality of water courses close to it and containing effluents from the plant (Water-Technology, n.d.). In 2009 the Jordanian government decided to expand the plant to address the needs of an ever-increasing population growth, and phase 2 (i.e. first expansion) was built from 2012 to October 2015. In 2016, the European Bank for Reconstruction and Development (EBRD) started working together with the Water Authority of Jordan (WAJ) on Phase 3 (second expansion).

Currently, As-Samra WWTP treats wastewater from Amman, Zarqa, Russeifa, Sukhnenh, Hashemiyeh and Wadi Dhuleil municipalities using the activated sludge process with nutrient removal and chlorine for disinfection[29] (Myszograj & Qteishat, 2011; Mrayyan, 2005). It is considered an innovative WWTP in treatment technologies as well as renewable energy towards self-sufficiency, funding and involvement of local companies and farmers (SUEZ, 2017).

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[28] In literature, the names As-Samra and Khirbet-es-Samra are used indistinctly to refer to the plant, as well as different variations on them (e.g. Khirbat as-Samra, Khirbet Al-Samra). From now on, only As-Samra will be used in this document.

[29] See 'Description of the treatment process' in Appendix B for a detailed description of the treatment line

2.4.4.2 Water treatment in As-Samra WWTP

As-Samra WWTP collects wastewater produced by Amman Russeifa-Zarqa Basin, where around 60% of the population of Jordan live. Wastewater is conveyed to As-Samra WWTP through three units (see Figure 27): Ain Ghazal pretreatment plant, East Zarqa and West Zarqa pumping stations (PSs) (Degrémont - SUEZ, 2008; SUEZ, 2017).

Initially, the upgraded plant was designed to treat wastewater from 2.3 million inhabitants (i.e. phase 1, completed in 2008). It had a capacity of 267 000 m^3/day, expected to satisfy the demand through 2015. The first expansion (phase 2, completed in 2015) expected to treat the wastewater of 3.5 million inhabitants of Greater Amman and surrounding areas, and to extend its operation until July 2037. It added two more water treatment lines to the existing four (phase I), increasing water line capacity by 37%. Sludge line capacity enlarged by 80%, and mechanical dewatering was added to the overall sludge treatment system (phase 1 and 2) (World Bank Group, 2016b).

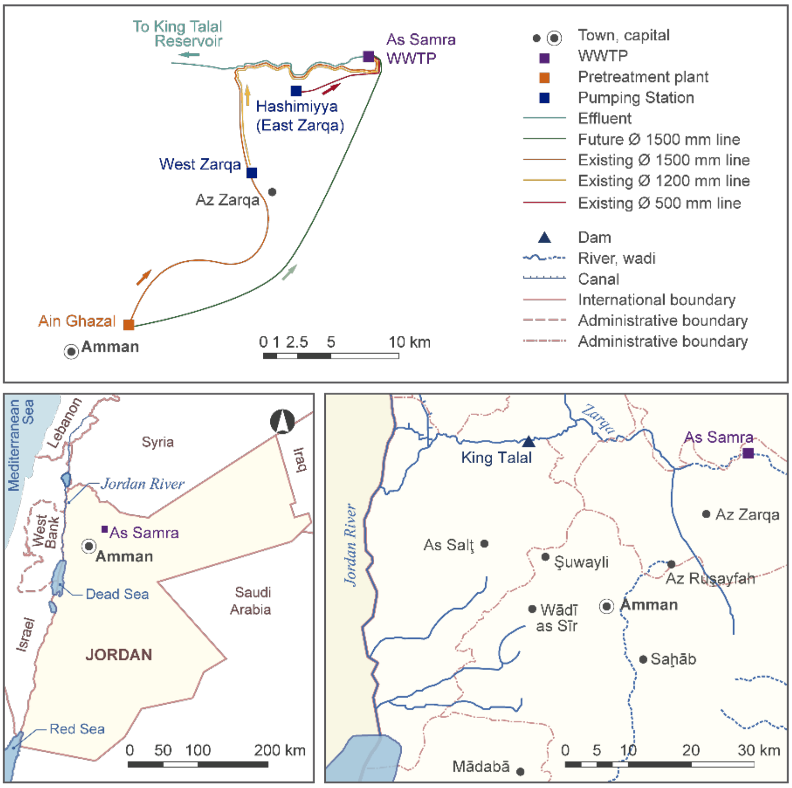

Figure 27 – Location of As-Samra WWTP, and Inlet and outlet flows into and out of the plant. Source: Own elaboration based on (USAID, 1993; Degrémont - SUEZ, 2008; SUEZ, 2017)

In terms of capacity, the plant constitutes 61% of all the Jordanian WWTPs (MWI, 2016a). It is designed to treat 364 000 m^3 of wastewater per day, with a peak flow rate of 840 000 m^3/day. The increase in capacity was intended to meet the demand from 2015 to 2025 of a population estimated to reach 7 million in 2022 in Greater Amman (Degrémont - SUEZ, n.d.(a)). However, the actual amount of wastewater treated in 2016 averaged 304 357 m^3/day, which stands for 83.6% of the design capacity.

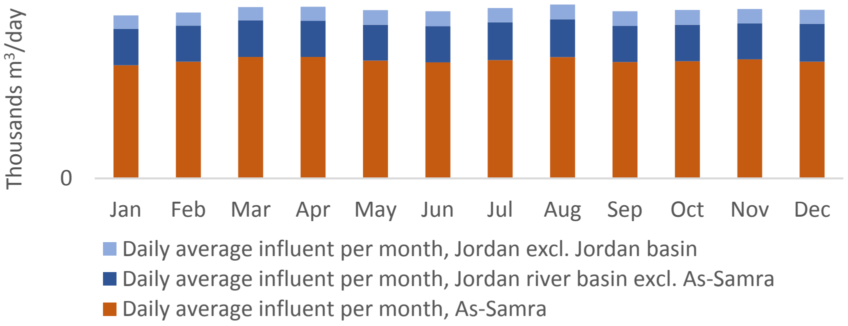

Figure 28 – Daily average influent in Jordanian WWTPs in 2016. Source: Own elaboration based on data from (MWI, 2017)

Figure 28 presents the daily average influent per month in As-Samra WWTP in 2016, together with the rest of wastewater treated in the LJRB and the remaining portion of wastewater treated outside the LJRB. Despite the average influent in As-Samra is always lower than its design capacity (364 000 m^3), it represents 71% of the total treated wastewater in Jordan, and 76.3% of the treated wastewater in LJRB (MWI, 2017). Figure 29 shows a diagram summarizing the treatment process occurring in the current line.

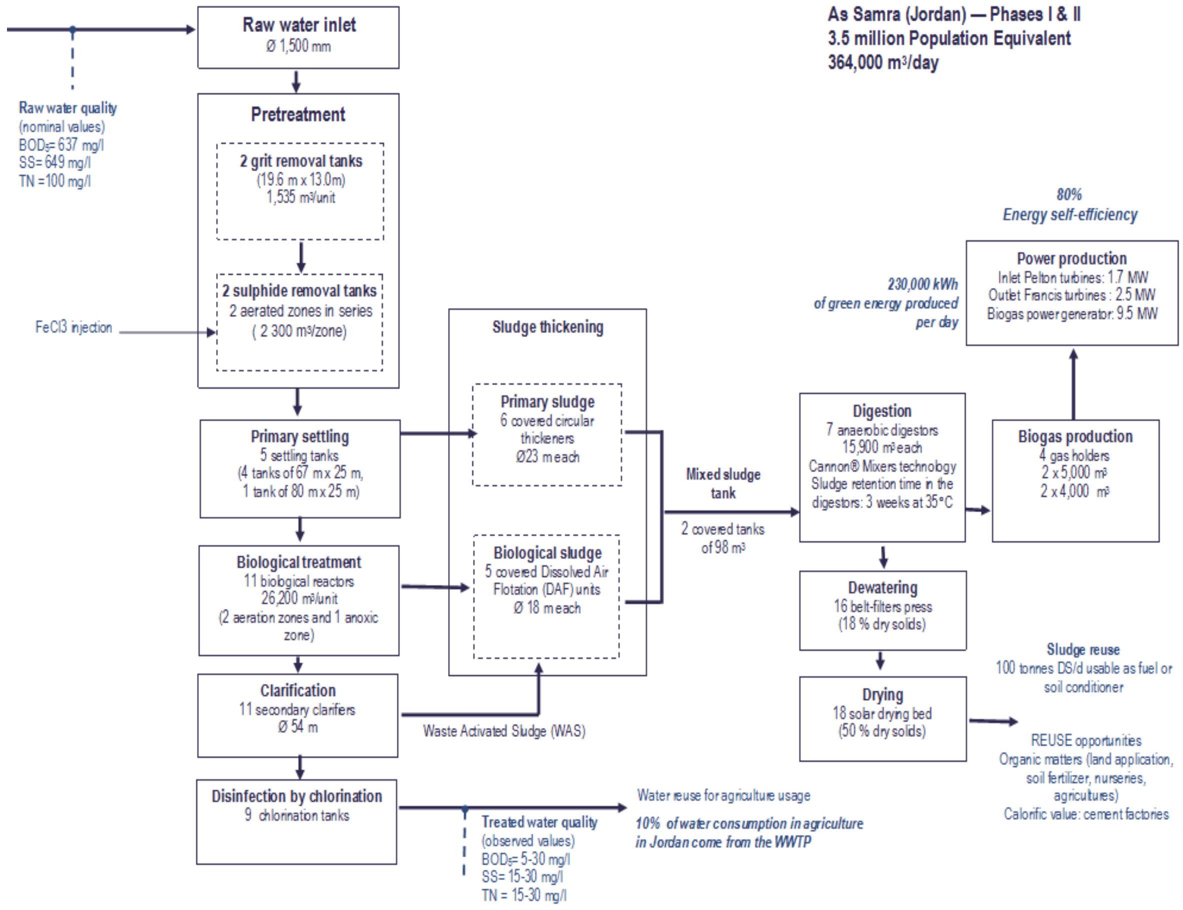

Figure 29 – Wastewater Treatment line in As-Samra WWTP after first expansion. Source: (Degrémont - SUEZ, n.d.(b))

As can be seen in Figure 29, the improvement of the effluent quality parameters is significant in terms of BOD_5, TSS, and TN (i.e. biochemically oxygen demand, total suspended solids and total nitrogen respectively) compared to the raw water parameters, but they remain the same from phase 1 (see Table 12 in Appendix 0). In the next table, water quality parameters for the inlet and the outlet of the expanded plant (phase 2) are presented together with the values from the Jordanian Standard for Water-Reclaimed domestic wastewater (JS 893:2006), to be accomplished by the effluents. As shown in the table, all parameters in the effluents from As-Samra WWTP (phase 2) complies with Jordanian standard, i.e. BOD_5, TSS, and TN.

Table 7 – Extended plant water-quality parameters: inlet, outlet and values from the Jordanian Standard for Water-Reclaimed domestic wastewater (JS 893:2006). Source: (SUEZ, 2017; Myszograj & Qteishat, 2011)

	Unit	Inlet	Outlet	Standard JS 893:2006[30]
BOD_5	mg/l	637	5-30	60
TSS	mg/l	649	15-30	60
TN	mg/l	100	15-30	70

Once treated, wastewater leaves As-Samra and flows by gravity through the Zarqa river basin, which is considered the most industrialized and heavily populated basin in the country (Al-Omari, et al., 2013). Since 1960s, the basin suffered a great groundwater overexploitation due to the agricultural development in the area, and as a result the spring dried out and the water table sharply dropped (i.e. 43 m since 1968). However, the stable discharge of treated wastewater directly to the river from As-Samra WWTP has revived the upper section of the river (Bajjali, et al., 2017). This is due to the regional fault systems, which enhances the infiltration and has created a strong hydraulic connection between surface and groundwater in the basin. Consequently, around 20% of the discharged treated wastewater reaches the aquifer, together with return flow from irrigation (excess water). These flows constitute a direct recharge, but also deteriorate the quality of groundwater and especially shallow groundwater due to their higher salinity and nitrates content (El-Rawy, et al., 2016; Bajjali, et al., 2017). Other negative impacts historically associated to the quality effluents from As-Samra WWTP include eutrophication, chemical and biological pollution of KTR, negative impacts of microbiological pathogens on soil quality, or impacts of chlorine and heavy metals contained in the effluents on land fertility and soil characteristics, making necessary the use of fertilizers and other remedy measures (El-Rawy, et al., 2016).

Currently, despite heavy pumping of groundwater downstream of As-Samra WWTP, the discharge of treated wastewater significantly augments the surface water and the groundwater storage (i.e. 20 cm per year since As-Samra WWTP was built), provides large reserve during dry periods and allows for expansion of agricultural practices in the area (Bajjali, et al., 2017; El-Rawy, et al., 2016). Nevertheless, the situation is critical and a water management strategy for irrigation is essential. According to El-Rawy et al., even if As-Samra WWTP reaches its maximum current capacity (around 135 MCM/year), if the abstraction rate for irrigation increases by 30% (based on land availability in the Zarqa River basin), the groundwater water level will decline by 0.36 m and water quality will deteriorate. (El-Rawy, et al., 2016).

After the As-Samra upgrade in 2008, the quality of the Zarqa River water significantly improved. Gradual but significant reductions in COD (chemical oxygen demand) and TP (total phosphorus) have been registered (Al-Omari, et al., 2013), and consequently, positive effects on irrigation practices and the enhancement of wildlife and its habitats have been produced (SUEZ, 2017). Occasional high concentrations of these parameters have been also identified, but have been related to local pollution from agricultural runoff with pesticides and fertilizers or illegal discharge of pollutants from untreated industrial wastes (Al-Omari, et al., 2013; El-Rawy, et al., 2016).

As a final point, it is worth mentioning that, due to external factors (e.g. growing population, the Syrian refugee crisis, etc.), the improvements in As-Samra from phase 2 will no longer meet the region's wastewater treatment needs through 2025, and a second expansion has been proposed to be implemented before 2020 (Petra News Agency, 2015). The new expansion would increase 100 000–145 000 m^3 per day the capacity of the plant, as well as the energy production on-site from treated sludge and bio-solids. Latest information about this new expansion states that a technical, financial and legal feasibility study (the FS) and an Environmental and Social Due Diligence (ESDD) is being carried out (EBRD, n.d.).

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[30] See Appendix B for an extended version of Jordanian standard JS 893:2006.

2.4.4.3 Energy use in As-Samra WWTP

As-Samra WWTP covers 80% of the plant energy needs by making use of endogenous energy resources, and it draws the rest (20%) from the national grid. In total, 13 MW of power are recovered from wastewater in form of hydropower and biogas power generators (see Figure 29). Thus, due to a difference of around 78 m between Ain Ghazal and As-Samra WWTP the wastewater from the pretreatment facility passes through Pelton turbines with a total power of 1.7 MW at the inlet of As-Samra WWTP. At the outlet of the plant, the treated water passes through Francis turbines with a total power of 2.5 MW. The biogas produced in the digesters is stored in four gasholders: two with 5 000 m^3 capacity each and two with 4 000 m^3 capacity each (i.e. 18 000 m^3 in total). After undergoing Hydrogen Sulfide (H_2S) removal, the biogas is used in ten biogas engine generators set for electricity production with a total power of 9.5 MW.

This configuration allows producing 230 MWh/day of electricity. Consequently, 300 000 tons of CO_2 are said to be saved annually. Nevertheless, it has not been possible to find empirical registers of this production. Other integrated energy-recovery steps are also found along the treatment line; i.e. in the digesters, the recycled compressed biogas is used to blend the sludge, and the hot water recovered from the cooling of the engines is used to heat up the recycled sludge using a shell-tube heat exchanger (SUEZ, 2017).

2.4.4.4 Agriculture in As-Samra WWTP

As-Samra WWTP is designed to produce 133 MCM/year of water of high quality for agriculture usage, fulfilling the Jordanian Standards as seen before. Nevertheless, as analyzed previously it usually works at partial capacity. In 2015 As-Samra WWTP treated around 107 MCM (MWI, 2016a), so using average water efficiency of Jordanian WWTPs (i.e. 88% of inlet wastewater), around 95 MCM have been estimated to be available at the outlet of the plant that year. Despite it is lower than the design capacity it constitutes around 18.5% of the total water resources used for irrigation in 2015, according to data from the MWI.

Irrigation with discharged water from As-Samra WWTP is very restricted upstream of KTR (Al-Omari, et al., 2013), but a portion of the effluent is used in crops near the plant and along the Zarqa River, accounting for around 16% of the total released water from the plant according to Mustafa et al. (Mustafa, et al., 2016). El-Rawy et al. state that this permanent flow from As-Samra WWTP has shifted the dependency for irrigation water of 20% of farms from groundwater to treated wastewater from the river (El-Rawy, et al., 2016). Regarding irrigated land that uses treated wastewater in this area, in 2016 the MWI conducted field trips along the Zarqa River from the outlet of the As-Samra WWTP to the KTR to study the lands in terms of irrigation and to discuss its regulation. In total, 1 094 ha divided into 296 farms that use treated wastewater from As-Samra WWTP were identified, but only 136 farmers corresponding to 350 ha had fulfilled the legal requirements by June 2016 (MWI, 2017).

The rest of the discharged water from As-Samra flows through the Zarqa River to KTR, where it is stored. The effluent is blended with precipitation and surface water by the passage through the *wadis* and especially in the KTR. Thus, when stored at KTR the quality of the effluent is enhance thanks to the run off from the country's upstream drained to KTR (Mrayyan, 2005). From the reservoir, the blended water is led through *wadis* and canals to the middle and southern JV or down streaming Yarmouk River without the need of pumping thanks to the altitude difference (i.e. KTR is placed at 600 m a.s.l. and the JV is located below the sea level). At the end of these canals, the reclaimed water is finally used in the agricultural fields for irrigation. It is estimated that reused water from As-Samra serves to irrigate about 4000 farms with an area of approximately 10 000 ha (Myszograj & Qteishat, 2011).

Finally, the sludge drying on site in the As-Samra WWTP allows transforming it into granule form and use it as fuel, compost (fertilizer) or fodder for agricultural activities (Degrémont - SUEZ, 2008; Degrémont - SUEZ, n.d.(a)). However, actual implementation of these applications has not been confirmed in literature.

3 Results and discussion

This section presents and discusses the main results. Subsection 3.1 condenses the main identified WEA nexus interlinkages, based on previously exposed contents in section 2.4. Therefore, for more details on any mentioned topic in this chapter, see sections 2.4.1-2.4.4. In subsection 3.2, future alternative pathways are proposed and analyzed. After being briefly presented, the pathways are evaluated in three tables, one per WEA nexus sector. Each table contains main potential impacts associated to each pathway, as well as proposed indicator to quantify the impact, when appropriate. Next, three "compound" pathways combining two selected pathways each are analyzed in more detail.

3.1 Nexus interlinkages

Along section 2.4, numerous nexus interlinkages have been implicitly included as part of the presentation of the Jordanian context at the three different levels of study (i.e. national, LJRB and As-Samra WWTP). This section aims at summarizing the main WEA interlinkages that have been identified in the current Jordanian context. The present section is divided into three subsections, one for each of the WEA sectors (i.e. water, energy and agriculture). Each subsection presents those interlinkages that address the core nexus sector in question in the first instance, e.g. in the *water* subsection, water for energy and water for agriculture interlinkages are considered, as well as inner implications within a sector (e.g. effects of overexploitation of surface water resources on groundwater). The exposition in sections 3.1.1-3.1.3 is mainly focused on the national level, and only if there are specific connections at the LJRB level, additional explanations are added. Therefore, comments on the LJRB are lacking whenever the information is not available or the interlinkages at national level also correspond to those at the LJRB level. At the end of subsection 3.1.3, a diagram presents graphically a qualitative summary for the Jordanian system, valid for national level and the LJRB level. Finally, subsection 3.1.4 exposes the WEA nexus interlinkages identified on As-Samra WWTP system, also with a diagram to summarize graphically the main interlinkages.

3.1.1 Water

Water resources in Jordan are very limited, with less than 105 m^3/year per capita. Most of its natural water resources are polluted, over-exploited or are being drained and dried out, and the situation is worsened by contextual factors such as uneven distribution of resources, climate change, great water diversion of shared resources, or an increase of water demand. As a result, Jordan is using more water than the country can provide in a sustainable manner, with numerous implications on energy and agriculture sectors.

3.1.1.1 Water for energy

The energy sector has associated a large use of water, including water use for mining, extraction and processing of energy resources and water requirements for electricity production. The use of water is divided into consumption, being the water lost to evaporation, and withdrawal. The water withdrawal is the extraction-release component of the water use, and although not lost, has important implications on the environment such as stress on aquifers, reduction of environmental water flows, thermal pollution, or effects on ecosystems. Within the energy sector, the power sector is the largest source of water withdrawals, although primary energy production is larger in terms of consumption.

In Jordan, mineral energy sources at a national level are very limited in terms of oil and gas, but the relatively low extraction and processing of local resources (i.e. 500 ton of oil from Hamza oil field and 121.8 million m^3 from Risha gas field in 2015) requires large volumes of water. Despite specific values for Jordan are not available, on average crude oil refining requires 200-800 liters of water per ton of crude oil. Much of the water is recaptured along with the produced oil, but generates a large waste stream to be treated and disposed. Gas extraction is generally less water intense but site-specific depending on geological formations, and can be different even within the same well field.

