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Development of a GIS model for water accounting in Jordan: focus on irrigation and energy usage in the water sector

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Abstract

With a water availability of less than 100 m^3 per capita and year, Jordan is suffering extreme water-scarcity. To its intrinsic limited water resources more pressure is being added every year as a result of socioeconomic factors, such as the accelerated population growth, and a reduction of rainfalls and increase of evaporation as consequence of climate change. What is more, the poor condition of the water system together with a considerably high water consumption for irrigation are not helping in such drastic situation. In a country with scarce surface water, groundwater is the main resource. As a result, Jordan's aquifers are being over abstracted and, consequently, depleted every year. Wastewater treatment arise as a solution as wastewater can be reused for irrigation, reducing the consumption of natural resources that can be, then, employed for domestic consumption. However, only 64% of people in Jordan is connected to the sewerage system, narrowing the amount of wastewater.

Water shortages are the direct consequence of all of this, limiting the agriculture development and reducing quality of life. Urgent action is required in the country to mitigate the effects of water scarcity and optimize the resources. What is more, the incredibly high energy consumption of the water system is adding more pressure to the energy system, which relies mostly on energy imports such as fossil fuels. Thus, the water scarcity problem should be assessed considering its synergies and trade-offs with the energy system.

Thus, the aim of this thesis is to create a Geographic Information System (GIS) model in which the water consumption was obtained and divided by sector with a resolution of 1 km^2. To do so, the population and water consumption per capita was taken into account for the domestic water consumption, while the evapotranspiration of the irrigated cropland in Jordan was calculated to ultimately obtain the water consumption in the agriculture sector. Then, taking advantage of the potential of a GIS model, the water consumption obtained in every spot was divided by source. Afterwards, the energy consumption of the water system is obtained. Lastly, three scenarios were built and simulated in order to analyze the consequence of the Jordan's Ministry of Water and Irrigation policies, set to fight against water scarcity. The results showed that, although a mitigation of water scarcity and reduction of natural resources depletion can be achieved, even more strict action is required in order to reach a sustainable water sector, eliminating water shortages and reducing the pressure on the natural resources.

Sammanfattning

Med en vattentillgänglighet på mindre än 100 m^3 per capita och år lider Jordanien extremt vattenbrist. Till dess inneboende begränsade vattenresurser läggs mer tryck varje år till följd av socioekonomiska faktorer, såsom den påskyndade befolkningsökningen, och en minskning av nederbörden och ökad avdunstning till följd av klimatförändringarna. Dessutom hjälper vattensystemets dåliga tillstånd tillsammans med en avsevärt hög vattenförbrukning för bevattning inte i en sådan drastisk situation. I ett land med knappt ytvatten är grundvatten den viktigaste källan. Som ett resultat överförs Jordans akviferer över och de tappas följaktligen varje år. Avloppsrening uppstår som en lösning eftersom avloppsvatten kan återanvändas för bevattning, vilket minskar konsumtionen av naturresurser som sedan kan användas för hushållskonsumtion. Men endast 64

Vattenbrist är den direkta följden av allt detta, vilket begränsar jordbruksutvecklingen och minskar livskvaliteten. Brådskande åtgärder krävs i landet för att mildra effekterna av vattenbrist och optimera resurserna. Dessutom ökar vattensystemet mer tryck på energisystemet, som mest förlitar sig på energiimport som fossila bränslen på grund av en otroligt hög energiförbrukning. Således bör vattenbristproblemet bedömas med tanke på dess synergier och avvägningar med energisystemet.

Således är syftet med denna avhandling att skapa en modell för geografiskt informationssystem (GIS) i vilken vattenförbrukningen erhölls och indelas per sektor med en upplösning på 1 km^2. För att göra det beaktades befolkningen och vattenförbrukningen per capita för den inhemska vattenförbrukningen, medan evapotranspiration av det bevattnade odlingslandet i Jordanien beräknades för att i slutändan få vattenförbrukningen inom jordbrukssektorn. Sedan, med utnyttjande av potentialen i en GIS-modell, delades vattenförbrukningen som erhållits på varje plats delad efter källa. Därefter erhålls vattensystemets energiförbrukning. Slutligen byggs och simuleras några scenarier för att analysera konsekvenserna av Jordans ministerium för vatten- och bevattningspolitik, som kommer att bekämpa vattenbrist. Resultaten visar att även om man kan minska vattenbrist och utarmning av naturresurser krävs ännu strängare åtgärder för att nå en hållbar vattensektor, eliminera vattenbrist och minska trycket på naturresurserna.

List of Abbreviations

AHP	Analytical Hierarchy Process
BAU	Business As Usual
CI	Consistency Index
CLEWs	Climate, Land, Energy and Water strategies
CM	Cubic Meters
CR	Consistency Ratio
DEM	Digital Elevation Model
DoS	Department of Statistics of Jordan
ET_0	Reference evapotranspiration
ET_c	Standard evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographic Information System
GIZ	Deutsche Gesellschaft fuer Internationale Zusammenarbeit
GDP	Gross Domestic Product
IEA	International Energy Agency
JV	Jordan Valley
KAC	King Abdullah Canal
KTD	King Talal Dam
M	Million
MCM	Million Cubic Meters
MEMR	Ministry of Energy and Mineral Resources

Mtoe	Million tonnes of oil equivalent
MWI	Ministry of Water and Irrigation
NENA	Near East and North Africa
NRW	Non-Revenue Water
O&M	Operation and Maintenance
R_s	Solar radiation
R_{so}	Clear-sky solar radiation
RSDSP	Red Sea- Dead Sea Conveyance Project
SDGs	Sustainable Development Goals
UN	United Nations
UNHCR	United Nations High Commissioner for Refugees
USD	United States Dollars
WWTP	Wastewater Treatment Plant

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Chapter 1

Introduction

This Master's Thesis was developed within the context of the FAO project *Implementing the 2030 Agenda for Water Efficiency/Productivity and Water Sustainability in NENA Countries*

1.1 Context: The water issue and the SDGs

According to [1], water scarcity is, and will be, one of the greatest challenges of our time. Every continent is already affected by water scarcity. The accelerated population growth is increasing water consumption. Furthermore, as a result of climate change, precipitation is decreasing every year whereas evaporation due to the increase of temperature has increased. What is more, extreme conditions such as droughts and floods are every year more common in many parts of the world [2]. As a consequence, people living in these countries feel the effect of less water available every year and have to deal with water shortages and very limited supply. On the other hand, agriculture is, at the same time, a cause and casualty of this water scarcity, as the food production is raising as a result of the increasing demand and water used for irrigation is, of course, higher every year. Actually, agriculture is estimated to consume 70% of the total water withdrawals in the world. As a result of water scarcity, this sector may suffer water shortages, with the consequent decrease of the crops productivity and limiting the food production in some cases.

But the water problem does not only concerns the agricultural sector. Energy is also affected by water scarcity and consumption. For instance, there is a both ways relation between both resources: water is needed both to produce energy and extract the resources, such as fossil fuels, and also to cool thermal power plants; and energy is needed to pump and treat water for the supply, treat wastewater and produce alternative water sources such as desalination [3]. According to the International Energy Agency (IEA), and focusing on the energy for water point of view, as it will be the objective of this thesis, in 2014 water consumed 4% of the worldwide electricity consumption [3]. To this value, 50Mtoe of thermal consumption should be added due to the use of pumps powered by diesel and gas generators. In total, more than 100Mtoe were consumed that year in the water sector. But this energy consumption is expected to raise in the following years as a result of the increase of water consumption, but specially due to the need of increasing the use of alternative water sources such as desalination, which is extremely energy-intensive.

So, it is clear these three sectors are closely interrelated. With the adoption of the The 2030 Agenda for Sustainable Development by all the members of the United Nations (UN), the known as the 17 Sustainable Development Goals (SDGs) were set in order to assess the huge challenges humanity is going to face in the upcoming years [4]. Among the 17 SDGs, food, water, energy and climate are found in the SDGs 2, 6, 7 and 13 respectively. With the objective of achieving the goals by 2030, initiatives to help developing countries to reach them are being released. In the Near-East and North-Africa (NENA) region concretely, where water scarcity is extremely severe and food production is under huge pressure, a collaboration between the Food and Agriculture Organization of the United Nations (FAO) together with the Stockholm Environment Institute (SEI) and the Royal Institute of Technology of Stockholm (KTH) began the project *Implementing the 2030 Agenda for Water Efficiency/Productivity and Water Sustainability in NENA Countries*. In this project, the Nexus methodology based on the Climate-Land-Energy and Water strategy (CLEWs) is being employed to try to optimize not only one but the three resources altogether, analysing their synergies and trade-offs.

Among the NENA countries, Jordan stands out as one of the most water scarce countries in the world. With a water availability of $100m^3$ per person per year, the country is far below the UN's threshold of absolute water scarcity, set as $500m^3$ per person per year. The inherent scarce renewable water resources are being exploited beyond their recharge rate, decreasing water quantity and quality. This issue is exacerbated by the decrease of precipitation and the increase of evaporation as a result of climate change, and also by the increasing population growth and the Syrian refugee crisis. Therefore, this thesis will focus on water accounting by using a Geographic Information System (GIS), paying special attention to water use for irrigation and analysing the energy consumption related to the water consumption, employing the CLEWs methodology for such purpose.

1.2 Motivation and Research Question

As it is already clear, Jordan is a country which is suffering a critical water scarcity. Action must be taken immediately to reduce its effects on other sectors, improve water supply and reduce the stress on the country water resources. Furthermore, in a workshop performed by KTH-dESA, FAO and SEI the main stakeholders (MWI, MOA and MEMR) stated that the greatest of their priorities is to fight against water scarcity.

However, when beginning the research, a question arises, followed by some sub-questions that should be answered along the development of the thesis: **How can water scarcity, and especially groundwater over exploitation, be mitigated?**

- How is water being consumed and abstracted?
- What is the energy cost?
- What measures can be implemented to reduce the stress on water resources?
- Would these improvements actually help to reduce the pressure on the natural water resources? How would the energy system be affected?

Throughout this project, all these questions are going to be answered.

1.3 Scope and Limitations of the Project

Due to the existent water shortage in the Near East and North Africa (NENA) countries, FAO is developing the project "Implementing the 2030 Agenda for Water Efficiency/Productivity and Water Sustainability in NENA Countries" to help these countries to increase their water efficiency and productivity [5]. Among these countries, Jordan, with a water availability of less than 100 m^3 per capita, is in need of action to mitigate its water scarcity.

In the frame of this project, and complementing the Thesis of Belda Gonzalez [6], the main focus of this project is to model the water system of Jordan using a Geographic Information System (GIS). Thus, the aim of this Master's Thesis is to assess the water issue in Jordan by using the Nexus approach, firstly analyzing the current state of the water system and then examining the effects of such problem on other sectors. Afterwards some examples of the improvements the Ministry of Water and Irrigation wants to implement in its

[7] will be introduced in the model to analyse the effects on the water and energy consumption. To do so, a GIS software will be employed, complemented with Python to analyze and process the data coming from the data-sets. Due to the available data, 2015 will be the base year for the development of this thesis.

Notice that this thesis will focus on the point of view of the water quantity, not evaluating the impacts these improvements may have on water quality. Moreover, although irrigation will be considered in the analysis, the repercussions on food productivity are not going to be quantified.Furthermore, only water issues in Jordan boundaries are going to be considered, setting aside those with transboundary cause and or repercussion.

Chapter 2

Literature review

Located in Western Asia, the Hashemite Kingdom of Jordan borders in the east with Saudi Arabia and Iraq, Syria in the north and Israel in the west [8, 9]. The kingdom is categorized as a upper-middle income country with a GDP per capita of US$ 4.247,769 [6, 10]. The country total area is 89,318km^2, distributed in 88,778km^2 of land and 540km^2 of water surface [6, 9, 11, 12, 13]. Jordan's territory is divided in 12 governorates, as can be seen in Table 2.1. The total population is nowadays around 10M people, and it is unevenly distributed in the country, living most of it in the governorates of Amman, Madaba, Irbid and Zarqa as can be seen in 2.1. This is due to the fact that 75% of Jordan territory is occupied by the Eastern Desert. These governorates correspond mainly to the north-western part of the country, which corresponds to the area, as it will be explained later, where agriculture is more suitable and more water resources exist. This area corresponds only to the 16.2% of Jordan total area [6]. Therefore, this part of the country will consume most of the water resources.

The country has faced water scarcity along all its history due to the scarce water resources existent in the country. These last years, however, this crisis has been increased due to numerous factors. In the following sections, the water resources of the country, as well as the factors that are worsening the situation will be explained.

2.1 Jordan context: Facing water scarcity

Catalogued as one of the most water scarce country in the world, Jordan's water availability nowadays is close to 100 m^3 per year and person [14]. This value is very far below UN's threshold of absolute water scarcity, considered when

Table 2.1: Population per governorate.

Governorate	Population	Percentage
Amman	4,327,800	41.98%
Madaba	2,043,000	18.54%
Irbid	1,911,600	18.54%
Zarqa	1,474,000	14.30%
Mafraq	593,900	5.76%
Balqa	531,000	5.15%
Karak	341,900	3.32%
Jerash	256,000	2.48%
Aqaba	203,200	1.97%
Ajlun	190,200	1.84%
Maan	171,100	1.66%
Tafilah	104,000	1.00%

water availability is lower than 500 m^3 / year per person [14, 15, 16]. Figure 2.2 shows the categorization of the water stress according to the CM available per year and person on the left and the percentage of water withdrawal related to the renewable freshwater availability. The water resources in Jordan are very limited, counting only with 780MCM of renewable resources per year [17]. Their over exploitation, worsened by the increasing population growth and other socioeconomic factors that will be further explained, increases the stress on groundwater and reduces surface water availability. Far from helping, huge losses in the water system and the great water consumption for agriculture increase the pressure on the resources.

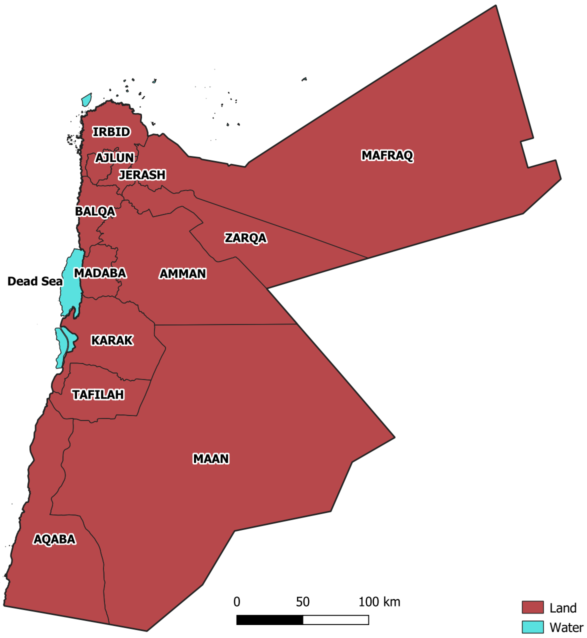


Figure 2.1: Jordan governorates

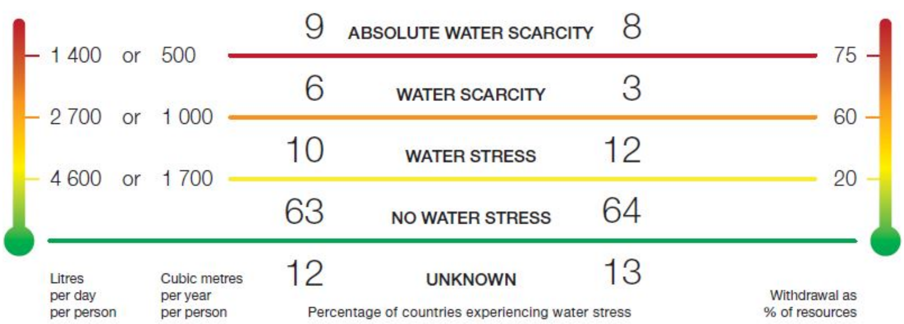


Figure 2.2: Water scarcity indicators [16].

2.2 Climate

As can be seen in Figure 2.3, three climatic regions are found in Jordan [10, 11]:

1. **Jordan Valley**: located in western Jordan, this region is dominated by Mediterranean climate, characterized by dry and hot summers, and mild wet winters. Rainfall in these areas are variable along the year.

2. **Highlands**: with annual precipitation reaching more than 500mm per year, the Highlands are, in the context of water scarcity, blessed with a more humid climate, reaching annual rainfalls above 500mm per year, with cold winters and mild summers.

3. **Desert**: occupying 75% of Jordan territory, the Eastern Desert suffers hot summers, followed by cold winters. Due to the arid and semi-arid climate of this region, the annual precipitation is lower than 200mm.

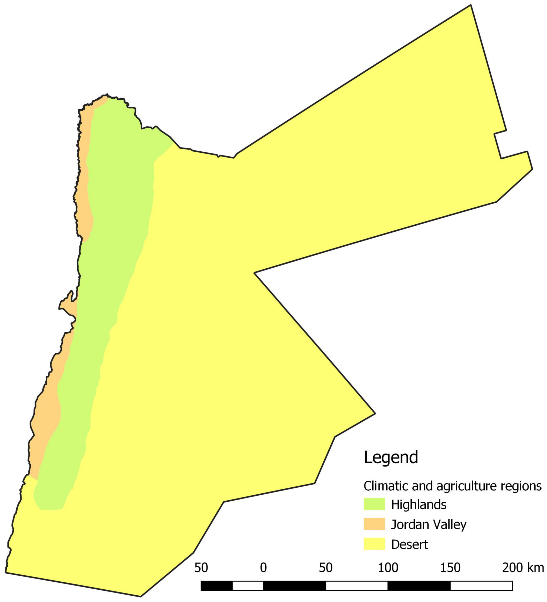


Figure 2.3: Climatic regions in Jordan.

Summing up, rainfalls in Jordan are very scarce. Figure 2.4 depicts the average anual precipitation in Jordan from 1970 to 2000. The total amount in 2015 was estimated to be 8884MCM [14], and slightly fluctuates every year, as can be seen in Figure 2.5. In this figure it is noticeable that 95% of the total rainfall is evaporated every year. This value is quite high when compared to the average ratio of the whole ground surface in the world, which is around 60% [18]. This fact can be explained by the predominant arid weather of the country previously explained. Other part of the rainfall is lost as unused runoffs, causing soil erosion [19], and a small part (485MCM) flows into the groundwater, recharging the aquifers.

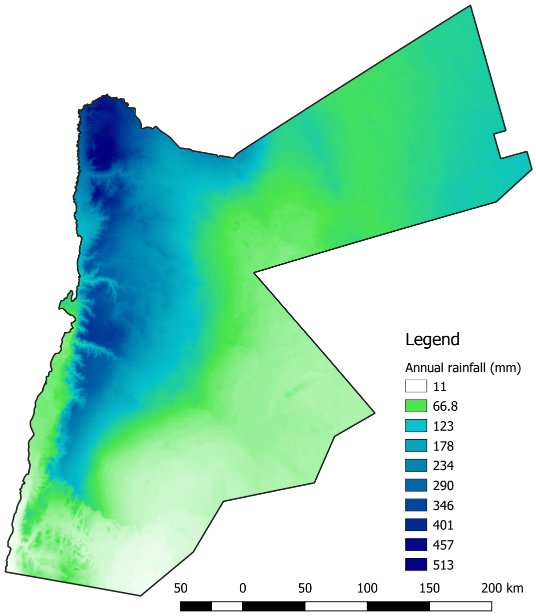


Figure 2.4: Annual precipitation in Jordan.

2.3 Water resources and use

Three main water sources are used in Jordan, as can be seen in Figure 2.6: surface water, groundwater and treated wastewater. In 2015, it was estimated that the country accounted with 780MCM of renewable water resources coming from the different sources [14]. However, that year the water supply of every sector summed 1004MCM. In this section, the main water sources of Jordan will be explained, as well as the domestic and agriculture uses.