Water for cooling constitutes a major part of the water use in electricity production, but specific values for Jordan have not been found. There are three main types of cooling technologies: once-through, wet-tower and dry cooling. Once-through technologies are generally the most efficient and with the lowest capital costs, but the withdrawal rate is the highest; wet-tower systems withdraw a smaller volume, but the consumption is higher; dry cooling uses very little water, but is costly and has the lowest efficiency. Hybrid alternatives, which combine dry and wet cooling systems, are projected to be extensively deployed together with dry options, due to their flexibility and more competition for water and strict regulation. In terms of operational water use, the average needs do not necessarily depend on the fuel or energy source, but on the applied cooling technology (see Table 25 in Appendix 0). For instance, CSP plants, which could be a suited renewable alternative for Jordan due to the high insolation, have an associated water use for cooling and cleaning of mirrors and lenses comparable to conventional thermoelectric plants. Consequently, dry or hybrid cooling systems are the most preferable options, and even with those cooling technologies, in some cases CSP could be never suitable. CCGT, which constituted 77% of electricity production in Jordan in 2016, usually presents the lowest rates of water use among thermal power plants when comparing the same cooling technologies, while nuclear power plants on average withdraw more water per unit of energy. Wind turbines and PV, which are growing in importance in Jordan (i.e. 480 MW were installed in 2015 and 2016), are the technologies with the lowest water demand. In the case of wind the water use is zero, and in the case of PV is 22.7 liters/MWh of withdrawal and consumption, mainly associated with cleaning. Therefore, these technologies are the most suitable for Jordan in terms of water use, although there are other aspects to consider (e.g. intermittence, land use, investment costs).

Another major water-for-energy linkage is constituted by hydropower production, but in Jordan the potential is reduced due to the water scarcity and the great seasonal fluctuations. Installed capacity accounted for 4.5% of total electricity-producing capacity in 2016. The precipitation regime, with periodic droughts and irregular thunderstorms that provide most rainfall along the year, make water storage an essential element of the water supply system, and only one out of ten main dams is used for hydroelectric production with an installed capacity of 6.4 MW (see footnote 18 on page 25). Additionally, there are 6 MW provided by hydropower turbines at the outlet of the cooling system in Aqaba Power Station, and 4.2 MW in As-Samra WWTP (see section 2.4.4.3).

In the case of WWTPs, there is a large potential for energy savings, which can offset the energy demand. The selection of an appropriate technology to match local climate conditions can reduce the energy needs. For instance, anaerobic processes can be more energy-efficient because require less energy for aeration. In the case of Jordan, anaerobic digestion is especially suited due to the warm climate, and allows for extracting part of the embedded energy in wastewater in form of biogas from the digesters. This bioenergy from recovered off-gas can be also combined with additional on-site renewable technologies to cover the energy requirements. Nonetheless, it should be noted that these alternatives decrease the dependence on external energy supply, but do not reduce the actual energy demand.

3.1.1.2 Water for agriculture

Agriculture is the largest water-demanding sector in Jordan, being responsible for 49% of the total water use in 2015, but its socio-economic impact is very low, with 2% of total jobs and 4.3% of GDP in 2016. The exploitation of water resources for irrigation purposes has changed over last decades, resulting in impacts on the environment, the energy sector and agriculture.

The main surface water resources that historically supplied most water in Jordan are drained and polluted. In general terms, agricultural run-off and untreated or poorly-treated wastewater containing chemicals and metals constitute a large part of these water streams, which make them unsuitable for domestic use and sometimes even for irrigation (see *Surface water* in section 2.4.2.2). Currently, most of the water from rivers and *wadis* is used or stored. The main existing dams in Jordan serve to store base flows and floodwater, and release it for agricultural use. Since surface water resources are polluted, water-storage systems are also experiencing higher salinity and levels of metals and chemicals, which in turn negatively affect the growth of crops. The desert dams, excavations and ponds in desert areas, which had been traditionally used for grazing only, last decades provide permanent water resources for irrigation, watering livestock and recharge purposes. In addition, several rainfall-harvesting projects have been developed, mainly for irrigation.

Jordan suffers periodic droughts and irregular thunderstorms that provide most rainfall along the year. This precipitation regime, together with degraded land, causes soil erosion and the decrease of groundwater recharge. Infiltration of wastewater into groundwater systems constitutes the main source of pollution of groundwater resources, and is responsible for the high nitrate concentration that has been identified in some cases. In turn, the lower quality of groundwater affects irrigated-agriculture.

Jordanian aquifers are being largely over-exploited, with an average over-abstraction rate of 149% (i.e. 419 MCM of safe yield over 624 MCM abstracted in 2015). Some main reasons for the over-exploitation of aquifers include increasing water demand and poor control of abstraction rates and private-well drilling. Thus, of 2 998 private wells that were identified in 2015, 33% were illegal and responsible for extracting 16 MCM. Additionally, agricultural wells constituted the largest sector in terms of water pumping with 1 580 wells (63% of working wells) and 215 MCM of abstraction (78% of total). Direct consequences of a lower recharge and a great over-exploitation of aquifers are increased salinity, intrusion of pollutants and lowering water tables, which affect the growth of crops. This is of particular interest in the Highlands, where 65% of groundwater-irrigated crops is concentrated.

Treated wastewater is the main non-conventional water resource in Jordan, accounting for 11% of total water uses in 2015 and increasing its total volume progressively. Over 91% of this treated wastewater is used in agriculture, especially in the JV, and the rest serves for industrial cooling or aquifer recharge depending on the level of treatment and the location of the WWTPs. However, the reuse of treated wastewater in agriculture not only brings about numerous benefits, but also drawbacks to consider. On the one hand, using treated wastewater for irrigation allows for the reallocation of freshwater resources that would have been employed in irrigated crops to other sectors without greatly affecting the available irrigation water. Moreover, a proper management of treated wastewater in agriculture can reduce or even eliminate the use of synthetic fertilizers due to the nutrients content of treated wastewater. On the other hand, in the absence of monitoring procedures and regulations, treated wastewater can have impacts on human health and the environment. These effects include soil damage due to alkalinity and salinity, changes in composition and rates of groundwater recharge, alterations of aquifer geochemistry, crop toxicity, and decrease of crop yield due to pathogens and heavy metals contained in wastewater. Furthermore, there are potential risks to public health such as risks of infection with the bacteria "Giardia", which have been associated with wastewater reuse and have been reported in the JV.

Another non-conventional water resource is desalinated water, expected to gain importance in next decades. Sources greatly differ on the current use of desalination in Jordan, ranging from 6 to 70 MCM of desalinated water produced annually, but it has been reported that farmers use private desalination plants in the JV to treat brackish groundwater for irrigation. After diluted in fresh water, desalinated water is used to irrigate high-value crops (e.g. bananas, strawberry, dates), which provide higher revenues than the desalination costs.

The use of the previous water resources make the agriculture sector (i.e. irrigation and livestock) the largest water-user in Jordan. Despite this large supply of water for irrigation, the agriculture has the lowest priority in the allocation of water resources, and not all the water demand in the sector is met. In 2015, the gap between water demand and supply amounted over 400 MCM, and this difference is widening through the years. Consequently, Jordanian farmers are experiencing a reduction in the volume of fresh water for their activity, being compensated, at best, by an increase in treated wastewater.

Even with the existent water-resource constraints, over last decades the agricultural productivity in Jordan has increased, mainly due to new farming and irrigation techniques. Some of these systems include greenhouses, drip-irrigation technologies, high-yielding crops and agrochemicals like pesticides and fertilizers. As a result of these improvements on irrigated crops (mainly fruits and vegetables), their production accounts for 90% of total agricultural yield, despite occupy around 40% of the cultivated area.

3.1.2 Energy

Jordanian energy sector mostly relies on fossil fuels (i.e. over 97% of the TPES in 2015), but renewable energy technologies are increasing their presence (mainly solar and wind), which can have implications in other sectors. At the same time, in a context characterized by scarce natural resources, improved access to modern energy services has the potential to enhance water and food securities.

3.1.2.1 Energy for water

The water sector involves an energy-intensive operation associated to different processes such as water abstraction, transport, distribution, irrigation systems, or treatment of water (including desalination) and wastewater. Most of the energy use corresponds to electricity consumption, primarily used for pumping purposes. Last decades, the development of the water sector has caused a generalized intensification of water pumping, which in turn has resulted in an increasing trend in the associated electricity consumption.

Groundwater abstraction requires the use of energy, and typically increases with the depth of the well. With growing water demand, the over-exploitation of aquifers is intensified, water tables decline and the associated energy consumption is larger. Additionally, water shortages due to droughts further exacerbate the situation, since the water supply from groundwater sources is more energy-intensive than that from surface water resources.

In the case of the sewerage systems, wastewater collection, distribution and treatment require certain amount of energy. In 2016, 159 MCM of wastewater were treated in 33 WTPPs, and the total volume of wastewater is increasing at a steady pace due to the population growth, the increase of water use, and a higher access and the development of the sewerage systems. Consequently, the energy consumption associated to sewerage systems is also growing. The energy demands in WWTPs typically increase with the complexity of the treatment process. Within the WWTPs, wastewater aeration, pumping, and solids processing constitute most of the electricity needs. Other aspects that affect the energy intensity in WWTPs and sewerage systems include climate conditions, inlet and outlet parameters of the treated wastewater, the size and age of the system, or specific design and operation characteristics of the facilities.

The desalination process is also very energy-intensive. For instance, in RO desalination plants, the electricity demand ranges from 0.5-2.5 kWh/m^3 for brackish water and 5-9 kWh/m^3 for seawater. In MSF systems, the energy demand includes 1.2-5 kWh/m^3 of electricity demand and 25-120 kWh/m^3 of heat demand. Therefore, a large deployment of desalination plants in Jordan will have a direct impact on the TPES. Despite the current use of desalination in the country is not clear it is said that all the plants use RO as desalination technology and are powered by the electric-power grid. In other countries, the required energy in desalination systems is supplied by low-grade excess heat from thermal power plants and renewable energy technologies such as solar collectors, PV or wind (see examples in Table 20, in Appendix 0), which can be suitable for Jordan, especially for the scattered brackish-water resources in rural off-grid areas. In particular, solar desalination can be a suitable solution because water shortages are common in summer when solar radiation is maximum. Similarly, hydropower has been proposed to take advantage of the reservoir that desalination systems require for the residual brine, using brine as a medium for pumped storage.

The domestic water supply in Jordan is very deficient, with an intermittent regime ranging from some hours every week to occasional supply every two or more weeks. The intermittence of the water supply leads, among other things, to a higher pipe burst and corrosion that result in leakages, which in turn causes water and energy losses. Other major aspect of the deficient domestic water supply in Jordan is the NRW associated to damaged equipment and pipes, inadequate maintenance, non-working meters and unauthorized connections. In 2014, NRW accounted for 52% of the water supply in the domestic sector. Apart from the evident reduction of water supply (61 l/day per capita instead of 126 l/day), the high volume of physical and administrative water losses bring about indirect energy losses.

In 2015, the average energy consumption per volume of supplied water was 4.43 kWh/m^3, but the specific energy-water ratios for WAJ and JVA differed a lot, ranging from 8.01 kWh/m^3 to 0.17 kWh/m^3, respectively. These differences can be attributed to different pumping needs to deliver water, origin and location of water sources, treatments, topography or amount of water and energy losses in the system.

A major factor that has contributed to increasing the average energy intensity of the water supply is the operation of the Disi project, which supplied 23% of the total abstracted groundwater in Jordan in 2015, mainly for drinking purposes in the Greater Amman area. The complete process consisting of groundwater pumping from 65 wells, 500 m deep, and water conveyance over 325 km and 800 height difference, required around 2% of Jordan's annual energy consumption. Since the Disi aquifer is not replenished, the abstraction rates are rapidly depleting the resource. Due to the drop of groundwater levels at an average rate of 2.3-10.5 m/year, the energy demand is constantly increasing to pump the water from deeper levels. If a similar extraction rate continues, in 25 years further abstraction will be economically unfeasible.

The untapped potential of energy-efficiency gains across the energy sector can reduce over 25% of the primary energy consumption by 2030. These energy savings can be considered as the most cost-effective source of energy supply, and bring about many positive impacts such as water savings in the energy production, and environmental, social or economic benefits. Some of the measures in the water sector that can increase efficiencies and reduce losses include improving O&M, optimizing system processes by means of monitoring and control systems (i.e. SCADA), and replacing, rehabilitating and upgrading equipment in water facilities and distribution systems with more efficient and right-sized machinery. Other options comprise reducing long-distance pumping through integrating decentralized water infrastructures that use rainwater or other local water sources.

The inclusion of renewable energy integrated in water utilities can provide low-carbon water production. Off-grid renewable energy production could promote rural electrification, water pumping, irrigation and low carbon food production. In addition, decentralized systems can reduce service interruptions and can be coupled with user-scale energy systems to cover the energy needs of treating water onsite. In these systems and particularly in those coupled with water-pumping systems, net metering schemes or similar strategies to monitor and regulate are advisable, in order to limit and control the exploitation of water resources.

Lastly, by importing most of the energy resources (i.e. 97% of the energy resources were imported in 2015), the water use associated to mining, extraction and processing is avoided, which can be considered as virtual water imports for Jordan.

3.1.2.2 Energy for agriculture

The agricultural sector is a great energy consumer. The direct and indirect energy dependence of agriculture is strong, and any aspect in the energy sector (e.g. dependence on fuel imports or electricity service intermittency) can affect the capacity to deliver reliable water services and ensure food safety. The energy input in agriculture is directly linked to the level of technology adoption and the level of production. Therefore, the agricultural modernization in Jordan, although essential for providing food for the growing population because contributes to higher productivity and water efficiency, is increasing the required amounts of energy, which can have long-term impacts on climate change.

Interestingly, the evolution of the agricultural sector during last decade shows a similar increasing trend in the electricity consumption for water pumping and the agricultural production. In contrast, the total water use in irrigation and the total harvested area have remained mainly constant (see Figure 22 on page 34). These results indicate that using the same land and water resources the production can be increased, but implies a higher electricity consumption associated to agricultural activities. This situation can be due to the deployment of water-efficient irrigation systems that save water but require more energy. Moreover, energy needs associated to water pumping can be higher because of lower energy and water efficiencies in the water system, and the increasing depths to abstract water from groundwater resources associated to the depletion of aquifers and the decrease of water tables.

In Jordan, 60% total energy consumption associated to the agricultural production is estimated to be linked to direct uses, while indirect uses constitute the remaining 40%. Before farming, the production and distribution of fertilizers, chemicals and other inputs require energy. Energy inputs during farming depend on the particular crop, but usually include high power-consuming machines (but also laborsaving), which are used in direct agricultural activities such as tilling, planting, pruning, thinning, harvesting and electricity for irrigation pumping. The energy from the sun is also an essential input, but since is not purchased is usually not considered. Moreover, every unit of water delivered during farming involves energy consumption, hence water that is not effectively used by the plant involves energy losses. After farming, transportation, storage (usually dry or cool storage), processing and retailing entail energy consumption.

Finally, agricultural systems and in particular water-pumping systems can be coupled with renewable energy technologies, and decreasing costs of these energy-efficient systems have caused an extensive proliferation. However, their uncontrolled use has become a threat for water resources management in the Arab region. In many cases, farmers use the renewable water-pumping systems as soon as the source is available (i.e. there is sun or wind), increasing the groundwater abstraction and over-irrigating crops. A possible solution to regulate over-abstraction of water is monitoring and limiting the energy consumption, but in the case of privately-owned renewable water-pumping systems the control can be very complicated.

3.1.3 Agriculture

In contrast to the existence of numerous nexus interlinkages where agriculture is the objective sector (i.e. energy for agriculture and water for agriculture), few interlinkages connect WEA nexus sectors in the other direction (i.e. agriculture for water and agriculture for energy. Thus, energy and water are essential inputs for agricultural production systems, but agricultural inputs for energy and water are less common. In this study, energy- and water-efficiency strategies applied to the agricultural sector have been considered as AE and AW, respectively. The main reason for this approach resides in the fact that efficiency measures in the agricultural sector result in energy and water savings, which can be seen as a virtual supply of natural resources that contribute to energy and water security.

3.1.3.1 Agriculture for water

Improved agricultural practices can contribute to increasing water-use efficiency, and consequently can save water to be reallocated in other sectors or in additional agricultural activities. Some of these practices include the use of pressurized irrigation systems like sprinkler or drip irrigation, which Jordan has adopted over last decades and especially in the JV. Thus, the water losses in pressurized irrigation systems are much lower than surface and flood irrigation systems, which also increase agricultural productivity. In particular, sprinkler irrigation systems are more water-use efficient than surface systems, but less than drip systems, which uses around 25% less water. Variants of the drip irrigation such as burying pipes and using a waterproof tarp or the buried diffuser can save up to 20-33% of water used in regular drip irrigation and up to 70% of energy (see typical water-efficiency values in Table 29, in Appendix 0).

Another crucial practice to optimize the use of water is the correct choice of crops. Generally, two factors determine the amount of water that is required: the growing periods and the water demands of particular crops. Therefore, a proper selection of crops should consider climatic conditions to enhance water-use efficiency. Traditionally, in Jordan the selection of crops has not been optimal, resulting in an average water-use efficiency for irrigation of around 50-60%. Instead of cultivating vegetables and fruits, Jordan has favored less efficient options, like raising cereals and other field crops or using agricultural fields as pasture.

Other agricultural practices that contribute to saving water include greenhouses and covered systems, the use of agroforestry, ploughing perpendicularly to the slope, terracing, appropriate scheduling for water-supply systems, or the burying of crop residues, which improve the water retention through lower evapotranspiration and reduced water run-off and percolation.

Despite water-efficient practices are considerably deployed in Jordan (see Figure 20 and Figure 21 on page 32), there is still room for improvement, not only in the case of fruits and vegetables (see 3.2.1), but especially in field crops. The adoption of these practices in field crops can greatly reduce water losses by evapotranspiration, which are usually higher than for fruits and vegetables.

Another measure for further water-efficiency gains is the reduction of water losses in water-distribution systems for irrigation. Leakages, seepage and operational losses in distribution systems for irrigation water result in large water losses, which amounted 25 MCM in 2015. A strict control of the water system and O&M strategies in the agricultural water system could provide great water savings to be reallocated.

However, in some cases agricultural activities contribute to the degradation of water and land resources. For instance, the high use of fertilizers in Jordan, even though enhances agricultural production, is partly responsible of the pollution of surface and groundwater resources, as well as the Jordanian storage systems. Especially when misused and overused, fertilizers contribute to the acidification of water and land resources by water run-off and infiltration.

Additionally, imported agricultural products constitute a large virtual supply of water that need to be considered. Jordan is a food-deficit country due to limited natural resources for agricultural production and increasing demand associated to population growth and changing diets. By importing 87% of the food, also imports embedded water (and energy), and the water that otherwise would have been used to produce food locally will be reallocated. Between 1995 and 1999, net virtual water imports per capita in Jordan associated to crops and livestock trading were 957 m^3/year, while total renewable water resources per capita were 129 m^3/year. On the contrary, by trading local agricultural products like vegetables and fruits, Jordan exports part of its water resources, which contributes to aggravating the water-scarcity situation in the country.

Following the same principle, agricultural losses constitute water and energy that are not effectively used, hence can be also considered as losses. As an example of this type of losses, 46% of the cultivated area in 2016 in Jordan was not harvested, which meant large water and energy losses. In the LJRB, these difference between the harvested and the planted area is especially high for cereals, namely wheat and barley, with 58%, followed by bananas, with 32% (see Figure 65 in Appendix 0). Nevertheless, despite specific estimations are not available, water losses associated to bananas are expected to be proportionally higher due to their large irrigation needs. Another example of agricultural losses consists in food products that cannot be sold and consumed due to an inappropriate supply chain. Once again, these losses include water (and energy) embedded in the products. Alternatives to reduce losses after farming include improvements in the supply chain management (e.g. transportation, cooling chains, storage, etc.) and agro-processing industries.

3.1.3.2 Agriculture for energy

A typical agriculture-for-energy interlinkage consists in producing gaseous or liquid biofuels from crop residues, selected crops, wild plants and algae, or agro-industrial wastes (as well as urban wastes). However, there are not registers of this activity in Jordan, although the potential of biomass resources including collection losses has been estimated at 6.6 PJ. In the future, only waste-to-energy technologies based on agro-industrial, human and animal residues should be considered as secondary sources of energy, because cultivation and processing of crops entails the use of water (as well as energy), and there are many essential water needs to cover and scarce water resources. Moreover, apart from producing energy, waste-to-energy strategies would reduce the quantities of waste that require final disposal, which also require energy.

As stated previously, importing agricultural products results in a virtual supply of water and also energy, hence part of the energy consumption associated to the agricultural production is avoided. Inversely, by selling agricultural products in international markets, the energy that is embedded in food is also exported.

In contrast to the benefits associated to pressurized irrigation, these systems require a higher energy input and have a larger environmental footprint. Moreover, the initial cost of these systems and the energy costs associated to their operation make them prohibitive for small farmers, which limit their complete adoption.

Lastly, agricultural losses also involve embedded-energy losses associate, which can reach up to 38% of the total energy consumption during the farming process. As said before, alternatives to reduce food losses include agro-processing and improvements in the supply chain management, but in terms of energy, these improvements can exacerbate the energy consumption associated to the agricultural production.