2.3.1 Surface water

Approximately 274MCM of surface water were consumed in 2015. Three main sources provide most of the surface water in Jordan [6, 10, 20, 9, 13]:

1. **Jordan river:** Flowing along the west border of the country, the Jordan River is used mainly for anthropogenic purposes [10]. Although historically its flow was close to 600MCM per year, coming from the Sea of Galilee [21], in the last decade its stream has decreased. Although it divides Israel and Jordan, according to [12] most of its water is used for irrigation and domestic purposes in the former. Due to the untreated wastewater flowing to the river and the development of agriculture in the

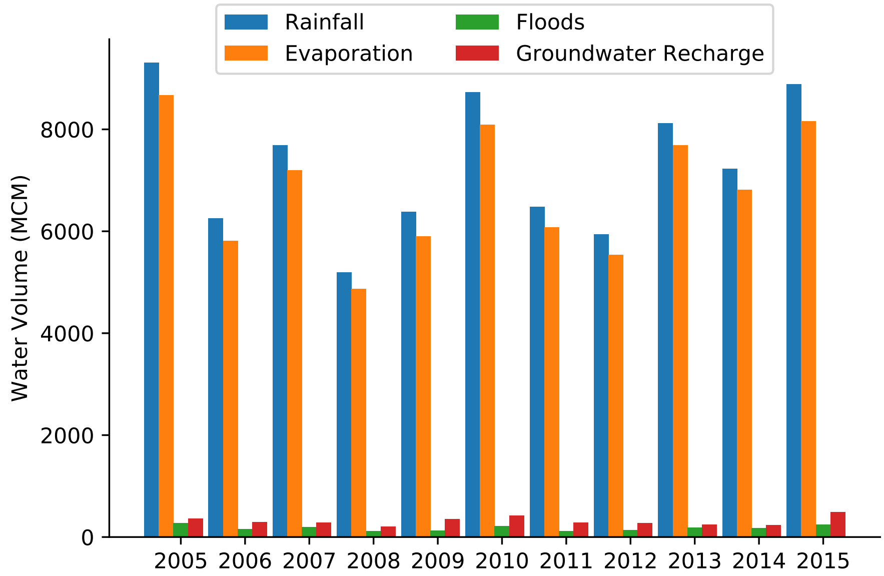


Figure 2.5: Surface Water Budget (2005-2015) [14]

Jordan River Valley and as a result of the runoffs of fertilizers, this river is nowadays polluted, being unfitted for domestic consumption [10].

2. **Yarmouk river:** Located in the north of Jordan, this river is the main tributary of the Jordan river. It contains most of the water resource consumed in the country. Nevertheless, in the 1980s the flow that reached Jordan was reduced from 400MCM per year to only 150MCM as a result of the development of catchments and droughts in Syria [9, 20]. This river is the main tributary of the Jordan river, which used to receive 470MCM/year of water from this river [21].

3. **Zarqa river:** Also located in the north of Jordan and a main tributary to the Jordan river, the Zarqa river catchment area is the most populated zone of Jordan. Due to the increasing industrialisation and the discharge of treated wastewater, the river is highly contaminated nowadays [9].

Besides these rivers, Jordan also has small springs and rivers called wadis that provide little amount of surface water. Both Zarqa and Yarmouk river supply water to the King Abdullah Canal (KAC), which is considered the backbone of the development of the Jordan Valley [10, 20]. This canal flows from north to south, going through 110km in parallel to the Jordan River and providing water not only for 40 % of the Jordan Valley irrigation, but also for 40% of Amman domestic consumption [10].

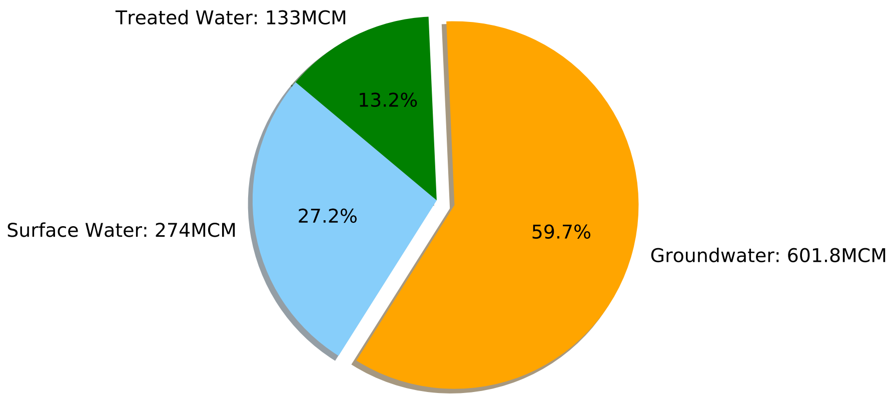


Figure 2.6: Water use from different sources. [14]

2.3.2 Groundwater

As the surface water is that limited, the main water resource of Jordan is groundwater. In 2015, groundwater provided 600MCM to the country, almost 60% of the total use, in spite of the fact that renewable groundwater is only 275MCM annually. This overabstraction is causing several issues such as the decrease of the groundwater table and the increase of salinity of the resource [21, 6, 22]. Jordan is divided in 12 groundwater basins, as can be seen in Figure 2.8. In this figure, it can be noticed that 9 out of the 12 groundwater basins are being exploited over their safe yield. It should be highlighted that 2 of these basins are considered non-renewable or fossil because they cannot be recharged, which are part of Jafr and the Disi aquifer.

Especial mention needs to be paid to the Disi aquifer, located in the South of Jordan, which is shared with Saudi Arabia. It was planned to provide 100MCM per year during 100 years. However, as can be seen in Table A.1 in Annex A, the actual abstraction is far above that limit, so it could be expected that the exploitation of this aquifer will not last as planned. Since 2015, a pipe of 325Km connects the aquifer to the capital, Amman, to increase its water supply in, theoretically, 35MCM per year. As for the other aquifers, according to [17], the water that is abstracted is consumed in the very same basin. Some of the aquifers in Jordan contains brackish water, requiring this water not only to be treated and desalinated to make it suitable for irrigation, but also obliging farmers, in some cases, to choose specific crops that can be irrigated with saline water.

The over abstraction of groundwater is causing that the groundwater table

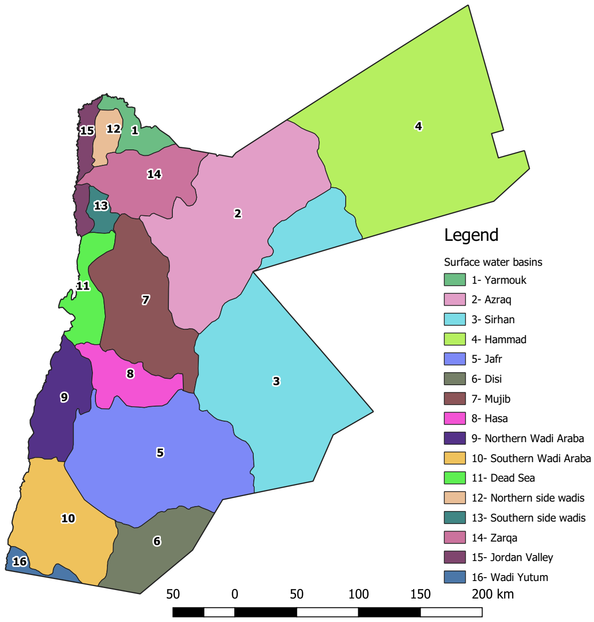


Figure 2.7: Jordan surface basins.

is decreasing every year in those basins in which the abstraction is exceeds the safe yield. [23] reports that in those aquifers that are being exploited the groundwater level is decreasing at a pace of 1 meter per year as an average. Due to this, the salinity of groundwater is increasing, which may in turn cause problems for irrigation.

2.3.3 Treated wastewater

The last relevant water source is the treated wastewater. In the last years, this non-conventional water resource has gained more importance, increasing its consumption year by year. This is due to the increasing number of wastewater subscribers, which has raised every year as can be noticed in Figure 2.9, with a current percentage of 64% of households subscribed. The Kingdom has 32 wastewater treatment plants (WWTP), with As-Samra standing out among all of them as it treats 80% of all the domestic wastewater. Concretely, in 2015 this plant treated 294,862m^3 per day. That is why this thesis will pay special attention to this treatment plant. As-Samra is located in the North-East of Amman, collecting and treating most of the wastewater coming from the capital. Once treated, the water is sent to the King Talal Dam (KTD), where is distributed for irrigation purposes in the JV [10, 20]. Another three WWTP

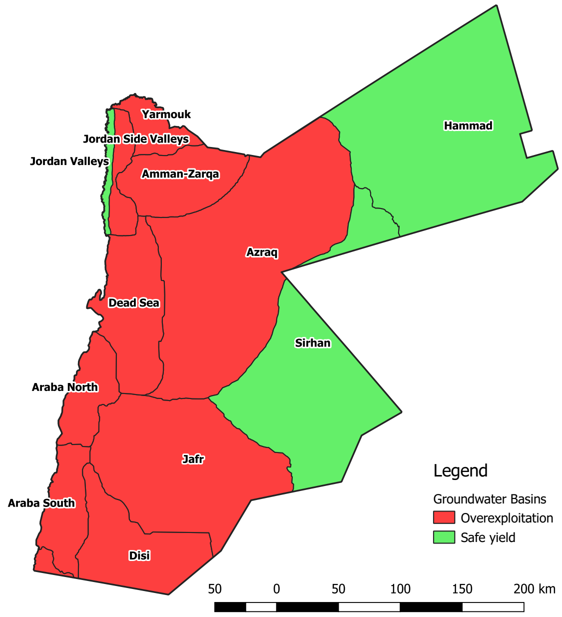


Figure 2.8: Jordan groundwater basins.

treat the wastewater coming from Amman. sending it to the KTD through the Zarqa river. The rest of the wastewater coming from the other WWTPs are used for irrigation purposes in the local area where the plant is located [24]. In Appendix B, Table B.1 displays the treated wastewater per WWTP. As wastewater is not suitable for drinking purposes, it is used mainly for irrigation purposes. Due to losses in the distribution system and evaporation in the dams, 90% of the total treated wastewater is actually employed for irrigation [20].

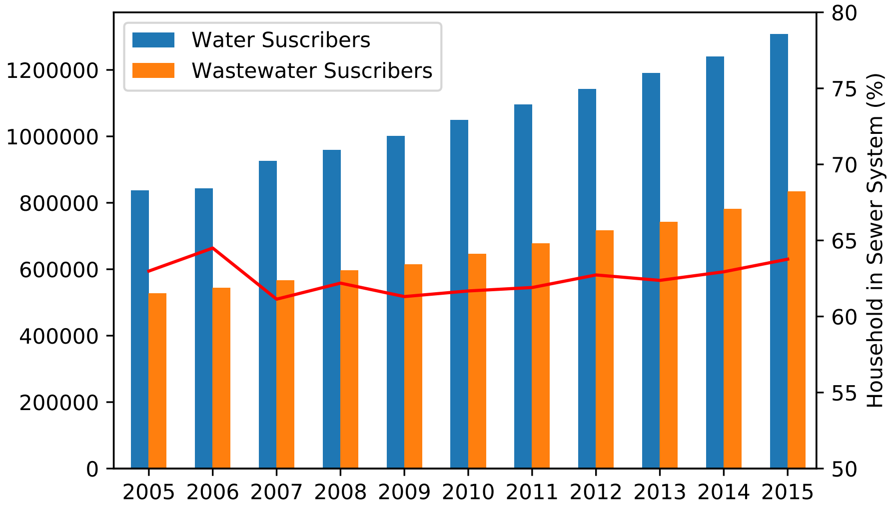


Figure 2.9: Water and wastewater subscribers. [14]

2.4 Domestic consumption

Currently, although in Jordan 98% of households has access to the water system, 93% has access to safely-managed source and 86% to a piped network [25]. Due to the scarcity, water is pumped from the source to tanks distributed in the cities, and from there it is supplied to the households. This fact creates shortages as, in most cities, water is pumped only twice per week, in the case of huge cities such as Amman, or once per week, having locations, specially small villages, where water is pumped just once every two weeks [25].

In 2015, the domestic sector, although being the second most water consuming one, was the sector that consumed most of the groundwater (332.5 MCM). The surface water consumed by this sector was 124MCM, summing a total of 456.5MCM in 2015. However, the actual water demand in the domestic sector is considerably lower, estimated in 234.18MCM in 2015. This is due to the known as Non-Revenue Water (NRW). The water system condition is very poor, having every year around 50% of water losses. This imply that the water supply is close to the double of the water demand in the sector. According to [11], water losses in Jordan can be divided in:

- Administrative losses: due to broken and bad installed counters, human error reading the measurements, etc., but also due to illegal connections to the water system, accounting in total the 74.4% of the total losses.

- Technical losses: these losses are mainly due to seepages and breakages in the distribution net and the tanks in cities and villages. These losses represent the remaining 25.6% of the total losses.

2.5 Agriculture consumption

Agriculture in Jordan is concentrated mainly in the Jordan Valley (JV) and the Highlands due to the higher rainfalls and water resources. In 2015, the total cropland area in Jordan was 2,344,794 Dunum[1]. The majority of the cropland are fruit crops, followed by fruit trees and vegetables. In Jordan, the majority of the cropland is rainfed, representing almost 70% of the total cultivated area [26]. However, productivity in the irrigated land is way higher, as the 30% of the cropland represented by the irrigated crops provides 90% of the total production [6].

For the irrigated land, three technologies are mainly used by Jordan farmers [26, 27, 28]:

- **Surface irrigation**: With this type of irrigation, water is distributed across the cropland by gravity through canals or flooding the entire field. This type of irrigation is the most inexpensive and does not consume energy as it is distributed by gravity. However, this is the method that consumes the most water. Its efficiency -defined by [28] as the relation between the water absorbed by the crop and the water that is lost through deep percolation and runoff (Equation 2.1)- is the lowest, being 60%.

- **Sprinklers**: A fixed or moving sprinkler is put in the center of the cropland and sprays the water to the field, imitating the effect of rainfall. This is the most energy consuming method as need water to be at a pressure of 3 bar [29], and has the second highest water efficiency, 80%.

- **Drip irrigation**: With a 90% of efficiency, drip irrigation consists of the application of small amounts of water with certain frequency by using a network of pressurized valves, usually at 1 bar [29]. Although this is the most efficient method, it is also the most expensive one, being prohibitive for small farmers.

[1] 1 Dunum = 0,1ha

$$e_a = \frac{d_{net}}{d_{gross}} \times 100 \qquad (2.1)$$

Being:

- d_{gross}: gross irrigation depth in mm.
- d_{net}: net irrigation depth in mm.
- e_a: field application efficiency in percent

Some years ago, surface irrigation was the main method. However, in order to increase the water efficiency of the country, the shares of sprinkler and drip irrigation have increased considerably [6], as can be seen in Figure 2.10, where the percentage of the irrigated area that uses every type of irrigation type is obtained from [26] per governorate.

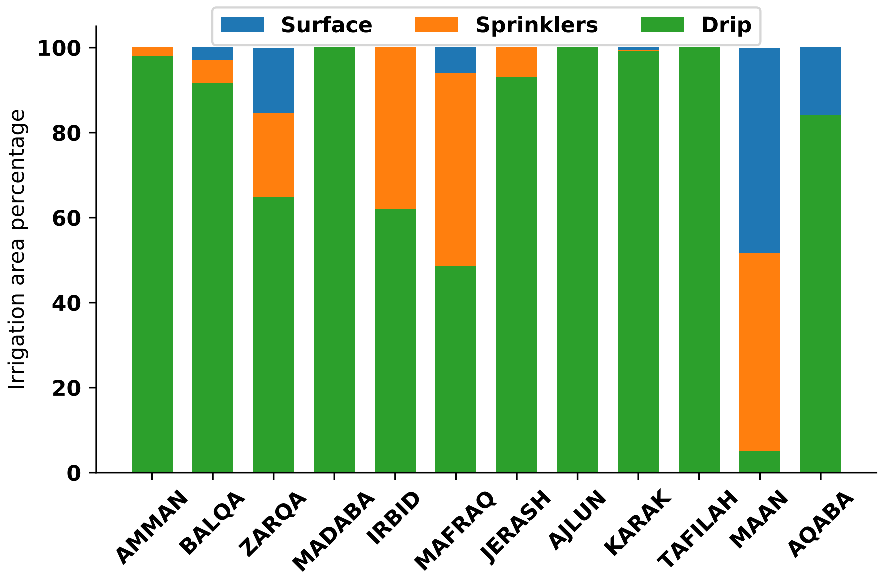


Figure 2.10: Irrigation technologies by governorate. Source: own elaboration based on [26].

In spite of this increase of water efficiency, agriculture is the most water-consuming sector in Jordan (more than 50% of the total consumption), with a total amount of 514.4MCM in 2015 [14]. As aforementioned, water for irrigation is provided by the main rivers of Jordan, wadis, groundwater and treated wastewater. What is more, water is harvested in 61 dams and 65 ponds for irrigation purposes, with a total capacity of 90CM [14].

The agriculture sector is highly influenced by water scarcity. Food insecurity is a direct consequence of the little water resources available in the country, obliging Jordan to import 87% of its food [6]. What is more, in 2015 the actual demand for agriculture was 700MCM, which means by that year farmers suffered a shortage of almost 200MCM [7]. In fact, in the survey performed by [30], 42% of the farmers in the JV reported being facing water shortages. This problem is due to the Jordan water allocation policy, in which the sector with the least water priority was agriculture, below domestic and industry. Consequently, farmers are forced to install illegal wells to irrigate their lands, increasing the stress on the groundwater resources and, then, reducing even more the scarce water resources.

2.6 The energy-water nexus in Jordan

The electricity consumption in Jordan in 2015 was 16,173GWh, of which 2,426GWh was consumed for water pumping [31], thus representing 15% of the total electricity consumption of the country by that year. This data from the Minsitry of Energy and Mineral Resources (MEMR) is in conflict with the MWI, which affirms in [14] that that year the energy consumption was 1,745GWh. For this thesis, it has been assumed that this value is for water pumping for the domestic consumption, and the other corresponds to the rest of the consumptions (water for agriculture and wastewater treatment mainly). Thus, the energy consumed per CM was that year 4.37kWh per billed cubic meter [14]. This value can be considered very high, especially when compared to other countries; according to [32], other developing countries energy consumption in water sector is below 0.30kWh/m^3, with China and India as examples with consumptions of 0.29kWh/m^3 and 0.30kWh/m^3 respectively, whereas developed countries such as Germany reach 1.71kWh/m^3. According to [32], this difference between developing and developed countries is mainly due to the increase of urbanization.

This huge energy specific energy consumption in Jordan's water sector can be explained by several factors:

- As previously stated, Jordan's surface water sources are located in the north-western border of the country. Therefore, water needs to be pumped very long distances to reach the consumption spots, having pressure losses in the system.
- The country has great elevation differences, having the lowest point on Earth, the Dead Sea, at 400 meters below the sea level, and some ar-

eas reaching 1700 meters. The capital, Amman, being the maximum consumer of water in Jordan has an elevation of more than 700m.

- The poor conditions of the water system aforementioned are translated as two issues from the energy consumption point of view: first, the water losses due to NRW can be also understood as energy losses, as the water pumped is double that consumed by end-users and, thus, the energy consumption per consumed water is the double as it should be. Secondly, the energy efficiency of the pumps installed in the system is very low. According to [33], in an energy audit performed by Deutsche Gesellschaft fuer Internationale Zusammenarbeit (GIZ), German company which is assessing and helping Jordan to increase energy efficiency in the water sector, in the audited pumping stations the energy efficiency of the pumps was found to be in the range of 29% to 60%.

- In order to transport water in the Disi-Amman conveyance, 2 pump stations are needed to send the water through 325km of pipes to Amman, with an elevation difference of 800m [34]. This means 2% of the total energy consumption of Jordan is consumed for this purpose, increasing considerably the energy consumption of the water sector.

Energy is also required to pump water from the aquifers. No data was found regarding the energy consumed for this purpose. However, as it will be explained in Chapter 3, this project will estimate this consumption. As previously commented, the groundwater level is decreasing and, thus, it is expected that the energy consumption for groundwater abstraction will increase in the future.

Lastly, WWTP requires high quantities of energy to treat the incoming wastewater. It is estimated that As-Samra consumes around 90GWh to treat water, although 80% of the energy that is consumed is supplied by the WWTP itself, as it has biogas gensets and hydropower turbines [6].

2.7 External factors increasing the pressure

This situation of severe water scarcity is aggravated by external factors. Both socioeconomic factors and climate change have and are expected to increase the pressure on water resources and even decrease the resource. Also trasboundary issues add strain to this emergency, but as stated in Chapter 1.3 this is out of the scope of the thesis.

2.7.1 Socioeconomic factors

- **Population growth**: The population of Jordan is characterized by a rapid growth in the last few decades. The growth rate between 2006 and 2016 has been of 4,7%, reaching the total amount of 10 million inhabitants in 2018, doubling in less than a decade the 5 million people that used to live in this country by the year 2000 [10]. Due to this, the availability of water per person, having the same or less resources every year, is reduced, achieving the current availability of less than $100m^3$ per person per year and also increasing the pressure on the natural resources [6]. However, more people means not only less water availability, but also more food consumption. Therefore, the indirect water consumption, translated into more water used for irrigation due to the increase of food demand, also increases. In the future, population is expected to keep increasing at a growth rate of 2.2% [35]. This expected increase and the population growth in the last years is noticeable in figure 2.11.