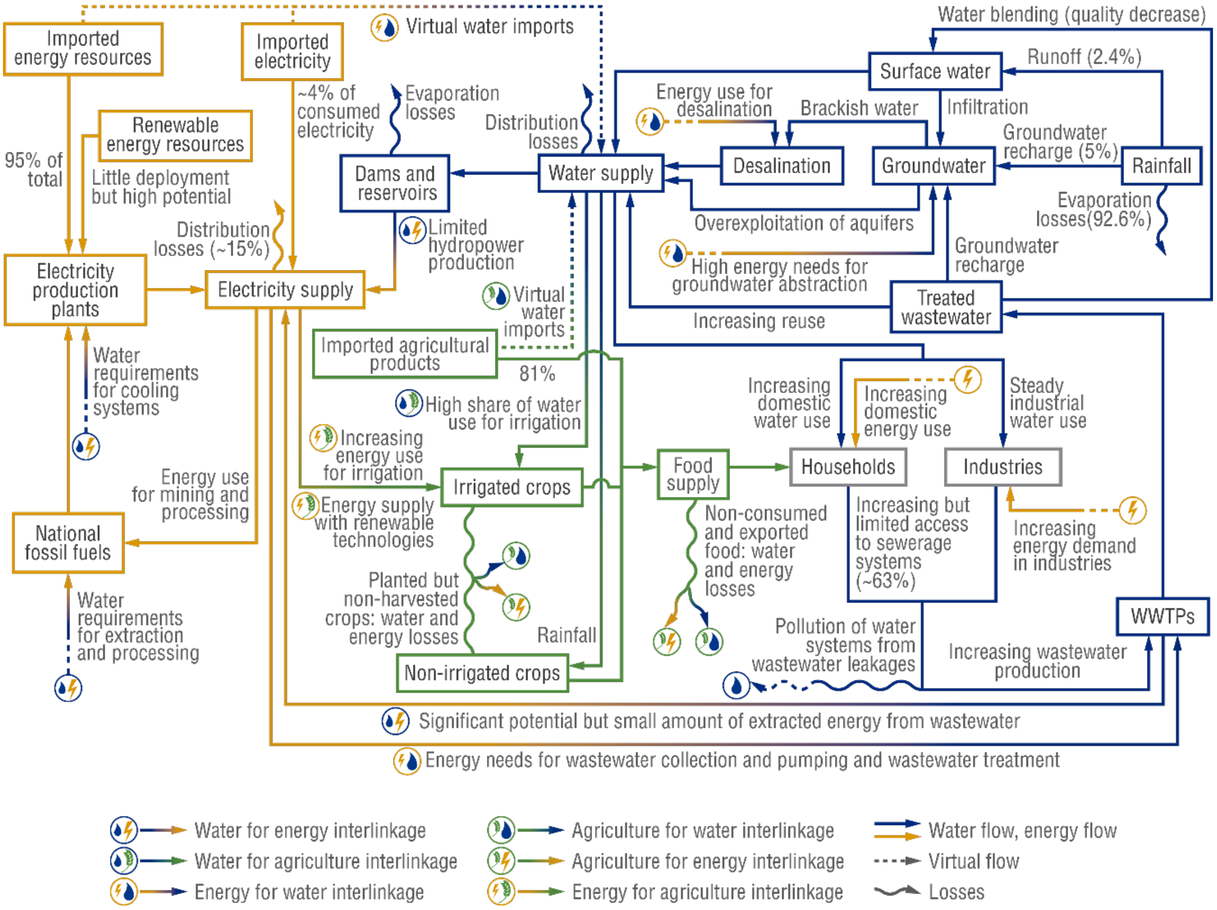

Figure 30 – Graphic summary of the WEA nexus interlinkages in Jordan

Figure 30 presents a simplified graphic summary of the existent WEA nexus interlinkages in Jordan. As can be observed, the amount of interconnections between sectors is great, and water constitutes the center of the WEA nexus being both the main enabling and limiting factor in the development of the country.

The previous analysis highlights the limited natural resources in Jordan and their critical state in terms of exploitation. This condition is mainly due to generalized inefficiencies and unsustainable uses of the natural resources, which in turn are associated to a lack of regulatory framework and a resource management that traditionally was separated by isolated sectors. In last years, this situation has started to be amended through cross-sectoral coordination and new regulations, but there is a high risk of incurring in unsustainable practices due to increasing efforts to enhance self-sufficiency of natural resources.

It is apparent that the dependence of Jordan on natural resources is inherent to its nature and is being intensified by the contextual conditions, hence changing this condition can result contrary to the expectations and can exacerbate the unsustainable exploitation of natural resources. Therefore, main efforts should be made to decrease losses, increase efficiencies in all sectors, and reallocate natural resources to optimize their use in a sustainable manner. To this end, monitoring strategies would be advisable to evaluate the WEA nexus interlinkages and to control anomalous performances within the system.

In the water sector, the elimination of illegal wells, leakages and unauthorized diversions of water resources should be promoted, which would greatly increase the quantity and quality of water and would reduce the energy consumption associated to the water sector. Furthermore, abstraction rates in aquifers should be decreased to safe-yield levels, being replaced by other available resources in increasing order of required energy: rainwater harvesting systems, treated wastewater, and desalination.

Regarding the energy sector, a close analysis to evaluate the nexus impacts and implications of each alternative should be performed to select the best energy mix from the perspective of WEA nexus security, and especially in terms of water use. Some of the options to consider should include the exploitation of local resources and renewable energy technologies (e.g. wind, PV or biogas from WWTPs), either centralized or integrated in small and medium-scale systems (e.g. rural areas, municipalities, etc.).

In the case of agriculture, the water scarcity and the unsustainable exploitation of resources makes inevitable the reallocation of part of its water resources to higher-value uses. To compensate this decrease in water resources, agriculture should enhance its water-use efficiency through a better selection of crops and other water-efficient agricultural practices, and the intensive use of fertilizers should be studied in detail to determine their optimal use. Additionally, the combination of food imports from international markets with intra-region trade that could take advantage of complementarities in agriculture should be studied as a virtual supply of water and energy.

With such changes in all sectors and the promotion of demand-side management changes (especially in water and energy use), the additional resources to supply the future demand would be much lower.

3.1.4 WEA nexus interlinkages in As-Samra WWTP

As-Samra WWTP treats wastewater produced in Amman Russeifa-Zarqa Basin, where around 60% of the population of Jordan live. Three stations collect and convey wastewater to As-Samra WWTP: Ain Ghazal pretreatment plant, East Zarqa and West Zarqa pumping stations. East Zarqa and West Zarqa units draw electricity from the national grid to cover the energy that this process requires. In the case of Ain Ghazal, wastewater flows by gravity towards As-Samra facility due to a height difference of 78 m, passing through Pelton turbines with a total power of 1.7 MW.

The treatment line consists of activated sludge with nutrient removal and chlorine for disinfection and has a design capacity of 364 000 m^3/day, but the actual volume of treated wastewater averaged 304 357 m^3/day in 2016 (83.6% of the design capacity). The resulting sludge dries on site and can be transformed into granule form and use it as fuel, compost (fertilizer) or fodder for agricultural activities. As part of the treatment line, there are seven anaerobic digesters of a capacity of 15 900 m^3 each where biogas is produced. After undergoing H_2S removal, the remaining biogas from the digesters is stored in four gasholders (18 000 m^3 in total) and used in ten biogas engine generators set for electricity production, with a total power of 9.5 MW.

Furthermore, along the treatment line integrated energy-recovery strategies contribute to reduce the energy demand. In the digesters, part of the recycled compressed biogas powers Cannon® mixers to blend the sludge, and hot water recovered from the cooling of the engines heats up the recycled sludge in a shell-tube heat exchanger (see Appendix B for more details).

Once treated, at the outlet of the facility wastewater passes through Francis turbines with a total power of 2.5 MW. In total, onsite power production (i.e. inlet and outlet hydropower turbines and biogas engines) amounts 13 MW that allows producing 230 MWh/day. Consequently, endogenous energy resources can cover 80% of the plant energy needs and the national grid supplies the rest.

Treated wastewater leaves As-Samra WWTP and runs naturally through the Zarqa river basin. The plant is designed to produce 133 MCM/year of water of high quality for agriculture usage, which fulfils Jordanian Standards (i.e. TSS, BOD_5, TN). In 2015, around 95 MCM of treated wastewater were available at the outlet of the plant according to estimations, which accounts for 18.5% of the total water resources used for irrigation that year. A higher volume of treated wastewater allows for reallocating freshwater resources to other uses or expanding agricultural activities in the area. Thus, around 16% of total discharged effluents from As-Samra are used for irrigation in around 1 094 ha along the Zarqa River. Moreover, the permanent effluent from As-Samra WWTP has shifted the dependency for irrigation water of 20% of farms from groundwater to treated wastewater from the Zarqa River.

Additionally, the stable discharge of effluents with a higher quality directly to the river has increased the surface water despite heavy groundwater abstraction, has contributed to recover the upper section of the river that was historically dried and polluted, and has positively affected irrigation practices. Moreover, about 20% of the discharged treated wastewater reaches groundwater resources together with excess water from irrigation, recharging the aquifer (i.e. 20 cm per year since As-Samra WWTP was built) and providing reserve during dry periods. However, these flows decrease the quality of groundwater because of their nitrates content and higher salinity and are not enough to counterbalance over-exploitation. Unless an effective water management strategy for irrigation is implemented, abstraction rates will be higher than recharge, so aquifer levels will decrease, water quality will decrease and future uses of the aquifer such as domestic or agricultural uses will be affected.

The rest of the effluents from As-Samra WWTP flows through the Zarqa River to KTR, where it is stored and blended with surface water and precipitation. Bad quality of these effluents have historically resulted in eutrophication, chemical and biological pollution of KTR, negative impacts of microbiological pathogens on soil quality, or impacts of chlorine and heavy metals contained in the effluents on land fertility and soil characteristics. From KTR, the blended water is driven by gravity through canals and *wadis* to the middle and southern JV or down streaming Yarmouk River, where is used for irrigation in approximately 10 000 ha. Figure 31 summarizes the main nexus interlinkages in As-Samra WWTP system.

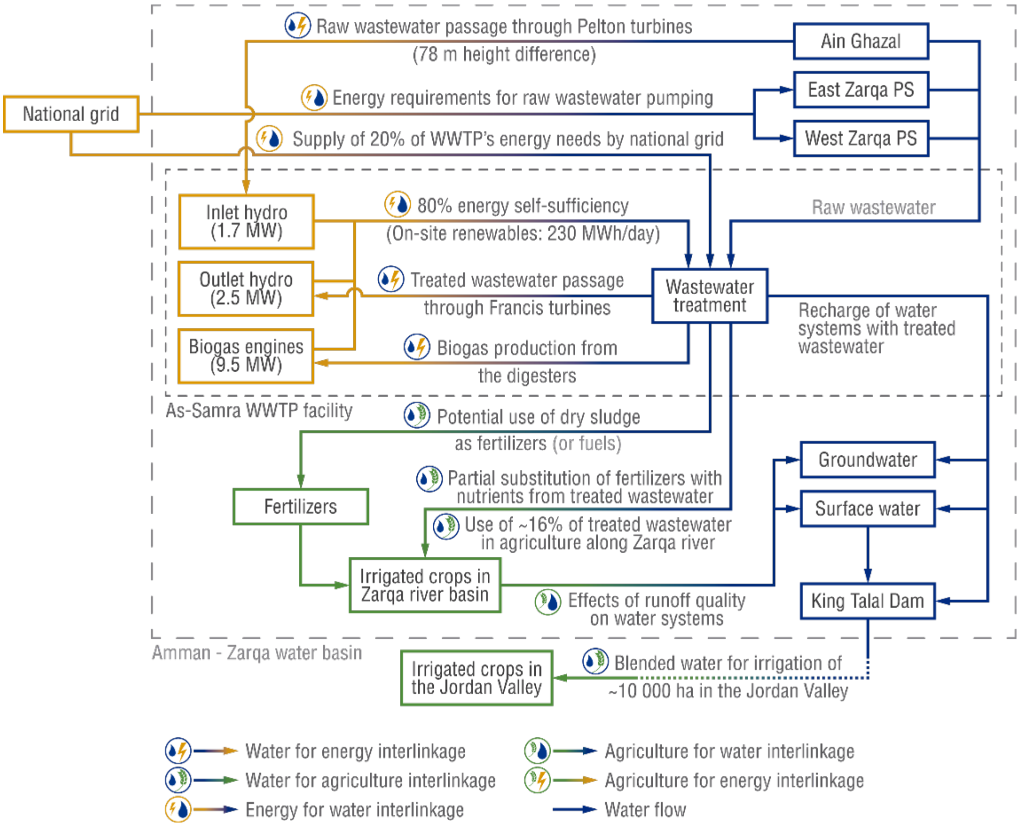

Figure 31 – Graphic summary of the WEA nexus interlinkages in As-Samra WWTP

These results show that, even at a 'local' level in a water-centered system, the WEA nexus interlinkages are very strong. Moreover, As-Samra WWTP stands out as an example of how a good cross-sectoral planning can optimize resources management and result in gains in form of energy self-sufficiency, higher water-efficiencies or indirect agricultural and environmental outcomes.

3.2 Pathways

In this section, different future alternatives have been proposed to the current Jordanian system in order to evaluate potential impacts on each of the WEA nexus sectors. These alternatives have been selected according to the current Jordanian context, the natural characteristics of the country (e.g. national energy resources, climate conditions, arable land, etc.), and trends, plans and prospects from governmental institutions.

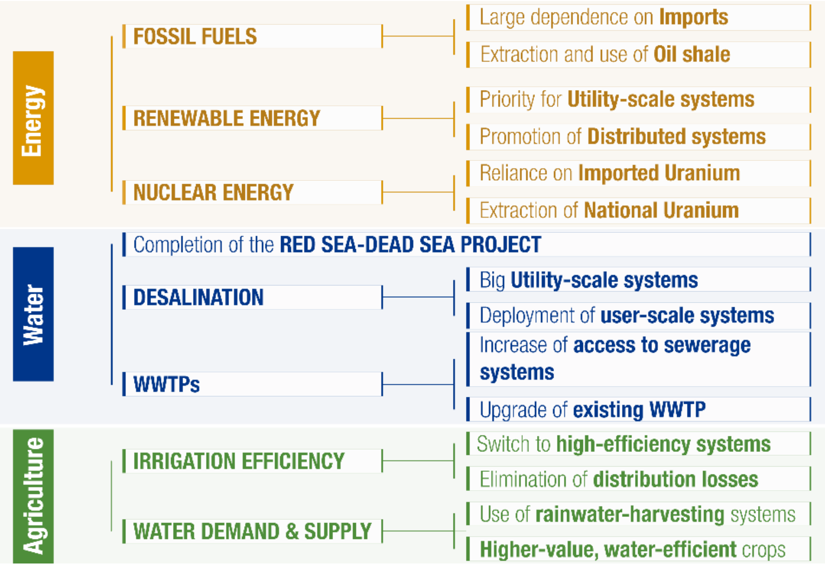

Figure 32 – Summary of the proposed pathways by area and topic

Figure 32, presents a summary of the proposed pathways for Jordan, divided by area and topic. A brief description of every proposed pathway is included below:

Fossil fuels

1. Large dependence on imports: business as usual scenario, with fossil fuels from non-local resources constituting the main supply of energy.
2. Extraction and use of oil shale: mining, processing and use of oil shale from local deposits, to cover part of Jordanian energy demand.

Renewable energy technologies

3. Priority for utility-scale renewable systems: deployment of large renewable-energy systems.
4. Promotion of distributed renewable systems: extensive installation of small-scale renewable-energy systems, e.g. solar and/or wind systems on rooftops and farms.

Nuclear energy

5. Reliance on imported uranium: operation of 2 GW of nuclear power powered with fuel from external supplies (i.e. imported enriched uranium).
6. Extraction of national uranium: mining of uranium ore from national deposits (only extraction of the mineral, excluding enrichment).
7. **Completion of the RSDSP:** construction and operation of the first phase of the project that would connect the Red Sea with the Dead Sea in order to provide an additional water resource to the national water budget.

Desalination

8. Utility-scale desalination systems: development of utility-scale systems for brackish and/or seawater desalination across the country.
9. User-scale desalination systems: deployment of small, distributed systems to provide desalinated water at a small scale, e.g. farms or small industries.

WWTPs

10. Increase of access to sewerage systems: extension of the Jordanian sewerage systems to provide access to 80% of Jordanian population by 2025 (from 63% in 2015).
11. Upgrade of existing WWTPs: substitution of existing less-efficient treatment processes in WWTPs (i.e. WSP, tricking filters, extended Aeration, oxidation ditch and rotation biological contactor) by advanced treatment processes, i.e. activated sludge.

Irrigation efficiency

12. Switch to high-efficiency irrigation systems: substitution of sprinkler and surface irrigation systems in field crops and vegetables to more efficient irrigation systems, i.e. drip irrigation.
13. Removal of distribution losses: reduction of water distribution losses in the irrigation system from 12% to 5%.

Water demand and supply

14. Rainwater-harvesting systems: development of projects aiming at harvesting rainwater as additional water-storage options.
15. Shift to less-water consuming and higher-value crops: substitution of crops with low water-use efficiency and low water productivity by alternative options with higher values, as well as high-value crops such as medicinal herbs and aromatic plants.

The pathways have been proposed in an independent manner, so that they could coexist in a same scenario in most cases, even within the same sector (e.g. an alternative compound pathway could combine reliance on imported uranium, extraction and use of oil shale and promotion of renewable distributed systems). Below, Table 8, Table 9 and Table 10 present the main identified impacts[31] on every WEA nexus sector (i.e. water, energy and agriculture, respectively) for each of the pathways. One or more indicators have been identified in order to propose a way to quantify the impacts, where appropriate. As stated previously, *rainwater-harvesting systems* and *shift to less-water consuming and higher-value crops* are eventually not included in this analysis.

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[31] In columns containing potential impacts, (P), (N) and (O) stand for positive, negative and neutral impact, respectively.

Table 8 – Potential impacts on Jordanian water sector by pathway and proposed indicators

Area		**Potential situation**	**Impacts on Water sector**	
			Potential impact	Proposed indicator
Energy	Fossil fuels	Large dependence on imports	(O/P[32]) Avoidance of water consumption and quality issues associated to mining, extraction and processing of local fossil fuels	Water consumption by the industrial sector
			(N) Water prices exposure to volatilities in oil and gas markets	Water price volatility
		Extraction and use of oil shale	(P) Lower dependence of water prices (not subsidized) on oil and gas markets	Water price volatility
			(N) Large water used for mining and processing	Water used per barrel of oil refined
			(N) Potential pollution of water resources (i.e. aquifers, rivers and *wadis*)	Water quality parameters of surrounding water resources
	Renewable technologies	Priority for utility-scale systems	(P) Potential hybrid systems (e.g. desalinate seawater or brackish water, power WWTPs)	Installed capacity of renewable systems coupled with water systems
			(P) Potential reduction of evaporation losses in surface water bodies covered by solar (PV) plants, and better electrical efficiencies of solar panels	Reduction of evaporation losses from water reservoirs and water bodies
			(N) Significant water consumption for maintenance and cleaning purposes if extensively deployed	
		Promotion of distributed systems	(P) Potential integration of energy production and local available water resources through decentralized green water-infrastructure system (DGWIS)	
			(N) Significant water consumption for maintenance and cleaning purposes if extensively deployed	
	Nuclear energy	Reliance on imported Uranium	(P) Possibility to couple with desalination plants	
			(N) Great water use for cooling	Water use by nuclear energy (withdrawal and consumption)
			(N) Temperature pollution of discharge water (thermal pollution)	Temperature increase between inlet and outlet; Maximum temperature at the outlet (see footnote 19, on page 27)
			(N) Water consumption for extraction	Water used per ton of uranium mined
			(N) Potential pollution of water resources in case of radioactive contamination	Changes in the quality parameters in near water resources; Volume of tritium leaked into local water supplies
Water	Completion of the RSDSP		(P) Smaller gap between water demand and supply	Unmet water demand
			(N) Potential administrative water losses	Distribution efficiency in the RSDSP
			(N) Lower quality of water after blended with fresh water	Water-quality parameters
	Desalination	Utility-scale systems	(P) Smaller gap between water demand and supply (more available water for other purposes)	Unmet water demand
			(N) Need to process, store, and dispose brine; Potential pollution of water sources	
		User-scale systems	(P) Smaller gap between water demand and supply (more available water for other purposes)	Unmet water demand
			(N) Potential overexploitation of saline or brackish resources (difficulties to control in rural areas)	
	WWTP	Increase of access to sewerage systems	(P) Decrease of potential percolation to groundwater resources (and pollution)	Groundwater quality parameters
			(O) Need of higher capacity of WWTPs	
		Upgrade of WWTPs	(P) Better quality of WWTPs' effluents	Effluents quality parameters
Agricultur	Irrigation efficiency	Switch to high-efficiency systems	(P) Increase of the water productivity	Water productivity
		Removal of distribution losses	(P) Increase of available water (smaller gap between water demand and supply)	Water distribution efficiency

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[32] It can be considered a positive impact if compared to a case with oil extraction, because the overall water consumption would be less.