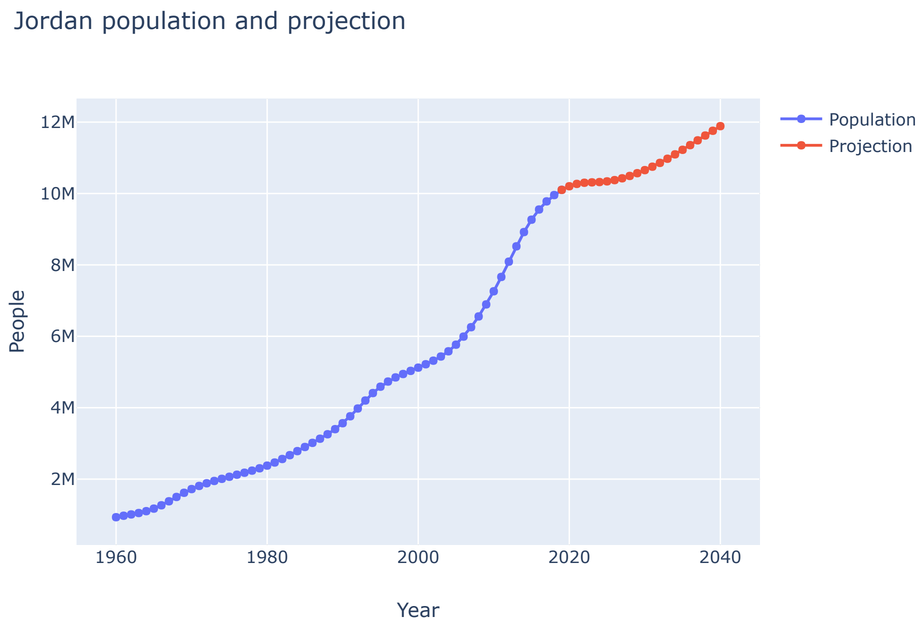


Figure 2.11: Jordan population. Source: [36]

- **Refugees' crisis**: This growth has been accelerated due to the constant influx of refugees. The Syrian crisis is obliging most Syrians to abandon their country, looking for opportunities in another place. As a neighbor of Syria, Jordan is the country which hosts the greatest number of refugees. According to The World Bank, by 2018 Jordan was hosting almost 3 million refugees, coming most of them, according to UNHCR, from Syria (671,579 registered refugees) [37, 38]. The precarious conditions of the water systems installed in the refugee camps are increasing the water losses in the water network, and the arrival of people is also decreasing the water availability.

- **Tourism**: In spite of the recent and continuous drop of tourism in Jordan due to the conflicts in the nearby countries [8], it is still an appealing destination not only for Arab countries, but also for tourists coming form all around the world. Only in 2016, 7,5M tourists visited the country. Compared to the total population of Jordan, of 9,5M people, it is remarkable there are almost as many foreigners as permanent residents throughout the year. Although this sector is a great contributor to the GDP of the country, summing a total of US$ 14,190 million only in 2008, 14,7% of the GDP of that year [39], it is also a driver of the pressure on water resources. Nevertheless, according to [39], tourism is a matter of concern among Jordan people as their drinking water is above the average, and hotels are great water consumers.

- **Economic growth**: As aforementioned, Jordan is now catalogued as an upper-middle income country. However, in the past years their GDP per capita was not that high. Thanks to an economic growth of around 2% per year, and reaching 8% during last decade, the country has increased its GDP from US$ 1651,62 per capita in 2000 to the current value. This economic growth means people have more purchasing power and can afford paying more to consume more water.

2.7.2 Climate change

The water sector is extremely sensitive to climate change. The constant increase of temperature accelerates evaporation, and together with the decrease of precipitation of the last years in Jordan, estimated to be reduced in the future a 25% according to [8], both the river flows and the groundwater recharge are being reduced, diminishing the water availability. What is more, a decrease of precipitation is a synonym to more water required for irrigation as crops are not irrigated naturally. Climate change is related to extreme events such as floods and droughts.

2.8 Mitigating water scarcity: The National Water Strategy (2016-2025) and the Red Sea Dead Sea Conveyance Project

In the last years, two national plans were released in Jordan as an attempt to mitigate the water scarcity in Jordan. First, in 2009 the MWI released the Jordan's Water Strategy (2008-2022) [40]. The main aim of this plan was to reduce the gap between demand and supply, which was by that date of 659MCM per year, and achieve a continuous water supply. To do so, policies encouraging the use of desalinated water and the increase of wastewater reuse were promoted, as well as the intention to cap the water use for irrigation. Furthermore, it was an attempt to reduce the groundwater depletion and the NRW, reaching by 2022 a 25% of NRW by rehabilitating the networks and optimizing the O&M. However, as argued by [41], although the reduction of energy consumption was implicitly named, no actual policy was launched with the objective of reducing the consumption of energy in the water sector.

A few years later, in 2016 the same ministry published the National Water Strategy (2016-2025) [7] as a way to face the last challenges that appeared in Jordan: the aforementioned population growth and refugees' crisis [41]. In this document, updated goals were set, counting now with more explicit targets regarding energy in the water sector, such as the increase of energy efficiency in the water sector and the use of renewable energy with a pathway to achieve both of them and identifying the trade-offs between both sectors. For the development of this thesis, the most important objectives set in these documents are:

- **Reduction of NRW**: identified of one of the most important issues in the water system, the reduction of NRW seems mandatory as by reducing it, both water and energy consumption may be drastically reduced. It is expected that by 2025, the average NRW in Jordan could be reduced in order to reach 30% of the supply. This objective is expected to be accomplished by repairing the damaged equipment in the water system, reduce the human error when reading the counters by installing automatized SCADA systems, fixing leakages, etc. Furthermore, periodic inspections and information campaigns could reduce the illegal connections to the water system [11].

- **Increase of people connected to the sewage system**: as previously said, the percentage of people connected to the sewage system has remained more or less constant at a value of 64%. The objective of the MWI is to increase this percentage to 80% of the people. By achieving this, more treated wastewater would be available in the future for irrigation and less untreated wastewater would be poured in the rivers, reducing then the pollution of natural water resources. But this increase of people connected to the sewage system should go together with the construction of new WWTPs and the upgrade of the existent ones. The former is considered in the Decentralized Wastewater Management Policy, which looks for the installation of small WWTPs distributed along the country to make it possible for the rural and suburban areas to be also connected to the sewage system; whilst the latter is already under development, with several projects for upgrading existing WWTPs being both performed and projected. Among these projects, the Phases II and III of upgrade of As-Samra, completed in 2016 and expected to be completed in 2024 respectively, should be highlighted as are intended to increase the capacity of this important WWTP by 35MCM with every phase.

- **Reduction of water demand for irrigation**: Although no numerical objective seems to be targeted, MWI is concerned about the huge consumption for irrigation. In collaboration with the MOA, both ministries are encouraging more efficient agricultural practices in order to increase the average crop yields and, therefore, optimizing the use of water for this purpose.

Apart from these objectives and projects, Israel, Jordan and Palestine are working on an ambitious project: the Red Sea Dead Sea Conveyance Project (RSDSP). With this project, a conveyance of 180km between the Red Sea and the Dead Sea is going to be built [42]. The RSDSP seeks three main objectives: increase the incoming flow to the Dead Sea in order to mitigate or even revert its depletion, take advantage of the 400m of elevation difference between the Red Sea and the Dead Sea to produce hydropower and, the one that is going to be considered for this thesis, the desalination of part of the water flowing from the Red Sea to supply the greatest urban areas in Israel, Palestine and Jordan (see Figure 2.12). Focusing on the third objective, two phases are distinguished according to [7]: the first phase, expected to be finished by 2021, will supply the domestic sector in Jordan with 65MCM per year and 20MCM for irrigation; and the second phase is expected to increase the domestic supply another 150MCM by 2025. This huge desalination will result in a huge energy consumption, which is going to be analysed in this project.

Figure 2.12: Scheme of the RSDSP. Source: [43]

Both the National Water Strategy (2016-2025) and the RSDSP will used in this thesis as case studies to simulate some scenarios in order to prove the usefulness of a GIS model for a Water-Energy Nexus analysis.

Chapter 3

Methodology

This chapter will explain the methodology followed in order to obtain the GIS model, from the obtention of the GIS layers to the development of the scenarios.

For the development of this thesis, the combination of two softwares was necessary, using QGIS for the visualization of the datasets and the preprocessing of some of them, and Python to process the data in order to obtain the desired results. The proposed methodology follows the steps that appear in Figure 3.1. First, the raw datasets coming from open sources were introduced in QGIS. Then, the population and cropland layers were calibrated so as the regional statistics obtained in the dataset matched the national data. Afterwards, the water consumption of domestic and agriculture sectors was obtained, in the second case obtaining firstly the evapotranspiration of the irrigated cropland. With these layers, and taking into account all the gathered information explained in the previous chapter, it was possible to estimate the water source employed in every spot. Thereafter the energy consumption in the water sector per source was calculated. Finally, three scenarios were built and simulated to analyse the implications of some of the policies of the MWI.

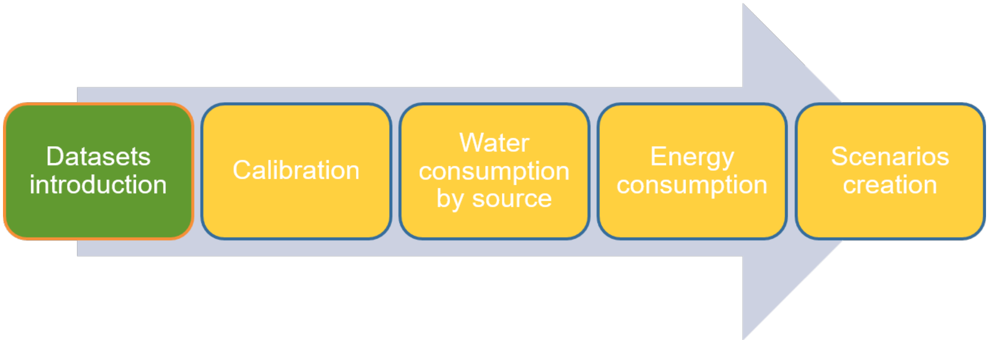


Figure 3.1: Methodology flow chart.

Throughout this chapter these steps twill be explained with detail.

3.1 Datasets introduction

As a starting point for the development of the GIS model, it is necessary to look for datasets that will serve as a basis for the obtention of the final results. For this purpose, the most updated datasets coming from open sources were searched. Table 3.1 shows the GIS layers that were used for the development of the project and the open sources in which they were found, followed by a short description of the layer.

Table 3.1: Initial GIS layers.