Table 9 – Potential impacts on Jordanian energy sector by pathway and proposed indicators

Area		**Potential situation**	**Impacts on Energy sector**	
			Potential impact	Proposed indicator[33]
Energy	Fossil fuels	Large dependence on imports	(O) Well known system that has historically provided the required energy resources	Price and price fluctuations of imported fuels; Net production surplus of importing countries
			(N) Energy dependence: impact of external conflicts, volatilities in the oil and gas markets, less energy security	Net import dependence; Shannon index
		Extraction and use of oil shale	(P) Increase of energy independence	Net import dependence
			(N) Relevant energy consumption associated to mining, extraction and processing before final use	Self-consumed energy ratio ($kWh_{extraction}$/$kWh_{generated}$)
	Renewable technologies	Priority for utility-scale systems	(P) Increase of energy independence; Possibility of demand response;	Share of renewable production; Net import dependence again
			(N) Decrease of security of supply due to the intermittence of the sources	Capacity factor; Reserve margin; Grid power quality parameters;
		Promotion of distributed systems	(P) Increase of energy independence	Net import dependence; Share of renewable production;
			(P) Lower transmission & distribution losses	Overall system losses
			(P) Possibility of autonomous system (off-grid), or VPP configuration (aggregated production)	
			(N) Decrease of security of supply due to the intermittence of the sources (if connected to the grid)	Capacity factor; Grid power quality parameters; Supply/Demand (SD) Index
			(N) Potential instability of the national grid (i.e. frequency) if massively connected to the grid	Grid power quality parameters; Power grid stability (see footnote 20, on page 27)
			(N) Uncontrolled over-pumping and over-abstraction	
	Nuclear energy	Reliance on imported uranium	(P) Reduction in volatility of electricity production cost	Fuel/ electricity price volatility
			(P) Strategic energy independence, but dependence on external suppliers	Net import dependence; Uranium import dependence ratio
			(P) Reliable for baseload power needs; higher energy security	Capacity factor; Share of nuclear energy in total primary energy supply
		Extraction of national uranium	(P) Increase of energy independence	Net import dependence; Shannon index
			(N) Energy consumption associated to mining, extraction and processing (refining) of uranium	
Water	Completion of the RSDSP		(P) Potentially, partial energy self-sufficiency through renewable technologies (e.g. hydropower)	Energy self-sufficiency
			(N) Great energy consumption associated (i.e. pumping, desalination, conveyance)	Energy consumption by the water sector
	Desalination	Utility-scale systems	(P) Potential use of brine for pumped-storage hydro	
			(P) Energy supply from waste energy (heat from industry or power plants) or from renewable systems (e.g. PV, solar thermal)	
			(N) High energy consumption	Energy consumption by the water sector
		User-scale systems	(P) Renewable user-scale systems (e.g. PV, solar thermal) can be coupled	
			(N) High energy consumption	Energy consumption by the water sector
	WWTP	Increase of access to sewerage systems	(P) Potentially, more energy to be extracted due to a greater amount of wastewater to treat	WWTPs' energy self-sufficiency
			(N) More energy required to treat the wastewater	Energy consumption by sewage systems (quantity and share within water sector)
		Upgrade of WWTPs	(P) Lower consumption due to higher efficiency of new equipment	Energy intensity ($kWh/m^3_{treated}$); Overall energy consumption by the water sector
			(N) Higher quality of treated water requires a higher amount of energy	WWTPs' energy intensity ($kWh/m^3_{influent\ wastewater}$)
Agriculture	Irrigation efficiency	Switch to high-efficiency systems	(P) Increase of agricultural energy productivity	Energy productivity
			(N) Potential energy intensity increase for former surface irrigated systems (decrease for sprinkler)	Energy productivity; Energy intensity ($kWh_{consumed}/m^3_{used}$)
		Removal of distribution losses	(P) Efficiency increase in terms of energy used to distribute the same amount of water	Energy intensity for water distribution ($kWh_{consumed}/m^3_{released}$)

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[33] Main source: (Sovacool & Mukherjee, 2011)

Table 10 – Potential impacts on Jordanian agricultural sector by pathway and proposed indicators

Area		**Potential situation**	**Impacts on Agriculture sector**	
			Potential impact	Proposed indicator
Energy	Fossil fuels	Large dependence on imports	(N) Exposure of prices of agricultural products to volatilities in the energy markets	Food prices volatility
		Extraction and use of oil shale	(P) Less dependence of prices of agricultural products on oil and gas markets; Less volatilities of food prices	Food prices volatility
			(N) Potential modification or destruction of arable areas; potential contamination of soil or crops (via polluted water)	Decrease of area due to mining activities
	Renewable technologies	Priority for utility-scale systems	(P) Lower emissions and air pollution that can affect (open-air) crops	
			(N) Potential reduction of arable land occupied by renewable generating facilities	Arable land occupied by renewable systems
			(N) Potential reduction of water for irrigation associated to water used for maintenance	
			(N) Potential reduction of natural carbon capture (if green areas are removed)	
		Promotion of distributed systems	(P) Lower emissions, so potential increase of air quality and positive effects on (open-air) crops	
			(P) On-farm use potential (e.g. PV coupled with groundwater pumping and drip irrigation)	Installed capacity of renewable-pumping systems
			(P) Potential use of space under PV plants for high-value crops (e.g. medicinal plants, spinach)	
			(N) Potential reduction of arable land occupied by renewable generating facilities	
			(N) Potential reduction of natural carbon capture (in case of removal of green areas)	
	Nuclear energy	Reliance on imported uranium	(N) Decrease of treated wastewater for irrigation due to the reallocation of effluents from As-Samra WWTP to water-uses in nuclear power plants	
		Extraction of national uranium	(P) Lower dependence of prices of agricultural products on fossil fuels markets	Food prices volatility
			(N) Decrease of treated water available for irrigation due to mining and extraction water consumption)	
Water	Completion of the RSDSP		(P) Smaller gap between water demand and supply; Potential allocation of desalinated water for irrigation purposes	Unmet water demand
			(N) Potential negative effects on crops, soil and groundwater resources due to lower water quality, poor water blending or brine leakages	
	Desalination	Utility-scale systems	(P) Smaller gap between water demand and supply	Unmet water demand
			(N) Potential inappropriate growth of crops due to lack of minerals in case of unsuitable water blending	
		User-scale systems	(P) Smaller gap between water demand for irrigation and water supply	Demand covered by desalination
			(N) Potential inappropriate growth of crops due to lack of minerals, in case of unsuitable water blending	
	WWTP	Increase of access to sewerage systems	(P) Larger volume of treated wastewater to be reused in agriculture; smaller gap between water demand and supply	Amount of treated wastewater and reuse (as an annual growth)
		Upgrade of WWTPs	(P) Higher effluents' quality, lower potential pollution of crops	Water quality parameters
Agricultur	Irrigation efficiency	Switch to high-efficiency systems	(P) Less water consumption for the same irrigated area, hence more water available	Share of efficiently irrigated crops (drip, as % of irrigated crops)
		Removal of distribution losses	(P) More water available for agricultural purposes	

3.2.1 Irrigation efficiency – Switch to high-efficiency systems and distribution losses removal

This pathway is focused on reducing water use in the agricultural sector through the implementation of irrigation systems with higher water-use efficiency, and the reduction of water losses in the distribution system for irrigation. According to the MWI, the water losses attributed to seepage, leakage and operational losses in the irrigation system accounted for 12% in 2015: 181 MCM out of 206 MCM were eventually used for irrigation. The proposal for this pathway is to reduce the water losses in the distribution system for irrigation from 12% to 5%, and to substitute all the non-efficient irrigation systems (i.e. surface and sprinkler) to drip irrigation.

The affected area by the substitution of irrigation system would amount 12 080 ha in total, of which 8 390 ha are located in the LJRB, according to data for 2015. This area would include 6% of total area of field crops (i.e. 8 360 ha in total; 5 640 ha in the LJRB), with the same distribution for national and LJRB levels: 5% surface irrigation and 1% sprinklers. In the case of vegetables, 8% of the cultivated area would be affected (i.e. 3 720 ha in total; 2 750 ha in the LJRB). All the area would correspond to surface irrigation in the LJRB, and at national level 6% would correspond to surface irrigation and 2% to sprinklers (see Figure 20 and Figure 21 on page 32, and Figure 66 and Figure 67 on page 93). Specific information about fruit trees has not been found.

The substitution of surface and sprinklers irrigation systems by more efficient systems (i.e. drip irrigation) would reduce the water that is consumed for irrigation. Due to the lack of data, it has not been possible to estimate these water savings. In any case, a shift to drip irrigation systems would result in a higher water-use efficiency (see Table 30 in Appendix 0), and a higher water productivity ($kg_{product}/m^3{}_{water}$). In turn, the reduction of water losses in the distribution system would increase the water distribution efficiency and would potentially save around 15 MCM/year, based on data from 2015. In both cases, these water 'savings' would be available to be reallocated for other uses and would contribute to closing the gap between water demand and supply.

In terms of energy, a decrease of water losses would imply a lower energy consumption for the conveyance and the distribution of water for irrigation. The implementation of drip irrigation systems would offer different results depending on the former system. In the case of surface irrigated fields, the installation of drip irrigation would increase the energy consumption associated to the pressurization of the system. In contrast, in the case of sprinkler systems, since the operating pressures are similar, the implementation of drip irrigation could reduce the overall energy consumption. Thus, for a same agricultural field, a drip irrigation system would require a lower volume of water than sprinklers (because of a higher water-use efficiency), so the new energy consumption could be lower.

These results show the great potential underlying water inefficiencies, which can be transformed into virtual water supply. This pathway, combined with a monitoring and restrictive strategy for groundwater abstraction, could result in a large overall reduction of water used in agriculture and the increase of groundwater water tables. However, the modernization of the irrigation systems could be limited by the traditional structure of farms. Thus, Jordanian farms are typically small agricultural fields that are cultivated by rural, poor families, and unless a subsidy program is implemented, many farmers could not afford installing and operating efficient irrigation systems due to the investment and energy costs.

3.2.2 WWTP – Increase of access to sewerage systems and upgrade of existing WWTPs

According to the MWI, the access to sewerage systems in Jordan will increase from 63% in 2015 to 80% in 2025. This pathway assumes this projection as true, and also considers the upgrade of existing WWTPs based on less-efficient treatment processes (i.e. WSP, tricking filters, extended Aeration, oxidation ditch and rotation biological contactor) to advanced treatment processes (i.e. activated sludge).

In terms of water, the generated wastewater in Jordan is estimated to increase from 140 MCM in 2015 to 240 MCM in 2025. This increase is attributed to the combined effect of the population growth, a higher access of Jordanian inhabitants to the sewerage systems, and a higher wastewater production per capita. Thus, taking into account population prospects the expansion of the sewerage system will result in new 2.7 million inhabitants gaining access to these services (i.e. from 5.8 million users in 2015 to 8.5 million users in 2018). In turn, according to projections from the MWI the wastewater production per capita will increase from 24.3 m^3/year to 28.3 m^3/year, mainly due to a higher domestic water use and new living standards.

In the case of industrial wastewater, if trends are assumed invariable by 2025, a total of 259 MCM of wastewater will enter Jordanian WWTPs. However, this estimated influent exceeds the current design capacity of Jordanian WWTP (i.e. 218 MCM), and either an extension of existent WWTPs or the construction of new WWTPs will be necessary. If the actual capacity over the design capacity of the Jordanian WWTPs is assumed to be as the average in 2015 in Jordan (i.e. 70% of design capacity), 153 MCM of new capacity will be necessary, to reach 371 MCM of total capacity. According to the latest plans, between 35 and 52.9 MCM of this increase will be covered by the future expansion of As-Samra WWTP.

The upgrade of existing WWTPs will not have a quantitative impact on the water sector, but only qualitative. More advanced treatment processes are expected to result in effluents with a higher quality, and consequently a potentially lower pollution of water resources by discharged effluents from WWTPs.

In terms of energy, a larger volume of wastewater to treat associated to the growth in the access to WWTPs will result in higher electricity consumption associated to wastewater collection, conveyance and treatment. However, a larger volume of wastewater will also result in more energy to be potentially extracted from wastewater (e.g. biogas). In the case of the upgrade of WWTPs, despite specific values for Jordanian WWTP were not available by the date this report was published, values for other countries show an increase of energy requirements with a more advanced treatment process. Using values from USA and Chile (see Figure 9 on page 14) the energy consumption increase associated to the upgrade of WWTPs has been estimated at 4-26%, depending on the energy intensity of the activated sludge systems. Nevertheless, these estimations and actual values could greatly differ, so new calculations with empirical values is advisable.

Finally, in terms of agriculture, more people with access to sewerage systems and better treatments will result in 96 MCM/year of additional treated wastewater to be potentially used for irrigation (i.e. from 133 MCM/year in 2015 to 229 MCM/year in 2025). Furthermore, an extension of the agricultural fields irrigated with treated wastewater will decrease the use of fertilizers due to the nutrients content of treated wastewater (if a proper management is performed), as well as a decrease of negative effects on crops associated to the existence of pollutants in wastewater.

As can be observed, the improvement of sewerage systems bring about numerous benefits with relatively minor negative impacts (e.g. higher energy consumption), not only in WEA nexus sectors. A better service of sanitation systems will reduce health risks on Jordanian population and will potentially decrease environmental impacts (e.g. land and soil contamination). Additionally, following the example of As-Samra WWTP, the upgrade of WWTP could be combined with the integration of on-site technologies into WWTPs, so at least part of the energy requirements could be covered by embedded energy in wastewater. Lastly, improvements on the sewerage systems could result, if properly managed, in a new water source that could contribute to closing the gap between water supply and demand.

3.2.3 Nuclear energy (imported uranium) and completion of the RSDSP

Assuming that the plans from the Jordanian government will be completed, 2 GW of nuclear power will be installed and first phase of the RSDSP will be operating by 2025. The major positive outcome of the nuclear power plant will be in terms of energy, and the main drawbacks will be water-related. In contrast, the RSDSP will provide an additional supply of water to the Jordanian system that will contribute to close the gap between water demand and supply, but the energy requirements will be great. In both cases, there will be potential effects on the agricultural sector and the environment.

In terms of water, the completion of first phase of the RSDSP will provide 65-85 MCM/year of desalinated water. For that purpose, a conveyance system will drive 190-300 MCM/year of seawater from the Red Sea to a RO desalination plant north of Aqaba. Of those 65-85 MCM/year, 30-35 MCM/year will be sent back to Aqaba for domestic water supply and 35-50 MCM/year will be conveyed to southern Israel. In exchange, Israel will transfer about 30 MCM from Lake Tiberias to the Jordanian northern regions at a previously agreed price (SWAP), which will relieve water shortages. About 110-220 MCM/year of remaining brine and seawater will be pumped 180 km and discharged to south of the Dead Sea. Figure 48, in Appendix 0, represents the complete system.

For its part, nuclear power is very water intensive and also presents environmental and safety issues such as radioactive waste storage or potential contamination of water sources (i.e. thermal or/and radioactive pollution). Nuclear is the power-producing technology that withdraws the highest amount of water per unit of energy, in part because has large cooling needs and cannot discharge heat directly into the atmosphere. An estimation based on generic values for water usage[34] in nuclear power plants states that around 100 MCM/year[35] will be necessary for the operation of the 2 GW of nuclear power (see Table 11), mainly required for cooling and for liquid waste dilution. This value exactly matches the projections from MWI in 2012 (see Figure 12), but differs considerably with the latest prospects from the same institution in the National Water Strategy 2016-2025, that reduces this value down to 70 MCM including oil shale demand. The less negative option would be a dry cooling system, but there is no examples for a large nuclear plant.

Table 11 – Estimated annual water use in Jordan by 2GW of nuclear energy (88% capacity factor), in MCM/year and as a percentage of the total volume of treated wastewater in As-Samra in 2016. Source: Own elaboration.

Water use	**Withdrawal**		**Consumption**		**Total**	
	MCM/year	% over As-Samra	MCM/year	% over As-Samra	MCM/year	% over As-Samra
Once-through	2743.0	2469%	23.3	21%	2766.4	2490%
Pond	64.2	58%	35.6	32%	99.8	90%
Tower	64.2	58%	42.0	38%	106.2	96%

According to the plans from the Jordanian government, As-Samra WWTP would provide the necessary water for the operation of the nuclear power plant, despite currently is supplying treated wastewater for agricultural activities. In Table 11, the different water use options are also expressed as a percentage of the total treated wastewater in As-Samra (2016). As can be observed, in any case (i.e. pond or tower as cooling system), the water demand would almost equal the current volume of treated wastewater from As-Samra, so any option will have a great impact in the national water budget.

However, in terms of energy the installation of 2 GW will potentially provide many benefits to the Jordanian energy system, including higher energy independence and less price volatility associated to fossil fuel prices. Thus, nuclear power is a commercially proven and carbon-free electricity supply, and has the lowest use of land per installed capacity: a minimum area of 0.3 km^2/GW and additional 0.1 km^2 if a cooling tower are required. It is reliable for baseload power needs with an annual working period of 7 500-8 000 hours, and the 2 GW are expected to cover 22% of total primary energy supply in Jordan by 2025, which will amount about 15 TWh or approximately 50% of total estimated electricity demand. Furthermore, according to the JAEC the construction of 2 GW of nuclear power will have an additional impact across economic sectors of USD 10 161 million and 7 726 associated jobs, including USD 155 million and 189 new jobs in the electricity and water sectors, and USD 108 million and 168 new jobs in the agriculture sector. Additionally, it is worth noting that, depending on the location of the nuclear power plant, the conveyance of water for the facilities will involve a significant energy consumption. Thus, the location of the nuclear power plant has changed several times, partly due to seismic characteristics of the different proposals, and the latest

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[34] See Table 26 in Appendix C.

[35] The once-through option is not considered as feasible since it surpasses the current national water demand, as well as water demand projections (i.e. 1550 MCM in 2025 according to MWI, (MWI, 2016d)).

selected site is located in Qasr-Amra, in Al-Azraq province, which is 70 km from As-Samra. If eventually the latter location is definitive and As-Samra WWTP supplies the necessary water, the water will be conveyed from the WWTP to Qasr-Amra, which could require a significant amount of energy.

In the case of the RSDSP, even though estimations are unknown due to the uncertain features of the project, it is apparent that the operation of pumping and conveyance systems and the desalination process will require great amounts of energy that will affect the national energy system. Nevertheless, according to the plans the RSDSP will include a hydropower station along the conveyance system, which could supply electricity to cover the energy requirements in the system. The power capacity is also known, but different studios state that the hydrological potential of the 400 meters between Red and Dead Seas can reach 400-800 MW. In case there is any electricity surplus, it could be sent to the national grid.

Regarding the agriculture sector, the nuclear plant will indirectly affect the supply of water used for irrigation in the JV by using effluents from As-Samra WWTP. Thus, a portion of treated wastewater from As-Samra that currently is used for agriculture would be used in the nuclear power plant and consumed in the cooling system. The rest (i.e. around two thirds of the water) could be re-used for a second purpose (e.g. agricultural activities), but the temperature of the water would be higher (see footnote 19 on page 27). The potential effects of this increase should be further evaluated, such as a higher volume of water that could be lost through evaporation (if the distribution canal is open), or changes in the growth of crops.

Finally, the RSDSP will provide 20 MCM/year from the SWAP exchange for agriculture, to be used in irrigation activities. However, apart from positive impacts such as the revitalization of tourism and the industry around the Dead Sea or the restoration of flora and fauna, the operation of the RSDSP will have potential negative changes in the environment and Jordanian natural resources. For instance, since the system will pass through an active fault, seismic activity could cause leakages of brine, resulting in soil, groundwater or crops contamination in the Wadi Araba. Furthermore, the pipeline could disrupt natural ecosystems, and the water with a lower rate of salinity could lead to deposits of gypsum, algal, blooms and microorganisms in the Dead Sea.

As can be seen, this pathway would significantly change the Jordanian system, especially in the terms of energy and water to a lesser extent. In both cases, the final configuration of the projects and the complementary measures will determine their technical feasibility. Thus, the nuclear power plant and the RSDSP would provide large energy and water supplies respectively that would enhance energy and water securities, but the associated water and energy uses, respectively, would make them inappropriate depending on the scenario. For instance, if eventually the RSDSP cannot recover significant amounts of energy to cover its energy needs and the SWAP agreement is not accomplished, the project will be likely unfeasible both technical and economically. Similarly, if the water use associated to the nuclear power plant cannot be reduced, at the same time that an alternative water source can compensate the decrease in water for irrigation coming from As-Samra WWTP, the project will be probably inviable.

4 Conclusion

The study of the Jordanian system has helped understanding the current scenario at all sectors and different levels. This study has highlighted the historical existence of a segmented and uncoordinated sectoral management of the natural resources in Jordan, which has resulted in the unsustainable exploitation of resources. The analysis of nexus interlinkages in the current Jordanian context has shown that reciprocal interconnections between water, energy and agriculture are numerous and strong, and has identified nexus challenges and opportunities to take into consideration for future planning. The existing nexus interlinkages between sectors are set to intensify, and new connections are expected in the future with the socioeconomic development of the country and the effects of climate change and extreme weather conditions. Therefore, there is an imperative need of shifting to a different development model based on coherent, responsible and collaborative planning between sectors. To that end, extensive monitoring and control programs of natural resources are crucial to evaluate the evolution of the nexus interlinkages and the effectiveness of the implemented strategies.

The analysis of As-Samra WWTP as a case study has emphasized the inherent existence of WEA nexus interlinkages at all levels, and serves as a reference example of how a proper integrated management of available resources can take advantage of those interlinkages and result in optimized outputs.

The exploration of future alternative pathways has emphasized the relevance of fostering cross-sectoral communication and planning to achieve successfully a sustainable development. The scarcity of resources in Jordan has arisen as the main limiting factor for a 'self-powered' development, but strategies aiming at providing additional resources might not be the only and most convenient solution for Jordan. Thus, results show that, due to the strong interlinkages between sectors, the obstinate search of new resources can result in a greater unsustainable development of the country. In the long-term new resources might be necessary, but the elimination of inefficiencies and losses and the reduction and reuse of waste can greatly decrease the required amount of additional resources. Furthermore, despite their associated risks, other alternative options such as regional cooperation and an efficient management of shared resources can offer better results and complement national projects to achieve water, energy and agriculture security.

5 Outlook

The present document aims at constituting a first step of a holistic, human rights-based WEA nexus approach in Jordanian context. However, as previously said, the analysis has been limited due to time constraints and data availability. In order to conclude this assessment, an extensive work is necessary to resolve deficient aspects such as inconsistent, incomplete and missing data, and to consider areas of study that have been excluded from this first analysis.

Based on previous studies and publications that had Jordan, the Arab region and nexus approaches as the main focus, the author of this thesis considers advisable to tackle some additional aspects in future work to complete the nexus analysis. The main aspects include climate change effects, an economic analysis of WEA sectors with emphasis on water pricing, a transboundary and intra-region WEA nexus approach (e.g. shared water resources, grid interconnections, agricultural intra-region trade…), and governance, institutional and policy frameworks. A comprehensive analysis including stakeholders at all levels and sectors would be also advisable. This study could be used as a basis for a harmonized work in policymaking to set coherent, common and clear objectives, ease agreement and collaboration between institutions, and achieve optimal results.

A model illustrating different pathways such as those proposed in section 3.2 would be desirable as part of the nexus analysis to provide a more dynamic picture of the nexus interlinkages and their implications at different levels. In order to do so, a comprehensive accounting study in the region to solve data gaps and inconsistent data would be essential. In particular, a water-energy quantitative analysis in the water sector could highlight structural inefficiencies and bottlenecks that would result in great savings and potential changes in the water system.

Finally, a nexus assessment report containing the main outcomes of the analysis would conclude the study. Based on stated priorities from Jordanian government and stakeholders, the main nexus interlinkages and the proposed pathways could be organized by relevance. Based on the results from the model, a full analysis of the most promising nexus alternative could be presented, including a set of actions to help achieving the SDGs.

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Appendices

A. Glossary

Arab states: (also referred to as Arab region) Algeria, Bahrain, Comoros, Djibouti, Egypt, Iraq, Jordan, Kuwait, Lebanon, Libya, Mauritania, Morocco, Palestinian Territory, Oman, Qatar, Saudi Arabia, Somalia, Sudan and South Sudan, Syrian Arab Republic, Tunisia, United Arab Emirates and Yemen (IEA, 2017).

Decentralized green water-infrastructure system (DGWIS): water system that integrates locally available water sources (i.e. rainwater and graywater) with renewable local energy sources to support potable and non-potable water services tailored to meet the needs of the customer (Lee & Younos, 2018).

Energy efficiency (in agriculture): ratio of total energy output from yield (i.e. energy sequestered in the product) to the total energy input required to produce that yield. Energy from the sun is usually not considered in the balance so energy efficiency of a yield should be greater than one (Ahmad & Khan, 2017).

Energy productivity (in agriculture): quantity of marketable yield per unit of input energy, expressed as kg/kWh. It includes all direct and indirect energy inputs that are regularly applied (Ahmad & Khan, 2017).

Food security: physical, social and economic access of all people at all time to sufficient, safe and nutritious food, which meets their dietary needs and food preferences for an active and healthy life (ESCWA, 2015).

Food self-sufficiency: share of food needs met through local products (ESCWA, 2015).

NENA region: (Near East and North Africa) region located in West Asia-North Africa that includes Algeria, Bahrain, Egypt, Iran, Iraq, Jordan, Kuwait, Lebanon, Libya, Mauritania, Morocco, Oman, Palestine, Qatar, Saudi Arabia, South Sudan, Sudan, Syria, Tunisia, United Arab Emirates and Yemen (FAO, n.d.).

Middle East: Bahrain, the Islamic Republic of Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, the Syrian Arab Republic, the United Arab Emirates and Yemen (IEA, 2017).

Pressurized irrigation systems: piped supply of irrigation water at a certain hydrodynamic pressure and controlled flow rate to operate modern irrigation systems like drip or sprinkler (Ahmad & Khan, 2017).

Wadi: dry valley (Bajjali, et al., 2017); small river (AQUASTAT, 2009b).

Water dependency ratio: indicator expressing the part of the water resources originating outside the country (FAO, 2003). This ratio can be calculated as follows:

$$Dependency\ ratio\ (\%) = \frac{IWR}{IRWR + IWR} \cdot 100$$

where: IWR is the total volume of incoming water resources from neighboring countries, and IRWR is the volume of internal renewable water resources.

Water-energy productivity (in agriculture): composite indicator defined as yield per unit of energy and water inputs and expressed as kg/(m^3·kWh) (Ahmad & Khan, 2017).

Water-use efficiency: ratio of water used against crop production, or actual water requirement and the total amount of water applied. It evaluates the performance of an irrigation system (ESCWA, 2015).

Water productivity (in agriculture): ratio between marketable yield and total irrigation water applied to the crop. Usually expressed as kg/m^3, it measures the productive performance of irrigated agriculture (Ahmad & Khan, 2017).

Water scarcity: limited availability, deterioration of quality, restricted recoverability and high cost associated with water resources (Ahmad & Khan, 2017). Renewable annual freshwater supplies below 1 700, 1000 and 500 m^3/person are considered water stress, water scarcity and absolute scarcity, respectively (IEA, 2016).

B. Additional information on As-Samra WWTP

Description of the treatment process[36]

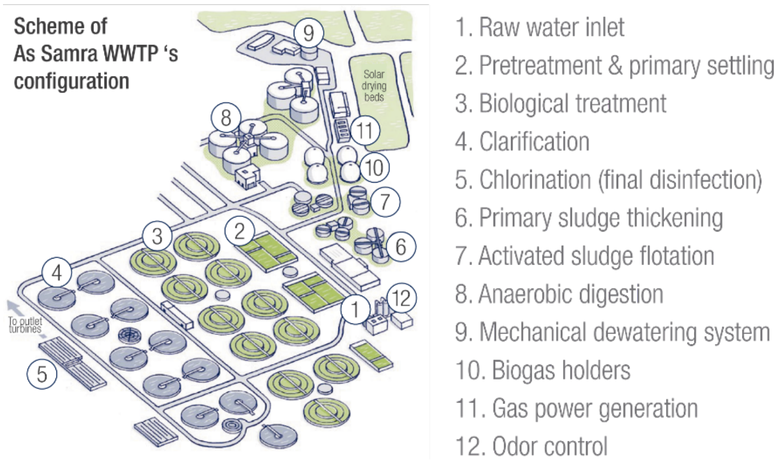

Figure 33 – Scheme of As-Samra WWTP's configuration. Source: Modified from (SUEZ, 2017)

Raw water inlet (1): wastewater from Ain Ghazal pretreatment plant flows through a Ø1 500 mm pipe into two Pelton turbines, producing electricity. Next, the stream joins raw water from Zarqa (West Zarqa) and Hashimiyya (East Zarqa) PSs. The flow is distributed into two grit and sulfide removal tanks.

Pretreatment & primary settling (2): The two grit removal tanks (19.6 m x 13.0 m) have a unit volume of 1 535 m^3 and an average hydraulic residence time (HRT) of 16 minutes. Air enters the bottom of the grit chamber causing heavy particles to settle and is collected by a screw and discharged into the grit classifier. Air bubbles causes scum, oil and grease to float onto the surface. Following wastewater is collected in a scum pit and conveyed to the digesters.

The sulphide removal is carried out via the injection of ferric chloride in the two corresponding tanks. Each tank has two aerated zones in series, and each zone has a capacity of 2 300 m^3. The effluent from the tanks is divided into five primary settling tanks: four tanks of 67 m x 25 m each, and one tank of 80 m x 25 m. These tanks remove around 65% of the TSS and 40% of the BOD_5. The oil and grease are skimmed and collected in the scum chamber (Degrémont - SUEZ, 2008).

Figure 34 – (2) Pretreatment & primary settling (SUEZ, 2017)

Figure 35 – (3) Biological treatment (SUEZ, 2017)

Biological treatment (3): The settled water is then divided into eleven biological reactors (26 200 m^3 each), with three different treatment zones; i.e. two oxic zones and one anoxic zone. (I) Exogenous denitrification in the anoxic zone (V = 6 875 m^3). (II) Carbon removal and nitrification in the oxic zone 1, where air is introduced continuously through air diffusers to remove BOD_5 and initiate nitrification (V= 10 825 m^3). (III) Nitrification in the oxic zone 2, by introducing air intermittently for complete nitrification (V = 8 500 m^3) (Degrémont - SUEZ, 2008).

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[36] Numbers in brackets on the pictures within this subsection follow the numeration from Figure 33.

Clarification (4): The effluent of the activated sludge process is distributed into eleven secondary clarifiers, of Ø54 m each. Biomass and suspended solids are settled and the settled sludge thickened and returned to the anoxic zone of the aeration tanks. Excess sludge is syphoned to flotation units for thickening.

Figure 36 – (4) Clarification (SUEZ, 2017)

Figure 37 – (5) Chlorination (SUEZ, 2017)

Chlorination (5): The clarified effluent of the secondary settling tanks flows to nine plug flow chlorine-contact tanks each with a volume of 3 500 m^3, where partially-treated wastewater will be in contact with chlorine for about 35 minutes for its final disinfection. The effluent is discharged into the Zarqa River and flows to KTR.

Primary sludge thickening (6): From the primary settling tanks the sludge is thickened in six covered circular thickeners, Ø23 m each.

Biological sludge thickening (7): from the aeration tanks the sludge is thickened in five covered Dissolved Air Flotation (DAF) units, Ø18 m each.

Figure 38 – (6 & 7) Thickening (SUEZ, 2017)

Figure 39 – (8) Digestion (SUEZ, 2017)

Digestion (8): The two types of thickened sludge are mixed in two covered tanks of 98 m^3 volume before to be pumped and introduced in seven anaerobic digesters of a capacity of 15 900 m^3 each[37]. In the digesters, Cannon® mixers blend the sludge using the recycled compressed biogas. The sludge stays in the digesters three weeks at 35°C. Heating of the recycled sludge is done by hot water recovered from the cooling of the engines in a shell-tube heat exchanger (SUEZ, 2017).

Dewatering (9): The sludge is then dewatered on sixteen belt-filters press (18% dry solids) (SUEZ, 2017).

Drying: The dewatered sludge is transported to eighteen solar drying beds which cover an area of fifty acres (20.23 ha), to reach 50% dry solids. Lime will be used if necessary for sludge stabilization (Degrémont - SUEZ, n.d.(b)).

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[37] The aeration tanks, secondary settling tanks, and anaerobic sludge digesters tanks are all pre-stressed with the DYWIDAG Strand Tendons (Water-Technology).

Figure 40 – (10) Biogas production (SUEZ, 2017)

Figure 41 – (12) Odor control (SUEZ, 2017)

Next table shows the design parameters for phase 1 of As-Samra WWTP in the inlet (raw water quality) and the outlet (effluent water and sludge quality). Nevertheless, these values have not been corroborated in subsequent, empirical analysis for Phase 1.

Table 12 –Design parameters in Phase 1: Raw water quality (inlet) and effluent water & sludge quality (outlet). Source: (Degrémont - SUEZ, 2008)

Parameter	**Unit**	**Inlet**	**Outlet**
BOD_5	mg/l	652	30
COD	mg/l	1 449	N/A
DO	mg/l	N/A	> 2
TSS	mg/l	551	30
VSS	mg/l	440	N/A
TN	mg/l	130	30
H_2S	mg/l	40	N/A
Grease	m^3/d	30	N/A
F-Coliforms	MPN/100 ml	10^8	< 1 000
Nematodes	eggs/l	5	< 1
Dry Solids	%	N/A	30
Fat, Oil & Grease	mg/l	N/A	< 8
pH	-	N/A	6-9

Jordanian wastewater quality standards

Jordanian standards for reclaimed wastewater regulate both environmental discharges and water reuse. These standards allow discharging treated wastewater to valleys and streams if effluents meet the specified parameters (i.e. DO, COD, TSS, BOD_5, etc.) (Myszograj & Qteishat, 2011).

Next, the main standards and regulations on wastewater management in Jordan are listed, according to WAJ (WAJ, 2010):

- JS 893/2007 – Water – Reclaimed Domestic Wastewater. Jordan Institute for Standards and Metrology (JISM)
- JS 202/2006 – Water – Industrial Wastewater Treatment. JISM.
- JS 1145/2006 - Sludge – Reuse of treated sludge in agriculture. JISM.
- Instructions for disposal of industrial wastewater to sewers public sewer of the year 1998 / Water Authority of Jordan.

However, these versions do not match the published documents (a priori in force) from the Jordan Standards and Metrology Organization (JSMO). Below, the published versions from JSMO are also listed:

- JS 893:2006 – Water – Reclaimed Domestic Wastewater
- JS 202:2007 – Water – Industrial reclaimed waste water
- JS 1145:2016 – Sludge – Uses of biosolid and disposal

No versions free of charge of updated standards have been found to consult, except for a summary table for required quality parameters from JS 893:2006, which is showed below and has been used to compare the effluent values from As-Samra WWTP.

Table 13 – Jordanian wastewater-quality standard in force[38]. Water-Reclaimed domestic wastewater: Standards for discharge of water to streams or wadis or water bodies (JS 893:2006). Source: (Myszograj & Qteishat, 2011)

Indicator	Unit	Water-Reclaimed domestic wastewater (JS 893:2006)
BOD_5	mg/dm^3	60
COD	mg/dm^3	150
DO	mg/dm^3	> 1
pH	-	6-9
NO_3	mg/dm^3	45
TN	mg/dm^3	70
Total phosphate	mg/dm^3	15
TSS	mg/dm^3	60
E. coli	MPN/100 ml	1 000
Nematode eggs	Egg/ dm^3	≤ 1

Table 14 – Coordinates of relevant sites related to As-Samra WWTP. Own elaboration using (Google Inc., 2018).

Site	Latitude (°)	Longitude (°)
As-Samra WWTP	32.154184	36.164033
Ain Ghazal Pretreatment plant	31.983750	35.977006
West Zarqa PS (Zarqa)	32.080566	36.067957
East Zarqa PS (Hashimiyya)[39]	32.133139	36.110311
Water PS - Jordan Water Company Station	32.017892	36.000384

Note: The coordinates were taken by the author using Google maps (Google Inc., 2018) and may thus yield an error.

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[38] JS 893:2006 was inforce by April 2018 according to the JSMO (JSMO, 2018)

[39] In literature, both terms are used to refer to similar locations, but it is not clear if both correspond to the same site. However, in the present document both names are used equally.

C. Additional tables and figures

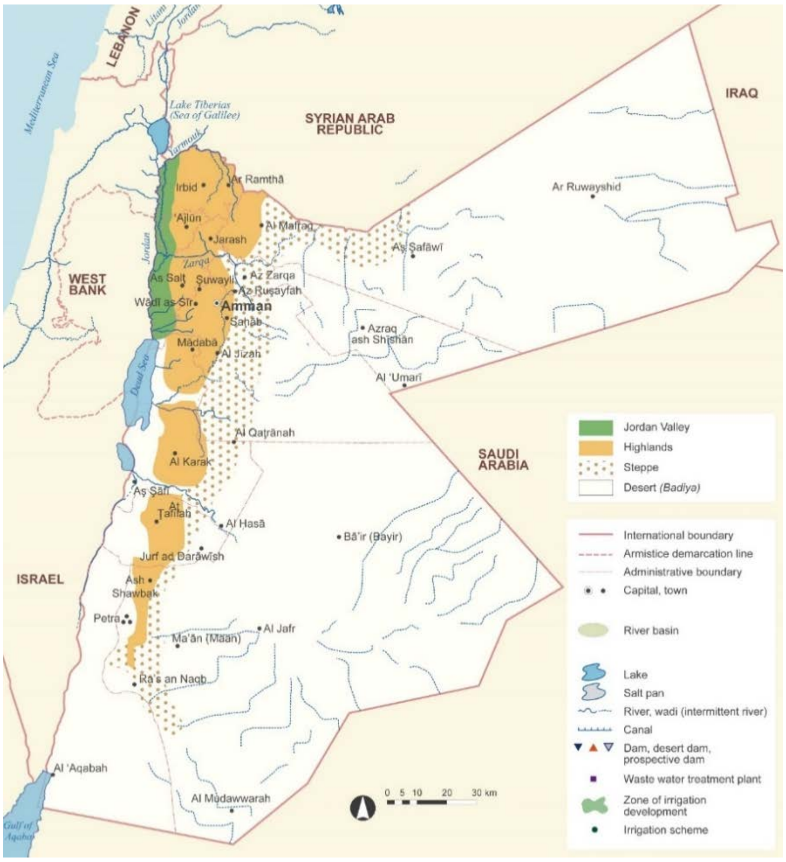

Figure 42 – Map of Jordan – Main cities, administrative and international boundaries and physiographic regions. Source: Own elaboration based on different resources (see Table 31 in Appendix D).

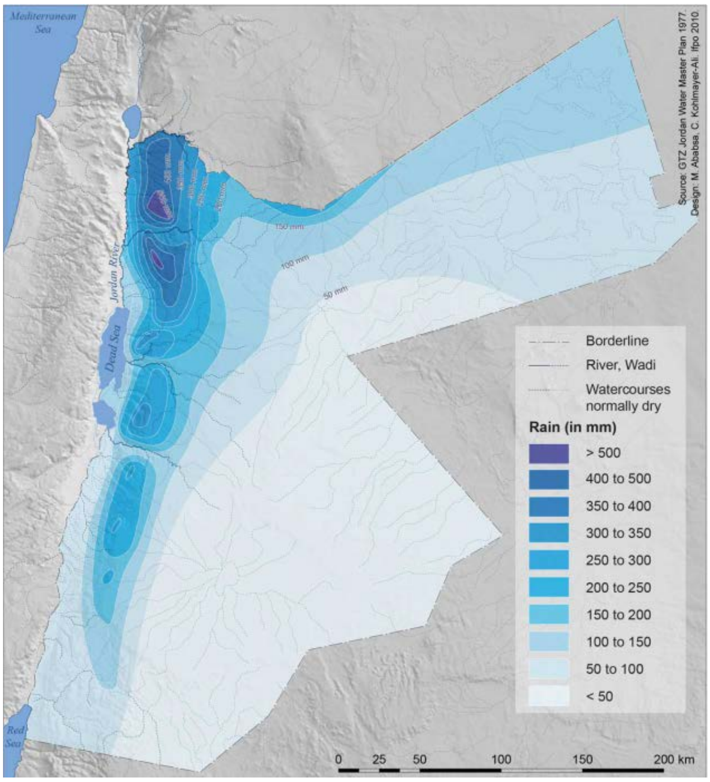

Figure 43 - Jordan average rainfall in Jordan. Source: (Ababsa, et al., 2014)

Table 15 – Surface water basins in Jordan: catchment area, average rainfall and drainage. Source: Own elaboration based on: (MWI as cited in DOS, 2018a; Hadadin, 2015; Rainfall-Runoff Model, 1937/38-2002/03 as cited in Ababsa, et al., 2014)

No	Surface Water Basin					Basin Code	Area (km²)	Average Rainfall (mm/year)	Annual discharge (MCM)
	Basin/Area			Basin Name					
1	Dead Sea Basin	Jordan River Subbasin		Yarmouk		AD	1 438	280	166
2				Amman-Zarqa		AL	3 596	220	84
3				Jordan Valley		AB	621	270	8
4				Jordan Valley Rift Side Wadis	North	AE, AF, AG, AH, AJ, AK	956	490	58
5					South	AM, AN, AP	730	370	58
6		Dead Sea Subbasin	Central Basins	Mujib		CD	6 587	180	102
7				Hasa		CF	2 531	130	43
8				Dead Sea Rift Side Wadis		C	1 470	240	43
9				North Wadi Araba		D	2 923	180	58
10	Eastern Desert Basins			Azraq		F	12 205	85	41
11				Hammad		H	18 576	85	24
12				Sirhan		J	15 693	45	18
13				Jafr		G	12 067	45	13
14	Southern Basins			South Wadi Araba		E	6 334	75	8
15				Southern Desert		K	3 540	15	1
	Total						88 267	100	713

Note: Areas are within the Jordanian Territory. Basin codes according to Figure 44.