DATA	SOURCE	DESCRIPTION
Solar radiation	WorldClim	Raster containing the average monthly solar radiation in KJ/m2/day.
Wind speed	WorldClim	Raster containing the average monthly wind speed in m/s.
Monthly maximum temperature	WorldClim	Raster containing the maximum temperature per month in °C.
Monthly minimum temperature	WorldClim	Raster containing the minimum temperature per month in °C.
Monthly average temperature	WorldClim	Raster containing the average temperature per month in °C.
Monthly precipitation	WorldClim	Raster containing the monthly rainfall in mm.
Monthly average water pressure	WorldClim	Raster containing the monthly averafe water pressure in kPa.
Population	SEDAC	Raster containing the Jordan population density per km2 in 2015.
Jordan boundaries	Jordan University of Science and Technology	Polygon delimiting Jordan's boundaries
Jordan governorates	Open Street Map	Polygon delimiting the 12 Jordan's governorates
Digital Elevation Model (DEM)	Aster NASA	Raster containing the elevation in meters.
Land cover	European Space Agency GlobCover	Raster that catalogues every square kilometer in different categories according to its land use (urban, crops, water bodies, etc.)
Roads	Humanitarian OSM Team (HOT)	Lines delineating the main roads of Jordan.
Water lines	Humanitarian OpenStreetMap Team (HOT)	Lines delineating the rivers, wadis, streams, etc.
Depth to water table	Glowasis	Raster layer containing the depth to groundwater in meters.
Wells	ArcGIS	Points symbolizing the spots of wells in Jordan.
Cropland	Global Food Security-support Analysis Data (GFSAD)	This dataset contains one band, cropland extent, with 0 = Ocean or inland waterbody, 1 = Non-Cropland, 2 = Cropland with a 30 meters resolution.

Some of the layers, such as the vectors containing administrative boundaries, will be used as a tool to compare the data coming from reliable sources such as the Department of Statistics of Jordan (DoS) and the ministries, and the datasets. Along this chapter, the way each layer was used to reach the final results will be explained.

To make possible the operations between different layers, it is essential that the rasters are aligned. Two rasters are aligned when [44]:

- Coordinate Reference System (CRS): all the layers have to be reprojected into an adequate CRS suitable for Jordan. For this model, the EPSG:3395 - WGS 84 / World Mercator CRS has been selected as it uses meters as units and will make it easier when using some of the tools that will be further explained in this section.

- Are projected in the same Coordinate Reference System (CRS). All the layers have to be reprojected into an adequate CRS suitable for Jordan. For this model, the EPSG:3395 - WGS 84 / World Mercator CRS has been selected as it uses meters as units and will make it easier when using some of the tools that will be further explained in this section.

- Are sampled to the same cell size and offset in the grid. The cell size selected for this model is 1km x 1km. There are two main reasons for using this resolution: a higher resolution requires more computational time when processing the rasters whereas a lower resolution implies less accuracy. The second reason is that most of the datasets found used this resolution.

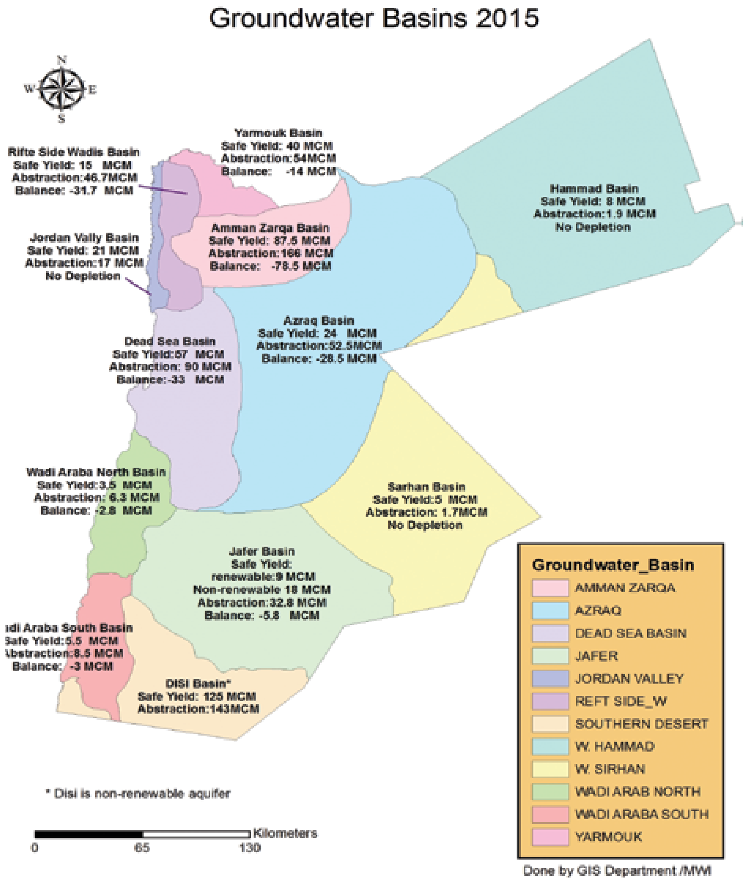
- Are clipped to the region of interest, in this case Jordan. This means that the raster data is limited to the country boundaries, reducing the size of the file and, thus, the time needed to process it.

3.2 Extra layers

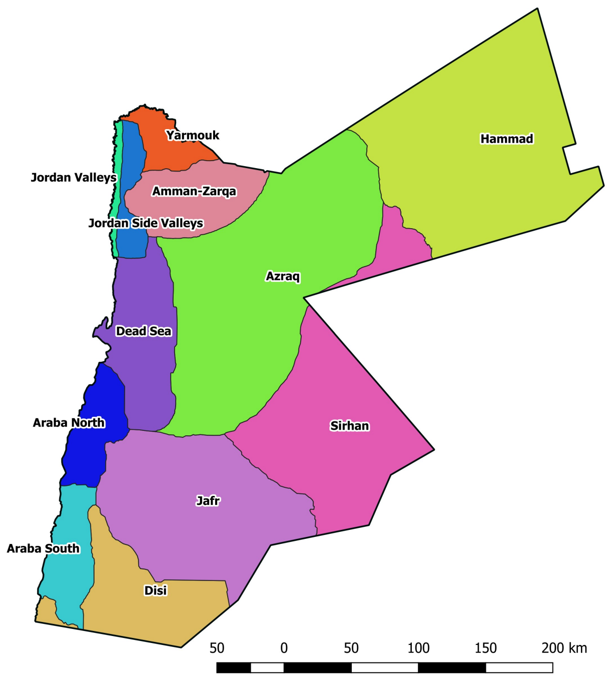
Apart from the aforementioned layers, other vectors were essential for the development of the thesis. These datasets were the wastewater treatment plants and the groundwater basins boundaries. Nevertheless, it was very challenging to find these layers within opnely available non-commercial datasets, forcing to use alternative ways to obtain the layers.

The groundwater basins are necessary for the elaboration of the project as this layer delimits the aquifers of Jordan. This will be very useful to obtain, firstly, the groundwater consumption per basin and, secondly, to obtain in the scenarios the future abstraction for every basin. In order to create this layer, the georeferencing tool of QGIS proved to be very useful. This tool allows the user to open an image file and, by setting some points- the more points the more precision- and assigning their corresponding coordinates and the transformation type, the plugin creates a GeoTIFF file, projecting the initial image to match the points with the coordinates according to the chosen CRS. In this case, the image which has been used is the one that appears in [14] and shown in Figure 3.2. Once the image has been georeferenced, a polygon layer is created, defining the boundaries of the groundwater basins and adding to the vector the abstraction, safe yield and over abstraction of every basin. The obtained layer in QGIS is displayed also in Figure 3.2.

Apart from these layers, the slope was also obtained derived from the DEM that appears in 3.1 by using the slope function of QGIS.



(a)



(b)

Figure 3.2: Groundwater basins from [14] (a) and the obtained vector layer in QGIS (b).

The location of the 32 WWTPs of Jordan may also be required as obtaining the cropland irrigated with treated wastewater is an objective of the thesis. A more rudimentary procedure was used in order to get the location of the WWTPs.

- First of all, the layer of Google Satellite is required in order to observe the satellite image to locate the WWTPs.
- A point layer is created. Each point will represent the WWTPs, introducing in the vector the fields of maximum capacity, annual treatment and technology.
- In the case of As-Samra, as it is the most important WWTP, the location is easy to obtain in Google Maps. With the layer of Google Satellite in QGIS and knowing the location of the plant, the point is set where the treatment plant is found.
- For the rest of the plants, the name of them refers to the town, city or village where it is located. Although more difficult to find, a similar procedure as the followed for As-Samra was used.

Following this method, 31 out of the 32 WWTPs were located in QGIS. However, the WWTP that was impossible to find is the smallest one, Mansorah, with a daily influent of 15CM and a maximum capacity of 50CM, which represents 0.03% of the annual treated wastewater. Consequently, this plant was considered negligible.

Once all this layers are introduced in QGIS, it is possible to proceed with the data calibration and processing.

3.3 Data calibration

In order to create a model as accurate as possible, it is imperative to check if the values provided by the datasets match the regional statistics coming from reliable sources such as the DoS, the MWI and the MOA. The more specific statistics found in these sources was defined by governorate, so the calibration process will make use of the governorates' administrative boundaries for this procedure.

Mainly two different calibration algorithms were used: a rule of three and an Analytical Hierarchy Process (AHP). The data calibration was required for the population and the cropland layers as a previous step to obtain the water consumption of domestic and agriculture sector, respectively.

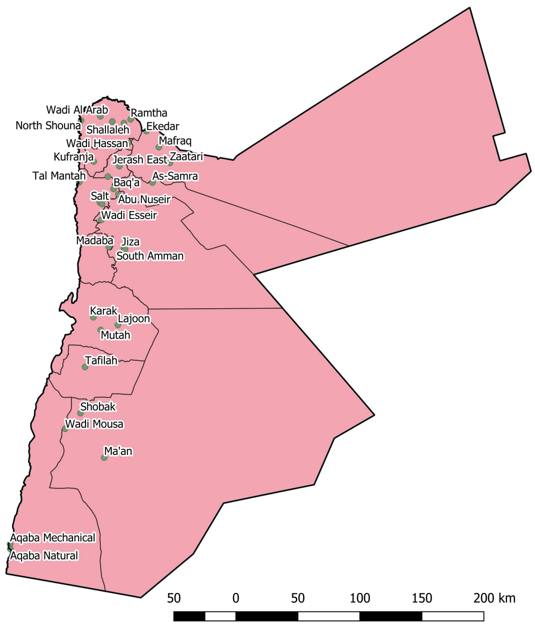


Figure 3.3: WWTPs in Jordan.