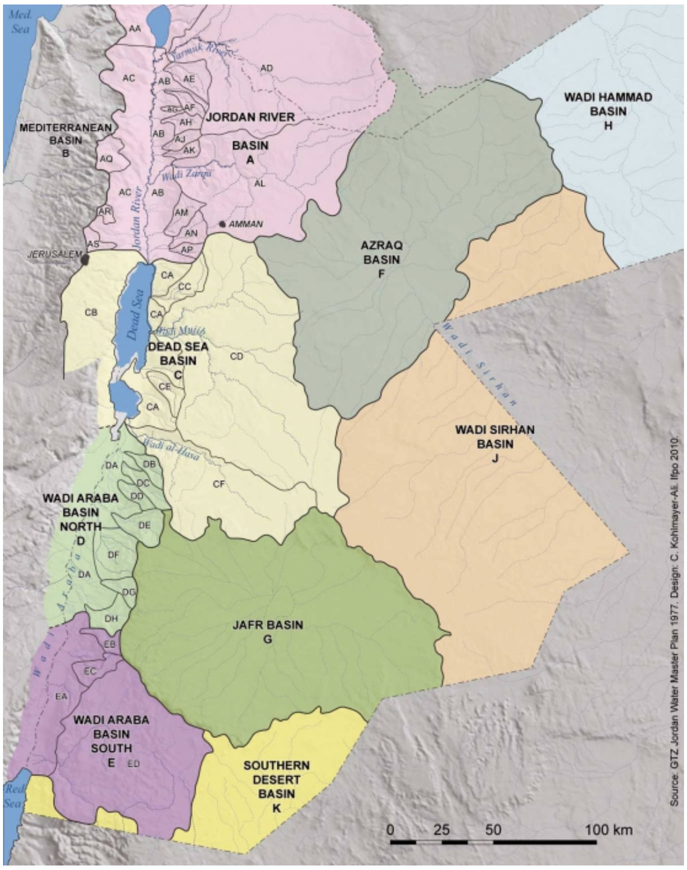

Figure 44 –Main surface-water basins and sub-basins in Jordan. Source: (Ababsa, et al., 2014)

Table 16 – Main characteristics of the Jordan River (Al-Zubari, 2017)

Length	Main tributaries	Basin size	Average discharge	Riparian countries
251 km	Dan, Hasbani, Banias, Huleh valley, Lake Tiberias, Yarmouk	19 839 km² (40)	1.34 BCM/year	Lebanon, Syria, Jordan, Palestine, Israel

Table 17 – Annual flow of resources in MCM (2014-2016). Source: (MWI, 2016a)

Resource	2014	2015	2016
Yarmouk River (to KAC)	16.04	19	7.52
Yarmouk river (to Wehda Dam)	40.47	60.12	79.96
Al Mokhaiba wells	23.81	23.32	23.26
Zaqlab valley	1.8	1.6	1.07
Jarm valley	1.94	2.51	1.94
Kofranja valley	2	2.39	3.88
Rajib valley	1.38	1.46	1.19
Zarka stream	127.51	133.59	139.59
Shuaib valley	6.33	8.97	7.01
Kafreen valley	10.27	15.39	12.17
Hasban valley	3.47	3.96	3.06
Conveyance Pipeline / Tiberius	55.15	48.25	51.87
Other minor northern valleys[41]	2.74	1.5	1.68
Total	**292.92**	**322.06**	**334.2**

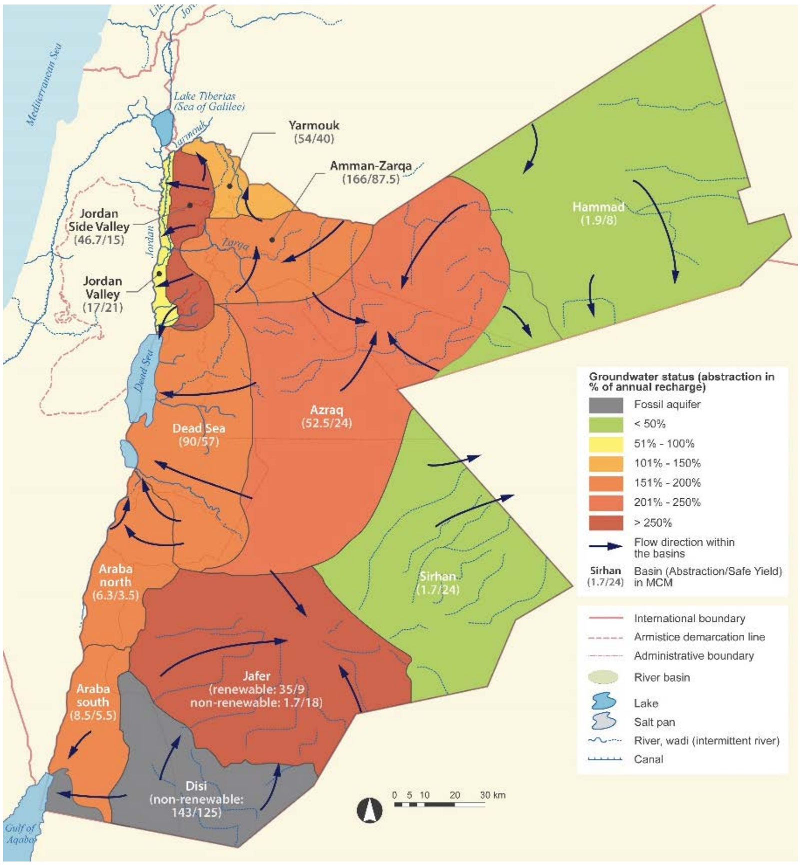

Figure 45 – Groundwater basins and water flows within the basins in Jordan, 2015. Source: Own elaboration based on different sources (see Table 31 in Appendix D)

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[40] According to AQUASTAT, the basin size is 18 500 km² (AQUASTAT, 2009b).

[41] Himma, Waqqas, Abu Zeyad streams, and Rayan valley.

Table 18 – Economic benefit per m^3 of water used, by sector. Source: (DOS, 2014 as cited in MWI, 2016d)

	Agriculture	Tourism	Industry
Financial return (JD/m^3)	0.36	25	40
Job opportunities (person/m^3)	148	1 693	3 777

Table 19 – Distribution of desert dams in Jordan (not complete). Source: (Hadadin, 2015)

Area	Governorate	Dam	Height (m)	Type	Capacity (MCM)
North	Mafraq	Sama Srahan	8	Concrete Face Rockfill	1.7
		Ghadeer Al Bayard	13	Concrete	0.4
		Bourq'u	5	Earth Fill	1
		Al Aqib	15	Earth Fill	1.1
		Dear Kahef	5	Earth Fill / Masonry Wall	0.05
		Al Shalan	3	Earth Fill	0
		Al-Ethna	5	Earth Fill	2.05
		Rouweshed	7	Earth Fill	10
	Irbid	Bowaidah	9.5	Concrete	0.1
Middle	Amman	Swaqa	19	Earth Fill	2.4
		Al Muaqar	10	Earth Fill	0.08
		Yajous	12	Earth Fill	0.2
		Jelat	6	Earth Fill	0.05
	Zarqa	Al-Lahfi	8	Earth Fill	0.4
		Abu Sowwaneh	4	Earth Fill	0.25
		Wadi Rajel	9	Earth Fill	3
		Wadi Al-Esh	8	Earth Fill	0.05
South	Karak	Qatraneh	4	Earth Fill	2
		Al-Sultani	8	Earth Fill	0.08
	Ma'an	Bayer	12	Earth Fill	4
		Juloakh	14	Earth Fill	0.05
		Al Jardaneh	15	Earth Fill	2.3
Total					**31.26**

Table 20 – Examples of desalination plants with PV and wind energy. Source: (Abou-Rayan, et al., 2014, García-Rodriguez 2002, as cited in Lee & Younos, 2018)

Renewable technology	Location	Power (kW)	Desalination technology and source	Plant capacity (m^3/day)
PV energy	Perth, Western Australia	1.2	RO—seawater	2.40–12.10
	Cituis West, Java, Indonesia	25	RO—brackish water	35.99
	Lipari Island, Italy	63	RO—seawater	47.99
	University of Almeria, Spain	23.5	RO—brackish water	59.99
	Fukue City, Nagasaki, Japan	65	RO—brackish water	199.89
Wind energy	Shark Bay, Western Australia	32	RO—brackish water	129.98-167.98
	Ruegen Island, Germany	200	MVC	119.98-299.96

Table 21 – Indicators and targets in the water sector for 2025. Source: (MWI, 2016d)

Goal	Indicator	2014	2025
Enhance water and wastewater services	Energy used per cubic meter billed (kWh/m^3_{billed})	4.31	3.66
	Population with access to water services (%)	94%	95%
	Population with access to a sewage system (%)	63%	80%
Water supply to meet the demand for all uses	Water share per capita (liters/day)	61	105
	Available water resources (MCM/year)	832	1341
	Main dams storage capacity (MCM)	325	400
Water resources sustainability and protection	NRW (%)	52%	30%
	Groundwater over-extraction rate from (%)	160%	140%

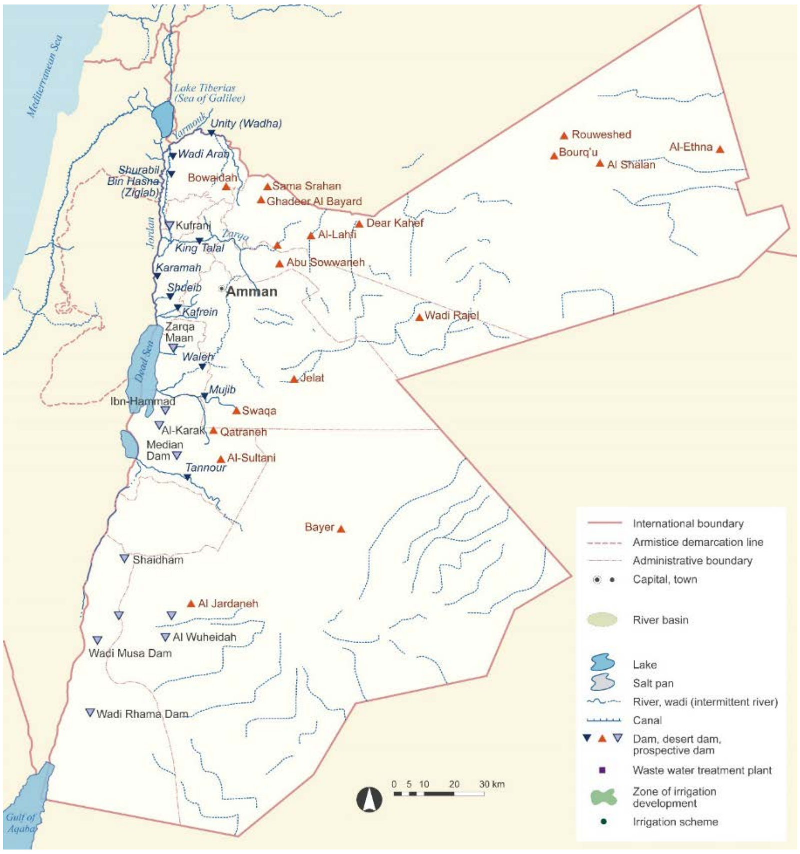

Figure 46 – Dams, desert dams and prospective dams in Jordan. Source: Own elaboration based on different sources (see Table 31 in Appendix D)

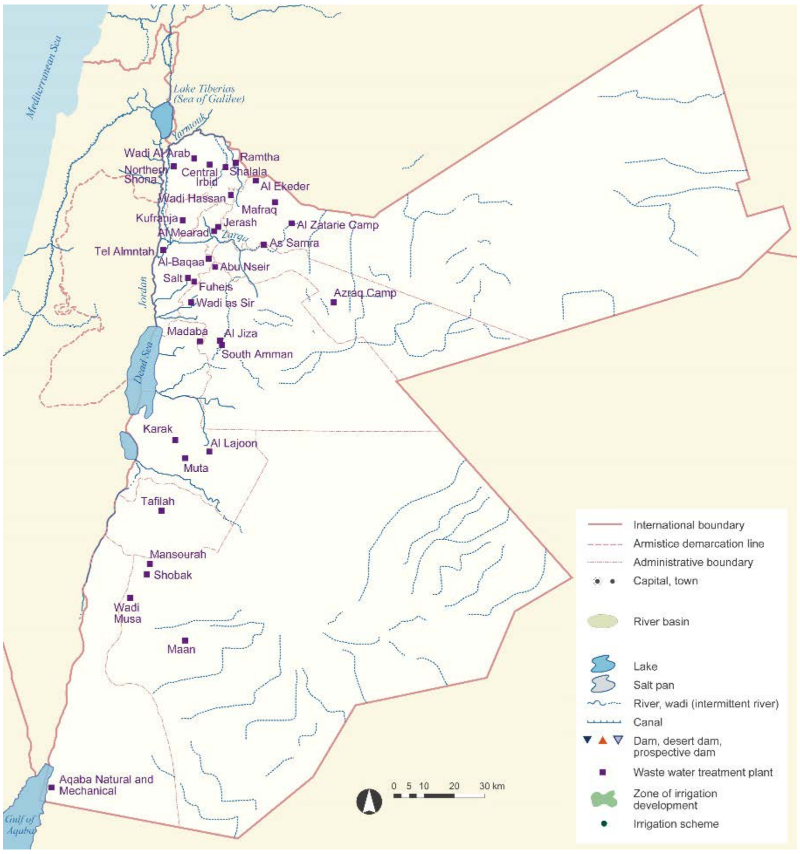

Figure 47 – WWTPs in Jordan, 2016. Source: Own elaboration based on different sources (see Table 31 in Appendix D)

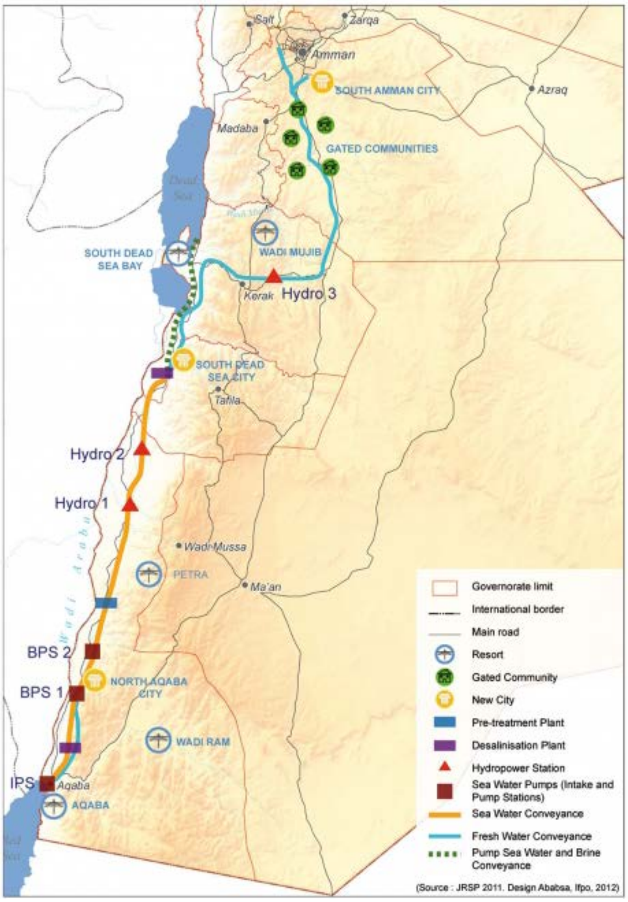

Figure 48 – Red Sea - Dead Sea project. Source: (Ababsa, et al., 2014)

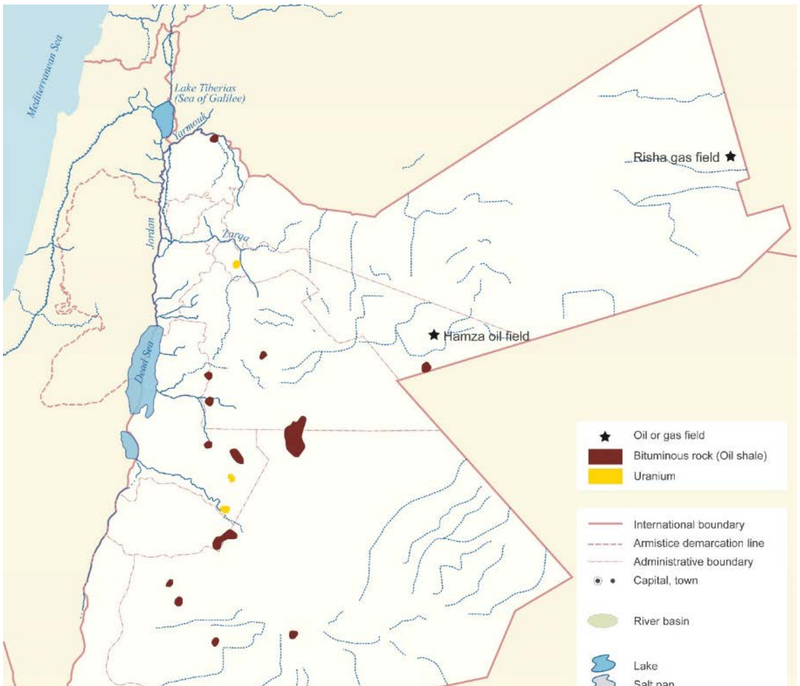

Figure 49 – Mineral energy resources in Jordan. Source: Own elaboration based on different sources (see Table 31 in Appendix D)

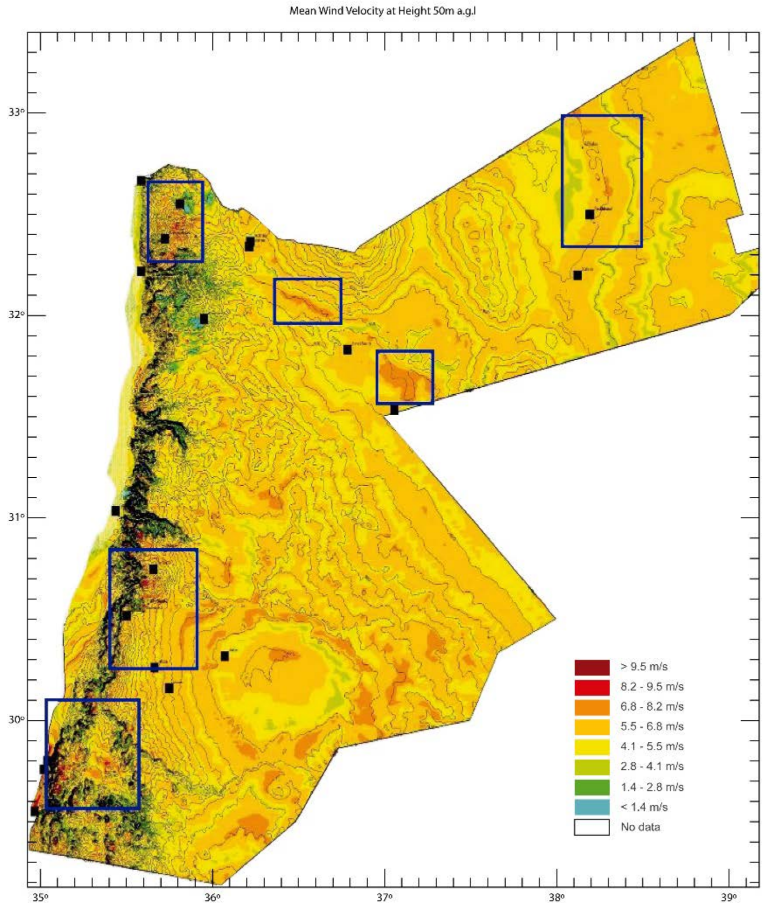

Figure 50 – Wind map of Jordan: mean wind velocity at height 50 m a.g.l. Source: (MEMR, 2016)

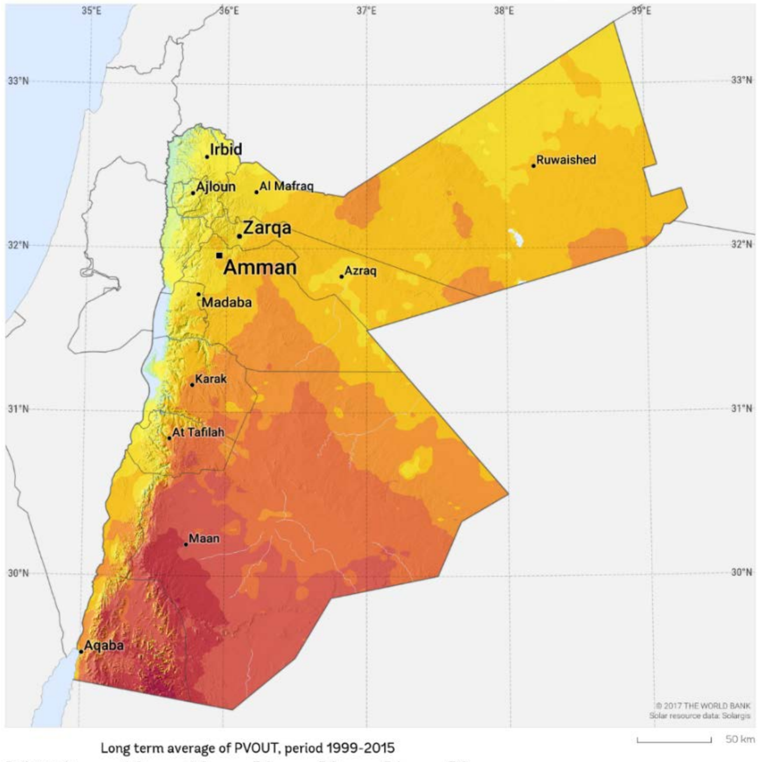

Figure 51 – Photovoltaic power potential in Jordan: Long-term average of PVOUT (1999-2015). Source: (Solargis, 2017)

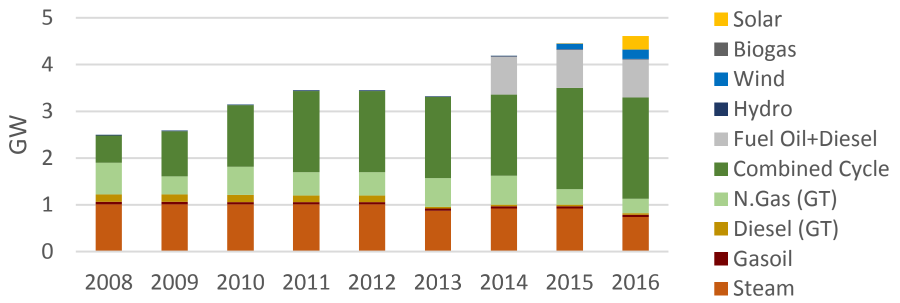

Figure 52 – Total operating capacity in Jordan by production type (electricity sector & industry), 2008-2015. Source: Own elaboration based on data from (MEMR, 2016; NEPCO, 2017)

Table 22 – Significant figures for the electricity sector in Jordan in 2015 and 2016. Source: (NEPCO, 2017)

		2015	**2016**	**Growth (%)**
Peak load (MW)	Summer	3 300	3 165	-4.1
	Winter	3 160	3 250	2.7
Available capacity (MW)	Electricity sector	4 266	4 419	3.6
	Jordan	4 455	4 609	3.5
Produced electricity (GWh)		19 009	19 730	3.8
Consumed electricity (GWh)		16 178	16 843	4.1
Exported electricity (GWh)		50	45	-10.0
Imported electricity (GWh)		604	334	-44.7
Losses (%)*		14.89	13.77	-7.5
Average electricity consumption per capita (kWh)		1 692	1 719	1.6
Electricity fuel consumption (ktoe)		3 992	3 947	-1.1
No. of consumers (thousands)		1 965	2 061	4.9
No. of employees in electricity companies		8 142	8 141	-0.01