3.3.1 Population calibration

A proper population layer is required to calculate the water consumption in the domestic sector. Hence, a rule of three was used so as to match the population of every governorate with the data coming from [45]. The first step is to use the zonal statistics tool in QGIS, suming all the population points of the initial layer and adding it as new field in the governorates vector layer. Then, the statistics of population coming from DoS data was compared with the obtained statistics in QGIS. In Figure 3.4 it can be noticed that most of the regional data differs when compared to the Jordan source. In total, the population in the layer counted with 7.5M people, 2M people less than the total amount reported by DoS.

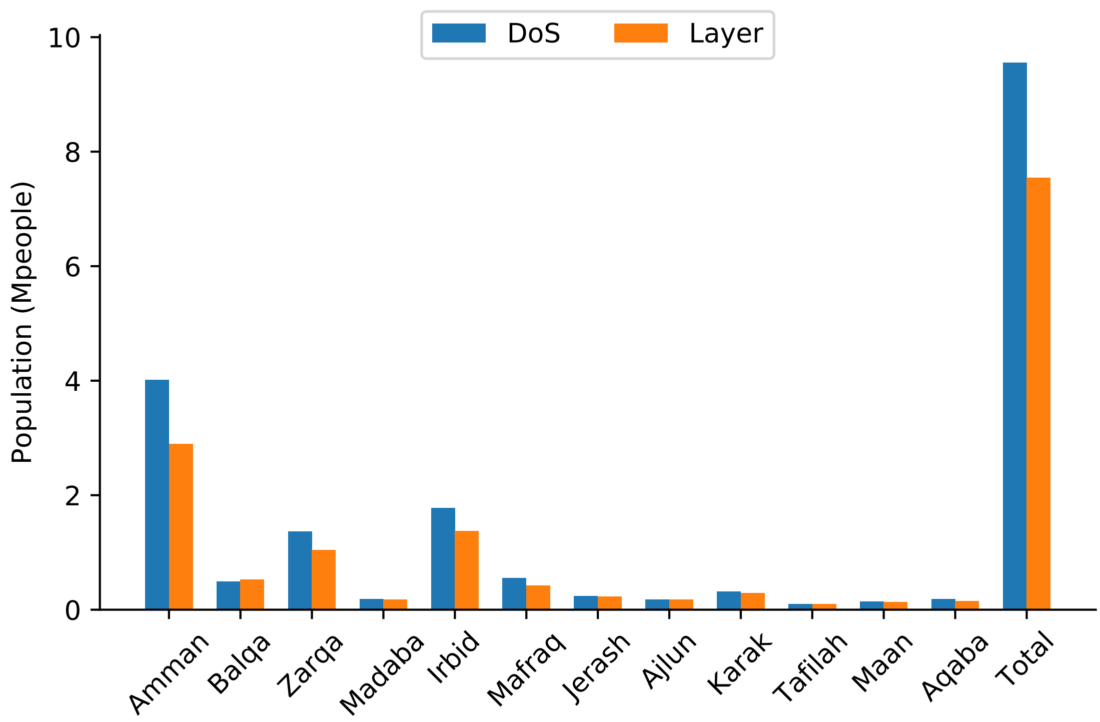


Figure 3.4: Population from [45] in blue and the layer in orange.

So, the calibration is required in order to obtain a more accurate layer. As aforementioned, a rule of three was used in this case. Equation 3.1 was used for this purpose, as was used by [46]:

$$PopCal_{x,i} = \frac{PopDoS_x}{\sum_i^n Pop_{x,i}} * Pop_{x,i} \tag{3.1}$$

Being:

- $PopCal_{x,i}$: Population calibrated layer for point i in governorate x.
- $PopDoS_x$: Total population of governorate x according to [45].
- $\sum_i^n Pop_{x,i}$: Sum of the population of the layer in governorate x
- $Pop_{x,i}$: Population of the layer in governorate x for point i.

3.3.2 Cropland calibration

A different and more complex algorithm was used for the calibration of the cropland: the AHP. But a previous step is needed to reduce the resolution of the layer by creating a $1km^2$ grid to obtain the cropland density per square kilometer. When it is obtained, once again the zonal statistics function of QGIS is used to obtain the total cropland area per governorate to compare it with the regional statistical data obtained in [26]. The comparison is depicted in Figure 3.5, observing that in most governorates, the cropland area obtained with the layer is greater than the actual area, with a total difference of 3M dunums[1], which represents a 112.6% difference against the regional statistics provided.

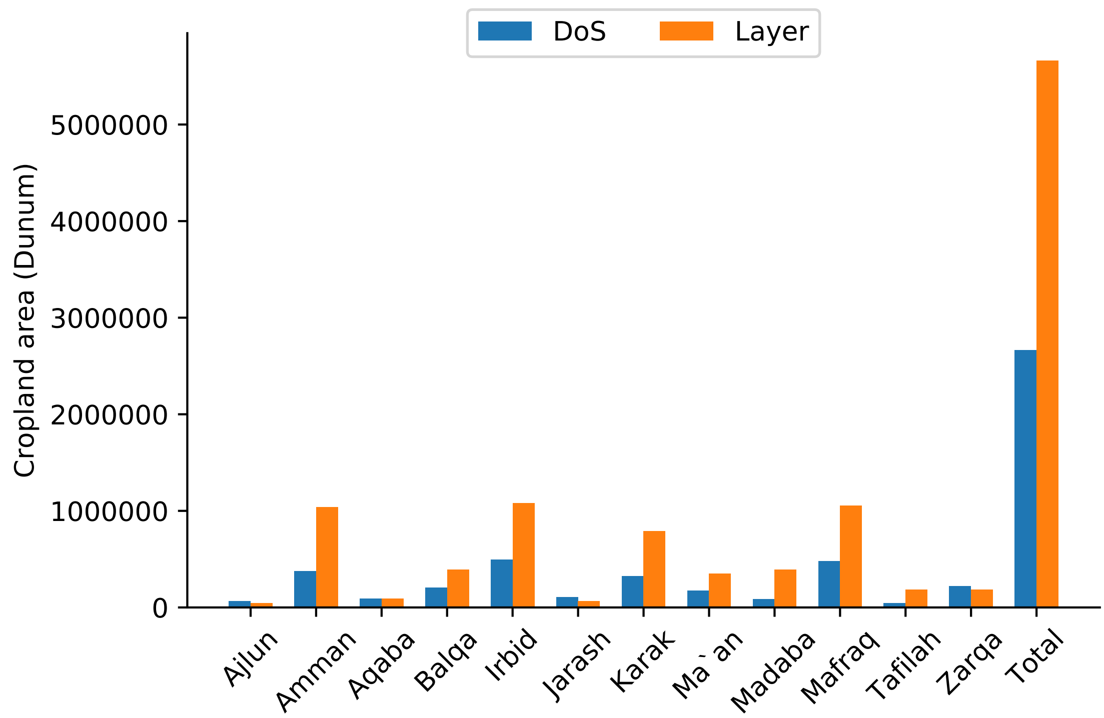


Figure 3.5: Cropland from [26] in blue and the layer in orange.

After completing these previous steps, it is moment to proceed with the AHP. In an AHP, the first step is to identify the problem and the objective [47], which have been previously mentioned. The next step is to identify the criteria that, from a decision maker point of view, may affect, in this case, the suitability of a certain area to contain agricultural land. In [48] a crop suitability layer was obtained with this method by using several data layers. As the purpose of the AHP in this model is to calibrate an already existent layer and due to differences in the objective region and existing databases,

[1] 1dunum = $0.001km^2$

some of the input layers were changed. The factors considered for the cropland calibration were:

- **Distance to rivers:** As previously said, the agriculture zones are mainly located in the north-west of the country, where most of the water surface sources are found. Thus, areas close to the main rivers and the KAC will be more suitable for the cropland development.

- **Distance to roads:** The existence of roads facilitates the transportation of inputs and outputs in the cropland. Therefore, the proximity of a road could mean an area would be more likely cropland.

- **Cropland density:** It was considered that, once the cropland density was obtained in the previous step, those areas where the cropland density was higher can stand a higher chance of being actually cropland, rather than areas in which the density was almost negligible. What is more, cropland areas are mainly located where the soil is more fertile and the water sources are more abundant, so it seems reasonable to think that croplands will be densely found in the suitable areas rather than scattered randomly.

- **Wells density:** Wells are used to pump groundwater. To reduce losses and energy consumption, the wells are located close to where they are required, such as for irrigation purposes. Hence, those points where the well density was higher are more suitable for the development of cropland.

- **Slope:** According to [48], "slope relates to the retention and movement of soil particles and the rates of runoff and soil erosion". Consequently, the lower the slope, it is, the flatter the terrain the higher the chances to find cropland on it.

- **Urban area:** With the land use layer, it is possible to obtain the urban regions in the country. This can serve as a filter, considering that those points where land is covered by urban area are unlikely to contain cropland.

To obtain the distance to rivers and to roads, the proximity raster analysis tool was used.

Once the factors that may affect the cropland suitability are chosen, the next stage is to build a pair-wise comparison. To do so, a matrix is built, having in both the rows and the columns the different layers, as can be seen in 3.3. Then, relative judgement values are specified, assigning relative scores to compare the criteria *j* with the criteria *k*. If the assigned score in the position j,k of the matrix is higher than 1, then $criteria_k$ is being considered more important than $criteria_j$ by the decision maker, being k the rows and j the columns. A number from 1 to 9 has to be assigned to the appropriate position, having the transpose position the reciprocal number [49]. It needs to be mentioned that the values in the diagonals, it is, when comparing the same criteria, the value has to be 1. Table 3.2 explains a little bit further the scores in the matrix.

Table 3.2: The fundamental scale of absolute numbers [49].

Values	**Interpretation**
1	k and j are equally important
3	k is slightly more important than j
5	k is more important than j
7	k is strongly more important than j
9	k is absolutely more important than j

Afterwards, the weights, or priorities, of each criteria is calculated. To do so, the average value of the division between the values of criteria k and the sum of column j, being j = k, is calculated, as shown in Equation 3.2.

$$Weight_k(\%) = \overline{X_k}\left(\frac{Criteria_{kj}}{\sum_{k=1}^{n} Criteria_{kj}}\right) \times 100 \tag{3.2}$$

With all these considerations, Table 3.3 can be built.