* Does not include power station internal consumption

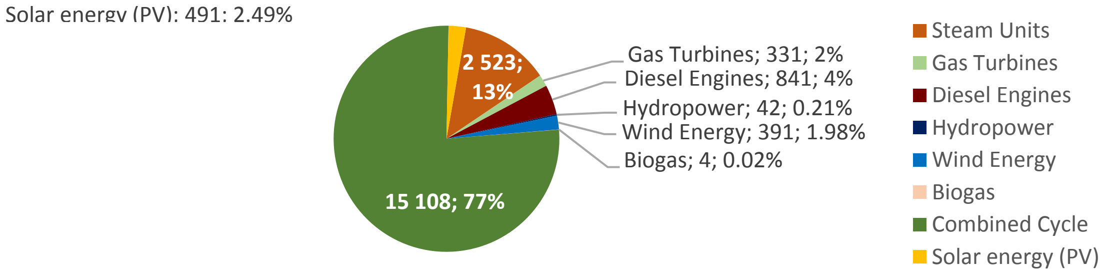

Figure 53 – Electricity production by type of production in Jordan (GWh), 2016. Source: Own elaboration based on data from (NEPCO, 2017)

Table 23 – Significant figures of the national grid in Jordan. Source: (NEPCO, 2017)

		2015	**2016**	**Growth (%)**
Peak load for interconnected systems (MW)	Summer	3 300	3 165	-4.1
	Winter	3 165	3 250	2.7
Available capacity for interconnected systems (MW)		4 266	4 419	3.6
Purchased electrical energy (GWh)		18 541	18 764	1.2
Sold electrical energy (GWh)		18 213	18 447	1.3
Substations Installed Capacities 132/33kV (MVA)		8 665	8 825	1.8
Substations Installed Capacities 400/132/33kV (MVA)		3 760	3 760	0.0

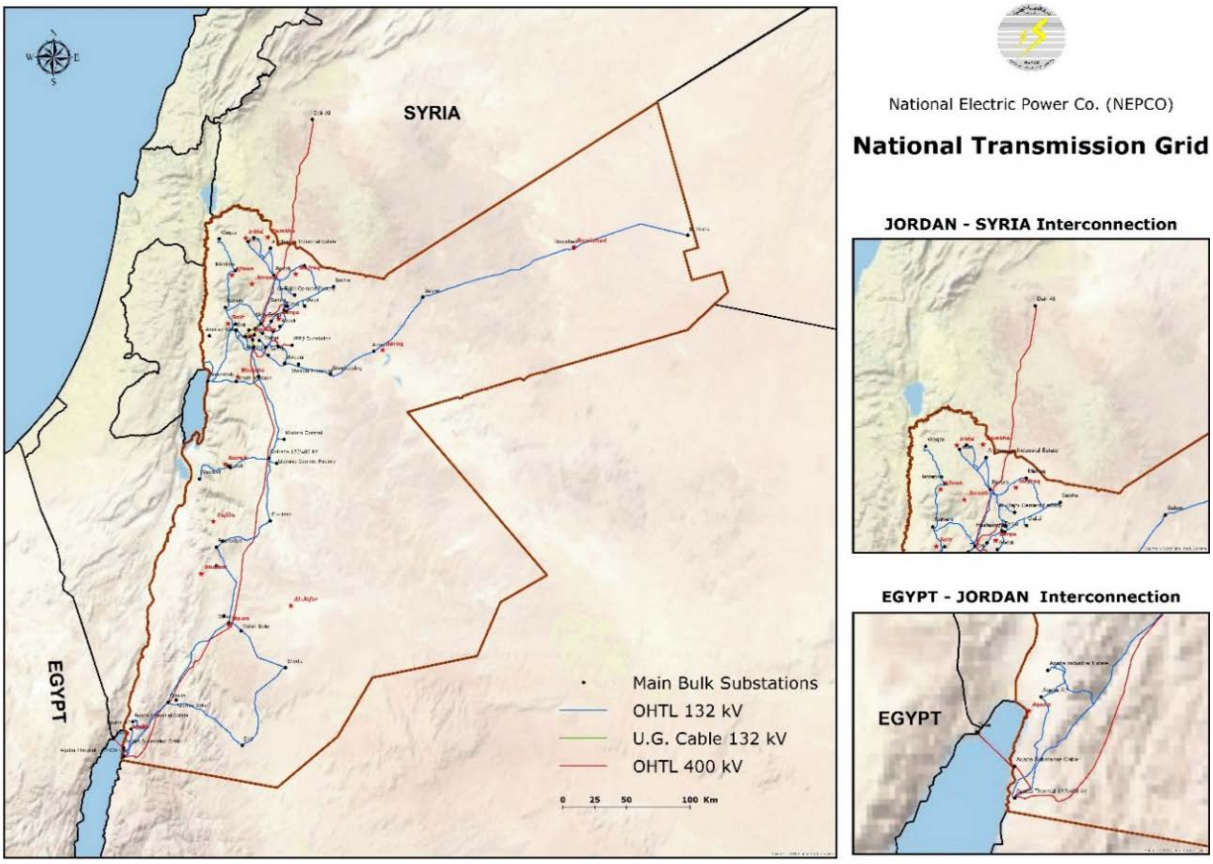

Figure 54 – National transmission grid in Jordan and main international interconnections. Source: (NEPCO, 2013)

Table 24 – Generated and traded electricity and electrical losses by level within the electricity sector. Source: (NEPCO, 2017)

		2013	**2014**	**2015**	**2016**
Production*					
Produced energy	GWh	16 957	17 863	18 516	18 924.1
Sent out energy	GWh	16 341	17 231	17 945	18 415.2
Power station Aux consumption	%	3.63	3.54	3.08	2.69
Transmission					
Purchased energy	GWh	16 719	17 691	18 541	18 764
Sold energy / Bulk	GWh	16 372	17 370	18 213	18 447
Losses	%	2.08	1.81	1.77	1.69
Distribution					
Purchased energy	GWh	15 445	16 305	17 282	17 663
Sold energy / Retail	GWh	13 429	14 057	14 856	15 385
Losses	%	13.05	13.79	14.04	12.90
Total energy losses in the electricity Sector**					
Sent out and imported energy	GWh	16 722	17 666	18 549	18 749
Consumed and exported energy	GWh	14 356	15 121	15 787	16 168
Losses	%	14.15	14.41	14.89	13.77

*Represents Electricity Production Companies **Aux not included

Table 25 – Average operational global water use for power production in liters/MWh. Source: (IEA, 2016)[42]

		Withdrawal	**Consumption**
None	Wind	0.0	0.0
	Solar PV	22.7	22.7
Dry	Geothermal	155.2	0.0
	CSP	295.3	295.3
Hybrid	CSP	1 287.0	1 287.0
Once-through	Bioenergy	132 489.5	1 135.6
	Coal SC/USC	87 064.5	378.5
	Coal Subcritical	132 489.5	946.4
	Gas CCGT	27 255.0	378.5
	Nuclear	177 914.4	1 514.2
	Oil (Steam)	49 448.9	37.9
Pond	Bioenergy	1 703.4	1 476.3
	Coal Subcritical	37 854.1	2 801.2
	Coal SC/USC	56 781.2	159.0
	Gas CCGT	22 712.5	908.5
	Gas (Steam)	1 022.1	1 022.1
	Nuclear	4 164.0	2 309.1
	Oil (Steam)	63 292.1	359.6
Tower	Bioenergy	3 323.6	2 093.3
	Bio CHP	3 323.6	1 048.6
	Coal generic with CCS	4 921.0	3 406.9
	Coal IGCC	1 476.3	1 211.3
	Coal IGCC with CCS	2 422.7	2 082.0
	Coal SC/USC	2 271.2	1 892.7
	Coal Subcritical	2 498.4	2 006.3
	CSP	3 634.0	3 369.0
	Gas CCGT	946.4	794.9
	Gas CCGT with CCS	1 930.6	1 438.5
	Gas CHP	946.4	749.5
	Gas (Steam)	4 542.5	2 763.4
	Geothermal	1 741.3	1 741.3
	Nuclear	4 164.0	2 725.5
	Oil (Steam)	1 241.6	359.6

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[42] The link to the Appendix in the WEO 20116 (IEA, 2016) that contains the information included above was corrupt as of the date of this document, and was provided via email on May 15th 2018 by Mrs. Walton, Molly A., energy analyst in the IEA.

Table 26 – Existing dams in Jordan[43]: main characteristics. Source: Own elaboration based on: (AQUASTAT, 2009b; Hadadin, 2015; MWI, 2016b; DOS, 2018a)

Dam	**Location, nearest city**	**River / Wadi**	**Catchment Area**	**Dam Type**	**Start of Operation**	**Capacity**				**Annual Evap.**	**Dimensions**				**Initial Cost[44]**	**Purpose**
						Total	Dead	Life	Reservoir Area		Height[45]	Length	Width	Body Volume		
			km^2			MCM	MCM	MCM	km^2	MCM/a	m	m	m	MCM	10^6 JD	
King Talal*	Eastern Heights, Jarash	Zarqa	3 700	EF	1977, raised in 1987	86	11	75	2.8	4.3	108	350	11.5	5.7	34	I, E, F,N
Wadi Arab*	JV, Irbid	Wadi Arab	262	EF	1986	20	3.2	16.8	0.8	1.5	83.5	434	8.5	3.1	20	I, M, Ind, E[46], F, N
Kafrein*	JV, Al-Balqa	Wadi Al-Kafrein	163	EF	1967, raised in 1997	8.5	0	8.5	0.8	1.5	37	552	6	2.1	9.3	I, R, F, O
Shuaib*	JV, Al-Balqa	Wadi Shauib	178	EF	1969	2.3	0.9	1.4	0.3	0.6	32	730	5	0.9	0.56	I, R, F, O
Ziglab*[47]	JV	Wadi Ziglab	106	EF	1967	4.3	0.3	4.0	0.3	0.56	48	745	6	1.35	0.9	I , M, Ind, F
Karameh*	JV, Al-Balqa	Wadi Al-Mallahah	61.2	EF	1997	55	0	55	5	N/A	44.5	2150	10	11	55	I, D, Recr, F
Tannur	Taffaila	Wadi Al-Hassa	2 160	RCC	2001	16.8	0	16.8	0.84	N/A	60	270	8	0.215	23.3	I , Ind
Mujib	Karak	Wadi Mujib	4 380	RCC, EF	2003	31.2	1.4	29.8	1.98	N/A	62	720	9	0.72 RCC, 1.0 Fill	50	I , M, Ind
Wala	Madaba	Wadi Wala	1 770	RCC, EF	2003	9.3	1.1	8.2	0.86	N/A	45	480	9	0.205 RCC, 7.0 Fill	25	I , M, Ind, R
Al Wehdah (Unity)*	Yarmouk / Irbid	Yarmouk River	5 000 (1 200 in Jordan)	RCC	2006	110	5	105	3.75	N/A	86	485	7.2	1.43	80	I , M, Ind, F, O, H[48]

Location, nearest city: *JV* = Jordan Valley; Dam type – *EF* = Earth Fill, *RCC* = Roller Compacted Concrete; Purpose: *D* = Desalination, *E* = Electricity, *F* = Flood protection, *I* = Irrigation, *Ind* = Industrial, *M* = Municipal, *N* = Navigation, *O* = Other, *R* = Recharge, *Recr* = Recreation

* Located in the LJRB

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[43] In this table, only dams with a height of more than 15 meters according to the International Commission on Large Dams (ICOLD).

[44] Initial cost refers to the construction cost of the dam.

[45] Height, length and width measured at the crest of the dam.

[46] Information on hydropower capacity is scarce and old, so can be assumed that is no longer available. Latest values state 375 kW of capacity, including hydro-pumping (Murakami, 1995)

[47] Also referred to as Shurabil Bin Hasna.

[48] According to the agreement between Syria and Jordan, Jordan would receive 75% of the water stored, and Syria would receive all of the hydropower production (AQUASTAT, 2009b)

Table 27 – Wastewater treatment plants in Jordan. Source: Own elaboration based on data from (MWI, 2016a; MWI, 2017; El-Rawy, et al., 2016; Salahat, et al., 2017; DOS, 2018a)

Plant name	**Alternative name**	**Service Governorate**	**Year of operation**	**Design flow (m^3/day)**	**Average influent (m^3/day)**			**Sludge (m^3/day)[49]**	**Treatment system**	**BOD5 design**
					2013	2015	2016			
Aqaba-Natural	Aqaba WSP	Aqaba	1987	9 000	6 730.6	6 699	7 618	150	WSP	900
Aqaba-Mechanical		Aqaba	2005	12 000	9 845.5	12 475	12 056	232	AS [EA]	420
Albaqaa (Baqa')	Ein Al Basha	Amman, Balqa	1987	14 900	10 209	11 862	13 070	250	Maturation pond [TF]	800
Fuhais and Mahis	Fuhis; Fuheis	Amman, Balqa	1997	2 400	2 221	2 719	2 859	16	AS	995
Irbid the Central		Irbid	1987	11 023	8 132	8 143	8 915	210	AS	800
Jerash East		Jerash	1983	9 000	3680.8	-	-	100	AS [OD]**	1 090
Al Mearad	Al-Maraad		2011	10 000	1 000	6 268	5 651	24	AS	800
Karak		Karak	1988	5 500	1 753.4	1 408	1 384	10	Maturation pond [TF]*	800
Kafranja	Kufranja	Ajloun	1989	9 000	2763	2 506	3 027	60	TF /AS	850
Madaba		Madaba	1989, 2005	7 600	5 172	6 557	7 176	250	AS***	950
Natural Mafraq	Mafraq	Mafraq	1988	6 050	2008.8	3 557	3 556	47	WSP	825
Ma'an		Ma'an	1989, 2009	5 772	3 170.8	2 288	2 485	100	AS [EA]	700
Abu Nasir	Abu-Nusier	Amman	1986	4 000	2 570.8	3 201	3 304	60	AS/RBC	1 100
Ramtha		Irbid	1987, 2008	7 400	3 488.3	4 743	4 256	100	AS***	1 000
Salat	Salt; Sult; As Salt	Balqa	1981	7 700	5 290.7	7 407	8 398	130	AS [EA]	1 090
Tafilah	Tafila, Tafiela	Tafila	1988	7 500	1 380	1 450	1 327	8	AS [TF]	1 050
Wadi Al Arab	Wadi Arab	Irbid	1999	21 000	10 264	12 880	12 770	240	AS [EA]	995
Wadi Hassan		Irbid	2001	1 600	1 131.8	1 594	1 471	40	AS [OD]	800
Wadi Musa	Wadi Mousa	Ma'an	2000	3 400	3 028.9	2 628	2 613	100	AS [EA]	800
Wadi Al Seer (Essir)	Wadisseer	Amman	1997	4 000	3 623.9	5 040	4 881	86	WSP [Aeration lagoon]*	780
Akeedar	Akadeer; Alekeder	Mafraq	2005	4 000	3 907.8	1 918	1 943	92	WSP	1 500
Al Lajoon	Lajjoun	Karak	2005	1 200	853.1	595	696	20	WSP	1 500
Tel Almntah	Tall-Mantah	Balqa	2005	400	300	358	383	7	TF/AS	2 000
Al Jeezah	Al-Jiza; Giza	Amman	2008	4 500	703.9	773	737	17	AS	800
Shobak	Shoobak	Ma'an	2010	350	100	92	102	2	WSP	1 850
Al Samra (As-Samra)	Khirbet As-Samra	Amman, Zarqa	1984, 2008	364 000	230 606	294 862	304 357	3 000	AS***	650
Mansoura/Shobak	Mansorah	Ma'an	2010	50	15	15	-	0.4	AS [WSP]	
South Amman		Amman	2015	52 000	-	5 436	9 939	-	AS	750
Shalala	Wadi Shallaleh	Irbid	2014	13 700	-	6 070	6 870	-	AS	762
Muta, AlMazar, Adnaniyah	Mu,ta; Mu'tah	Karak	2014	7 060	-	1 228	1 124	-	AS	
Northern Shona	North Shouneh	Irbid	2015	1 200	-	777	683	-	WSP	1 200
Al zatarie camp	Zatari		2015	3 500	-	964	1 716	-	MBR+TF	1 130

AS = Activated Sludge, *WSP* = Waste Stabilization Ponds, *EA* = Extended Aeration, *TF* = Trickling filter, *OD* = Oxidation Ditch, *RBC* = Rotation Biological Contactor

* Converting to mechanical; ** Under development; *** Converted from natural to mechanical; Note: treatment systems in square brackets from (Salahat, et al., 2017).

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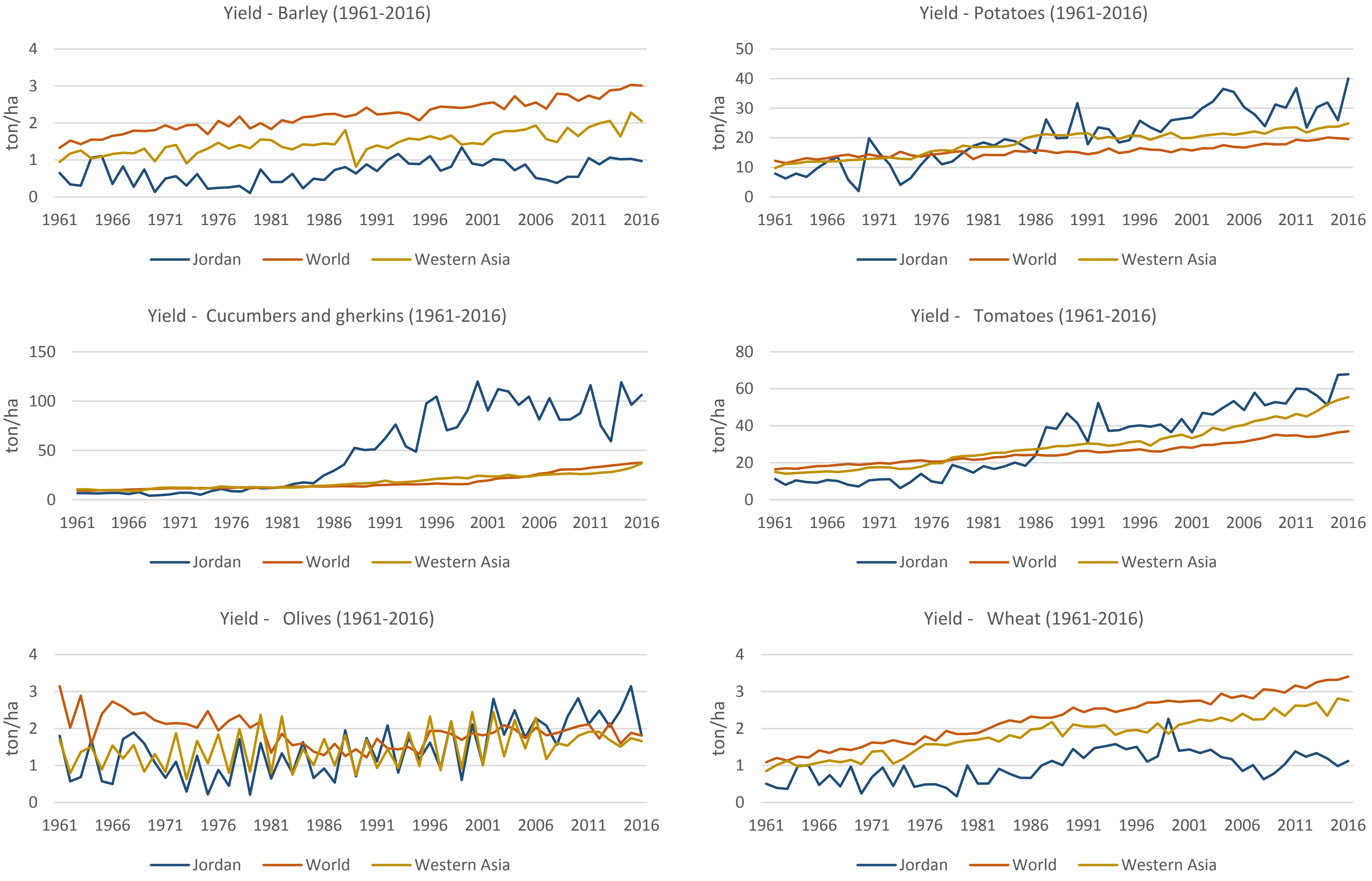
[49] Values from: (Salahat, et al., 2017). Not confirmed if they correspond to design values or historical values for liquid sludge (m^3/day) from 2013.

Table 28 – Harvested area by type of crop and region in Jordan, 2015. Source: Own elaboration based on data from (DOS, 2018b)

	Field crops			**Vegetables**			**Fruit trees**			**Total**		
	1000 ha	% over Jordan	% over LJRB	1000 ha	% over Jordan	% over LJRB	1000 ha	% over Jordan	% over LJRB	1000 ha	% over Jordan	% over LRJB
Jordan	71.2	100%		48.8	100%		86.4	100%		206.4	100%	
LJRB	48.3	68%	100%	38.1	78%	100%	75.2	87%	100%	161.7	78%	100%
JV	2.7	4%	6%	19.9	41%	52%	9.5	11%	13%	32.1	16%	20%
Amman	12.1	17%	25%	1.7	3%	4%	8.6	10%	11%	22.4	11%	14%
Balqa	0.5	1%	1%	1.3	3%	4%	4.1	5%	5%	6.0	3%	4%
Zarqa	3.7	5%	8%	3.7	8%	10%	10.4	12%	14%	17.8	9%	11%
Irbid	12.4	17%	26%	2.9	6%	8%	16.7	19%	22%	32.0	16%	20%
Mafraq	14.2	20%	29%	6.8	14%	18%	14.5	17%	19%	35.5	17%	22%
Jarash	1.0	1%	2%	1.3	3%	3%	7.4	9%	10%	9.7	5%	6%
Ajloun	1.7	2%	3%	0.5	1%	1%	4.0	5%	5%	6.2	3%	4%

Table 29 – Production by type of crop and region in Jordan, 2015. Source: Own elaboration based on data from (DOS, 2018b)

	Field crops			**Vegetables**			**Fruit trees**			**Total**		
	1000 ton	% over Jordan	% over LJRB	1000 ton	% over Jordan	% over LJRB	1000 ton	% over Jordan	% over LJRB	1000 ton	% over Jordan	% over LJRB
Jordan	349	100%		2 047	100%		621	100%		3 018	100%	
LJRB	243	70%	100%	1 538	75%	100%	534	86%	100%	2 316	77%	100%
JV	50	14%	21%	902	44%	59%	212	34%	40%	1 163	39%	50%
Amman	12	4%	5%	68	3%	4%	27	4%	5%	107	4%	5%
Balqa	1	0%	0%	65	3%	4%	21	3%	4%	88	3%	4%
Zarqa	40	12%	17%	111	5%	7%	34	5%	6%	185	6%	8%
Irbid	18	5%	7%	54	3%	3%	78	12%	15%	149	5%	6%
Mafraq	119	34%	49%	301	15%	20%	104	17%	19%	523	17%	23%
Jarash	2	0%	1%	27	1%	2%	19	3%	4%	48	2%	2%
Ajloun	2	0%	1%	12	1%	1%	39	6%	7%	53	2%	2%


Yield - Barley (1961-2016)

Yield - Potatoes (1961-2016)

Yield - Cucumbers and gherkins (1961-2016)

Yield - Tomatoes (1961-2016)

Yield - Olives (1961-2016)

Yield - Wheat (1961-2016)

Figure 55 – Yield for main crops in Jordan in 1961-2016, for Jordan, Western Asia and World average. Source: Own elaboration based on (FAOSTAT, 2017a)

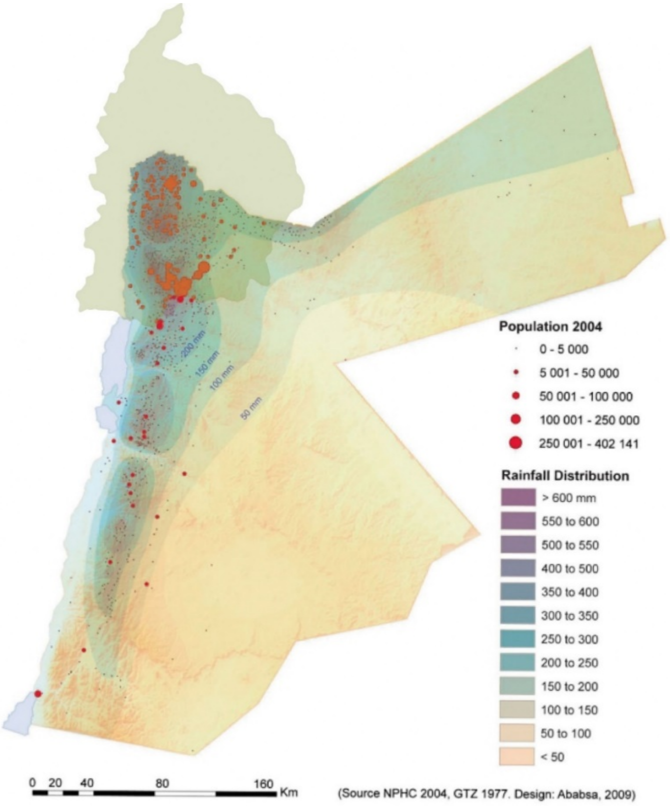


Figure 56 – Correlation between rainfall and population distribution in the LJRB. Source: Modified from (Ababsa, et al., 2014; AQUASTAT, 2009b).

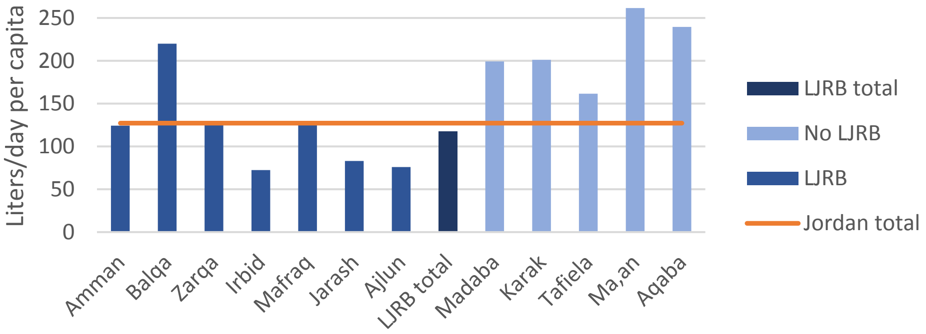


Figure 57 – Water supply per capita in Jordan by Governorate, 2015. Source: Own elaboration based on data from (MWI as cited in DOS, 2018a)

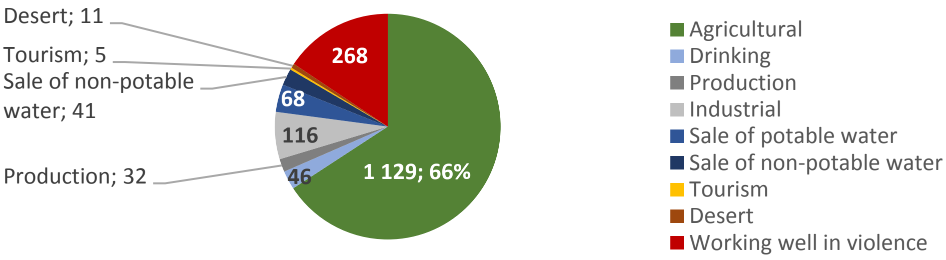


Figure 58 – Number of working wells in the LJRB by sector, 2015. Source: Own elaboration based on data from (MWI, 2016a)

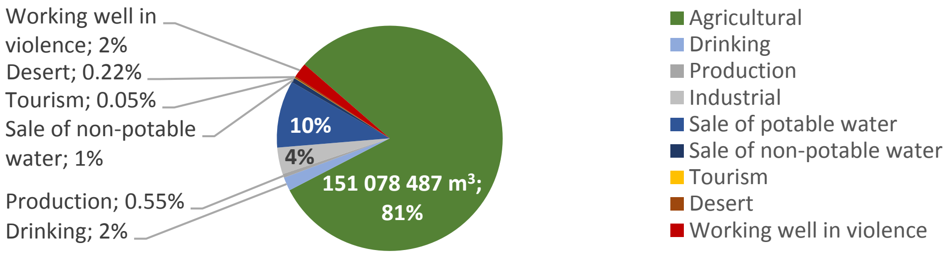


Figure 59 – Extracted amount from wells in the LJRB by sector, 2015. Source: Own elaboration based on data from (MWI, 2016a)

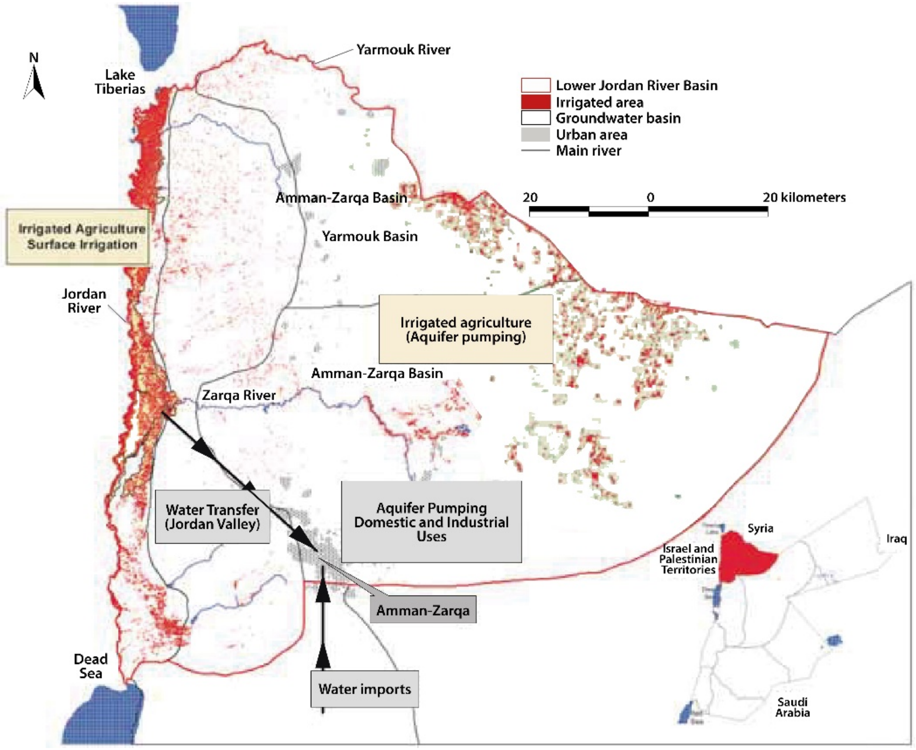


Figure 60 – Main water uses, water flows and agricultural areas in the LJRB in Jordanian territory. Source: Modified from (Venot, et al., 2007)

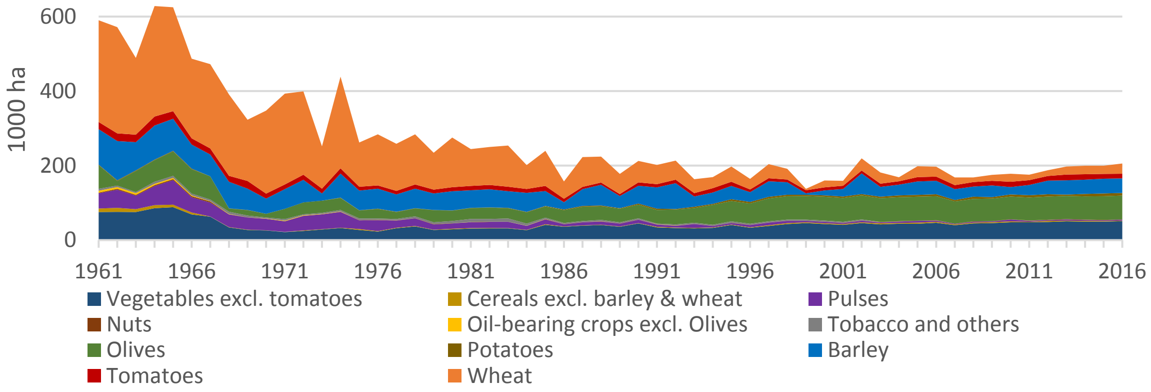


Figure 61 – Harvested area in Jordan (1961-2016). Source: Own elaboration based on data from (FAOSTAT, 2017a)

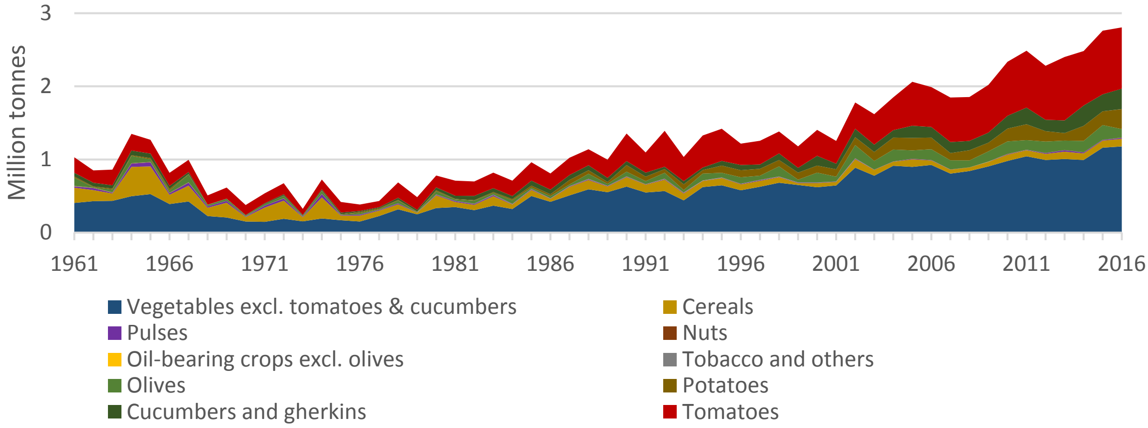


Figure 62 – Crops production in Jordan (1961-2016). Source: Own elaboration based on data from (FAOSTAT, 2017a)

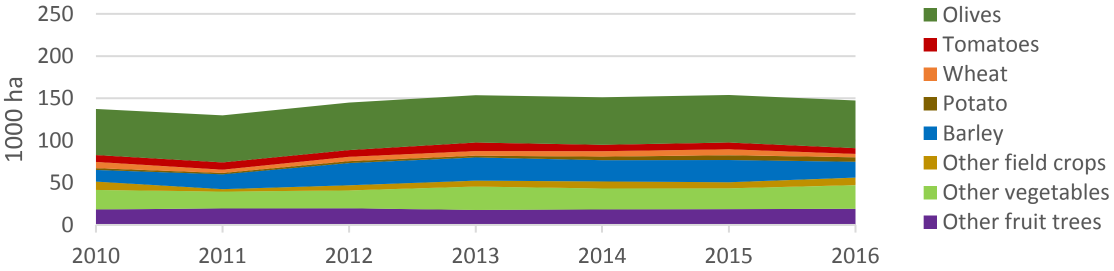


Figure 63 – Harvested area by main crops in the LJRB, 2010-2016. Source: Own elaboration based on (DOS, 2018b)

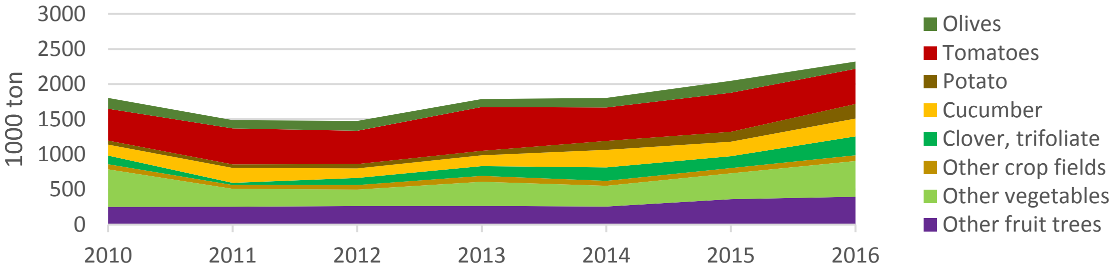


Figure 64 – Production by main crops in the LJRB, 2010-2016. Source: Own elaboration based on (DOS, 2018b)

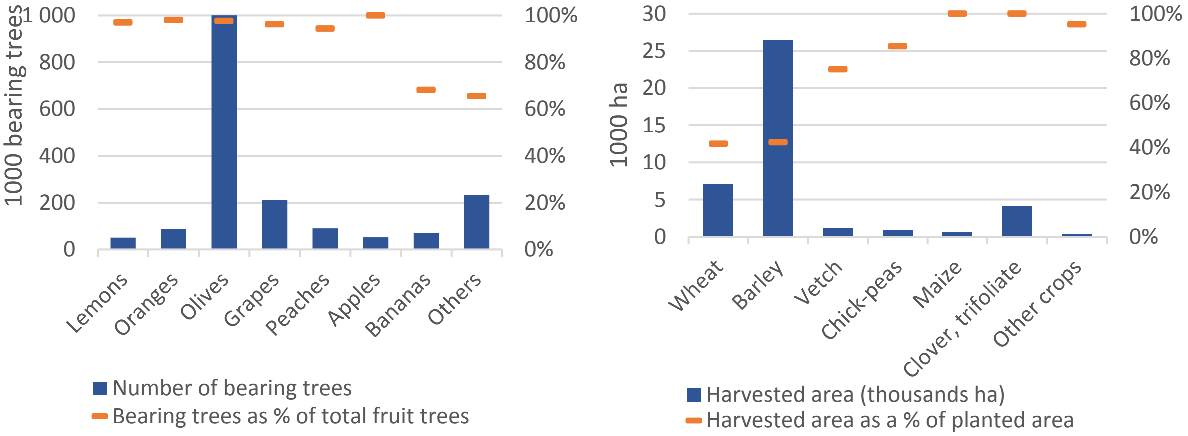


Figure 65 – Harvested area by main field crops (left), and bearing trees by type of main fruit trees (right). LJRB, 2015. Source: Own elaboration based on data from (DOS, 2018b)

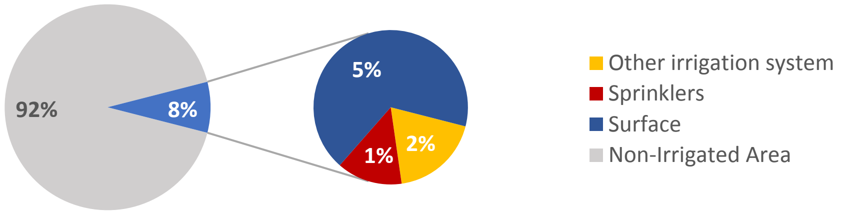


Figure 66 – Cultivated area with field crops by type of irrigation in the LJRB, 2015. Source: Own elaboration based on data from (DOS, 2016)

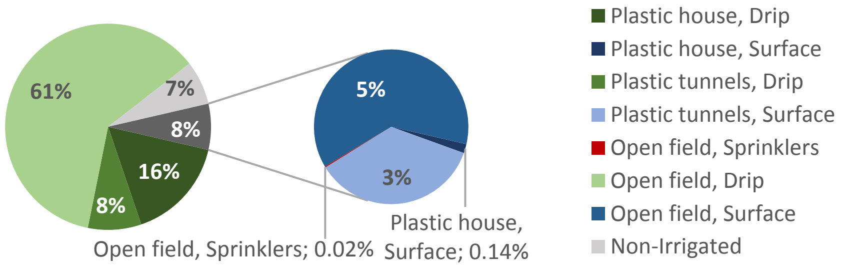


Figure 67 – Cultivated area with vegetables by type of irrigation in the LJRB, 2015. Source: Own elaboration based on data from (DOS, 2016)

Table 30 – Example of farm and field irrigation application efficiency and attainable efficiencies. Source: (Howel, 2008)

	Field efficiency (%)			**Farm efficiency (%)**		
Irrigation method	Attainable	Range	Average	Attainable	Range	Average
Surface						
Graded furrow	75	50-80	65	70	40-70	65
w/tailwater reuse	85	60-90	75	85	-	-
Level furrow	85	65-95	80	85	-	-
Graded border	80	50-80	65	75	-	-
Level basins	90	80-95	85	80	-	-
Sprinkler						
Periodic move	80	60-85	75	80	60-90	80
Side roll	80	60-85	75	80	60-85	80
Moving big run	75	55-75	65	80	60-80	70
Center pivot						
Impact heads w/end gun	85	75-90	80	85	75-90	80
Spray heads wo/end gun	95	75-95	90	85	75-95	90
LEPA* wo/end gun	98	80-98	95	95	80-98	92
Lateral move						
Spray heads w/hose feed	95	75-95	90	85	80-98	90
Spray heads w/canal feed	90	70-95	85	90	75-95	85
Microirrigation						
Trickle	95	70-95	85	95	75-95	85
Subsurface drip	95	75-95	90	95	75-95	90
Microspray	95	70-95	85	95	70-95	85
Water table control						
Surface ditch	80	50-80	65	80	50-80	60
Subsurface drain lines	85	60-80	75	85	65-85	70

* *LEPA* stands for Low Energy Precision Application.

D. Bibliography of maps

Some of the maps that have been included in this study were created based on preexisting resources that were used as a reference and adapted for optimal results. Each source provided different information, which was superimposed and integrated with the rest to create a new map. For that reason, the results may not be totally accurate, since any potential error or inaccuracies in the sources may have been accumulated. Below, Table 31 includes the sources that have been used by type of information, and Table 32 specifies the used sources in each of the maps that have been created for this document.

Table 31 – Bibliography of the contents included in the maps

	Sources
Administrative national boundaries (Governorates)	(University of Texas Libraries, 2004)
Cities (Jordan and surrounding countries)	(AQUASTAT, 2009b)
Dams	(Fanack Water, 2016; Hadadin, 2015)
Desert dams and prospective dams	(Hadadin, 2015)
Flow direction in the major watersheds	(Hadadin, 2015)
Groundwater basins (and abstraction rates)	(Fanack Water, 2016; MWI, 2016b)
International boundaries	(University of Texas Libraries, 2004)
Irrigation schemes, Jordan river basin and Zones of irrigation development	(AQUASTAT, 2009b)
Physiographic Regions	(Ababsa, et al., 2014)
Rainfall (Annual average)	(Fanack Water, 2016)
Surface water (e.g. rivers, *wadis*, lakes, seas)	(AQUASTAT, 2009b; Fanack Water, 2016)
WWTPs	(MWI, 2015b)

Table 32 – Sources used by map

Figure	**Title**	**Sources**
Figure 42	Map of Jordan – Main cities, administrative and international boundaries and physiographic regions.	(University of Texas Libraries, 2004; AQUASTAT, 2009b; Fanack Water, 2016; Ababsa, et al., 2014)
Figure 45	Groundwater basins and water flows within the basins in Jordan, 2015.	(University of Texas Libraries, 2004; AQUASTAT, 2009b; Fanack Water, 2016; Hadadin, 2015)
Figure 46	Dams, desert dams and prospective dams in Jordan.	(University of Texas Libraries, 2004; AQUASTAT, 2009b; Fanack Water, 2016; Hadadin, 2015)
Figure 47	WWTPs in Jordan, 2016.	(University of Texas Libraries, 2004; AQUASTAT, 2009b; Fanack Water, 2016; MWI, 2015b)
Figure 49	Mineral energy resources in Jordan.	(University of Texas Libraries, 2004; AQUASTAT, 2009b; Fanack Water, 2016; Ababsa, et al., 2014)