Table 3.3: AHP explanatory table

Parameter	$Criteria_j$ **(j=1)**	$Criteria_j$ **(j=2)**	$Criteria_j$ **(j=3)**	**Weights (%)**
$Criteria_k$ **(k=1)**	1	A	B	$\omega 1$
$Criteria_k$ **(k=2)**	1/A	1	C	$\omega 2$
$Criteria_k$ **(k=3)**	1/B	1/C	1	$\omega 3$

To check that the matrix is correctly built, it is, that the judgement values are consistent, the Consistency Ratio (CR) is calculated. To do so, several steps need to be followed:

1. A Weighted Sum Matrix (WSM) is calculated by using Equation 3.3:

$$WSM = \sum_{j=1}^{n} Weight_j \times \begin{vmatrix} Criteria_{1j} \\ Criteria_{2j} \\ . \\ . \\ . \\ Criteria_{nj} \end{vmatrix} \tag{3.3}$$

   Being:

   - WSM: The weighted sum matrix.
   - $Weight_j$: the weight of the different criteria.
   - $Criteria_{nj}$: the values in the comparison matrix.
   - n: the comparison matrix size.

2. A factor named *eigenvalue* (λ_{max}) by [47] is then obtained as follows:

$$\lambda_{max} = \frac{\sum_{j=1}^{n} \frac{WSM_{j1}}{Weight_j}}{n} \tag{3.4}$$

   Being:

   - λ_max: the eigenvalue defined by [47].
   - WSM_{j1}: the values of the weighted sum matrix.
   - $Weight_j$: the weights of the different criteria.
   - n: the comparison matrix size.

3. The Consistency Index (CI) is then calculated by using Equation 3.5:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3.5}$$

   Being:

   - CI: the consistency index
   - λ_max: the eigenvalue defined by [47].
   - n: the comparison matrix size.

4. The last step is to calculate the CR with Equation :

$$CR = \frac{CI}{RI} \tag{3.6}$$

Being:

- CR: the consistency ratio
- CI: the consistency index
- RI: the random consistency ratio defined in Table

Table 3.4: Values of random consistency ratio depending on the size of the matrix [47].

Size of matrix	1	2	3	4	5	6	7	8	9	10
Random consistency	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

With the CR it is possible to know if the judgement values are consistent. The matrix will be consistent if the CR is lower than 0.1 [49, 47]. If this conditions is not satisfied, then a reconsideration of the judgement values is needed in order to accomplish it.

After checking the consistency of the matrix and having the weights of the criteria, it is moment to obtain an "unsuitability" vector. To do so, the first step is to identify if the parameters are directly or inversely related with the cropland unsuitability, that is, if the higher the value or the lower the value, the higher the unsuitability. As an example, it has been considered that the higher the cropland density of the layer, the higher the probability of finding cropland in that area. Therefore, this factor is inversely related to the cropland unsuitability. Taking this into account, the next step is to normalize the values of the parameters of the matrix. This is a requisite to be able to compare directly all the parameters. Equation 3.7 normalizes the values when the relation is direct, and Equation 3.8 if not. It should be noticed that, in the case of Equation 3.8, the normalized value would be set as 1 if in that point the value of the layer is 0 to avoid errors due to dividing by 0.

$$NormalizedValue_{j,i} = \frac{Value_{j,i}}{Value_{j,max}} \tag{3.7}$$

$$NormalizedValue_{j,i} = \frac{{Value_{j,i}}^{-1}}{{Value_{j,max}}^{-1}} \tag{3.8}$$

Being:

- $NormalizedValue_{j,i}$: Normalized value of the criterion j in point i.
- $Value_{j,i}$: Value of the layer of the criterion j in point i.
- $Value_{j,min}$: Minimum value of the layer of the criterion j.

Applying these formulas, all the values in every layer will be in the range from 0 to 1. After completing this preparation process, the unsuitability of the points of the layer containing cropland can be finally estimated by using Equation 3.9.

$$Unsuitability_i = \sum_{j=1}^{n} criteria_{i,j} \times Weight_j \tag{3.9}$$

With:

- $Unsuitability_i$: the unsuitability value in point i.
- $criteria_{i,j}$: the value of the parameter j of the matrix comparison in point i.
- $Weight_j$: the weight of the parameter j.

Then, the algorithm compares the cropland area of the layer per governorate with the regional statistical data in [26]. An accuracy is set by the user in order to reduce the computational time and to help the algorithm to converge. If the values do not match, then the algorithm removes the point with the highest unsuitability until the condition is accomplished.

After all this explanation, it is time to return to the case of the cropland calibration. The comparison matrix that has been built for such process is shown in Table 3.5.

Table 3.5: Comparison matrix for the cropland calibration.

Parameter	Distance to river	Distance to road	Cropland density	Wells density	Slope	Urban area	Weights (%)
Distance to river	1	1/2	1/7	1/2	1/3	1/9	3.53
Distance to roads	2	1	1/4	1	1/2	1/9	5.76
Cropland density	7	4	1	7	3	1/2	26.44
Wells density	2	1	1/7	1	1/9	1/9	5.3
Slope	3	2	1/3	2	1	1/9	9.17
Urban area	9	9	2	9	9	1	49.79

The urban area has the highest priority so as to make sure that the cropland located in urban area is directly removed. The second highest weight is given to cropland density, as it was noticed that the areas in which the cropland density of the layer was higher, agriculture land was actually found. The weights of the other values were modified until a satisfactory layer was obtained. In order to analyze if the resulting layer was adequate, it was overlaid to a satellite image to check if the the different agriculture areas were really cropland and was also compared with different sources.

The accuracy was set as 0.05, it is, the expected error is 5% when comparing the regional statistics with the layer. It must be highlighted that this algorithm only eliminates already existent points, and thus the governorates in which the cropland area in the layer is lower than the statistical regional data will not be calibrated. In order to fix this error and the 5% error of the calibration, a rule of three is again used in Equation 3.10 with the data from [26]:

$$CropCal_{x,i} = Cropland_{x,i} \times \frac{DoS_x}{Cropland_x} \tag{3.10}$$

Being:

- $CropCal_{x,i}$: the final calibration layer value in point i of governorate x.
- $Cropland_{x,i}$: the cropland layer value in point i of governorate x obtained after applying the AHP.
- DoS_x: the value in [26] for governorate x.
- $Cropland_x$: the sum of the values of the cropland layer in governorate x.

3.4 Water consumption by sector

The calibration of these two layers was essential to obtain accurate layers of water consumption by sector and source. In this section, the methods employed for this purpose are explained.

3.4.1 Domestic water consumption

For obtaining the domestic water consumption layer, the regional statistics provided by [40] were used. It should be noticed that, although being the same source as the one used in the literature review, this document is not as updated as it is from 2013. However, in [14] the domestic water consumption was not divided per regional statistics, whereas in [40] the domestic water consumption is itemized per governorate, as well as the NRW. So, a more precise water consumption layer can be obtained by using this source and applying a correction factor as the water consumption in 2013 was lower than in 2015, 380.7MCM and 456.5MCM respectively. A correction factor was also applied to the NRW due to an increase of the average value in these years, from 48% to 51.3%. Finally, the water supply was calculated by dividing the water consumption by the NRW. The total water consumption and supply are calculated using the following formulas:

$$wcons_i = \sum wpc_{2013x} \times Pop_{x,i} \times \frac{wcons_{2015}}{wcons_{2013}} \tag{3.11}$$

$$wsup_i = \sum \frac{wcons_{x,i}}{NRW_{2013x}} \times \frac{NRW_{2015}}{NRW_{2013}} \tag{3.12}$$

Being:

- $wcons_i$: water consumption obtained in point i.
- wpc_{2013x}: water consumption per capita of governorate x.
- $Pop_{x,i}$: population of governorate x in point i.
- $wcons_{2015}$: total water consumption of domestic sector in 2015.
- $wcons_{2013}$: total water consumption of domestic sector in 2013.
- $wsup_i$: water supply calculated in point i.
- $wcons_{x,i}$: water consumption obtained in Equation 3.11 of governorate x in point i.
- NRW_{2013x}: NRW of governorate x in 2013.
- NRW_{2015}: average NRW in 2015.
- NRW_{2013}: average NRW in 2013.

3.4.2 Agriculture water consumption

For the agriculture water consumption, a more detailed process needed to be performed. First, the calibrated cropland layer was distinguished between irrigated and rain-fed cropland. Then, the evapotranspiration of the irrigated cropland was obtained by following the methodology of [50]. Finally, the water consumption was calculated. This procedure will be explained along the following sections.

Irrigated and rain-fed cropland

Distinguishing between irrigated and rain-fed cropland is a prerequisite for calculating the water consumption for irrigation, as only those areas where irrigation is developed will consume water. An AHP algorithm was again used for this to obtain the irrigated land. In this case, rainfall was considered with a direct relation, as the more abundant the rainfall the more suitable for rain-fed cropland and less likely for irrigation use. Cropland density was also taken into account with a reverse relation, as a higher density would mean, on the one hand, the need of more water, meaning that it would require more rainfall. On the other hand, a higher density of crops optimizes and reduces the cost of irrigation techniques. Rainfall was considered as the most important factor in this case, being the comparison matrix:

Table 3.6: Comparison matrix for irrigated cropland.

Parameter	Rainfall	Cropland density	Weight
Rainfall	1	4	0.8
Cropland density	1/4	1	0.2

Again, an accuracy of 0.05 was set. The calibration values were obtained from [26]. In this document, the dunums of every group of crop- field crops, fruit trees and vegetables- are divided per governorate and if they are irrigated or rain-fed, being extremely useful for the development of this thesis. What is more, the area of every type of crop- olive tree, apples, dates, etc.- is also specified, as well as the use of every irrigation technique, which will be used later. Thus, the calibration value in this AHP is the sum of the regional statistical data of irrigated land of the crop groups.

Once the irrigated land is obtained, it has been assumed that, in every point of the raster layer and taking into account the area of every crop group that is being irrigated, the many types of crops are equally distributed, it is, the percentage that represents every crop in its group remains the same in every point of the layer.

Evapotranspiration

The next step after obtaining the distribution of the different type of crops in the irrigated land is to estimate the evapotranspiration layer. For this purpose, the methodology proposed by FAO in [50] was performed. The evapotranspiration is, basically, the sum of the evaporation of water in a crop soil and the transpiration of the crop. With the evapotranspiration, it is easy to obtain the irrigation demand as the evapotranspiration can be understood as the crop water consumption. A scheme of the evapotranspiration in a crop soil is depicted in 3.6.

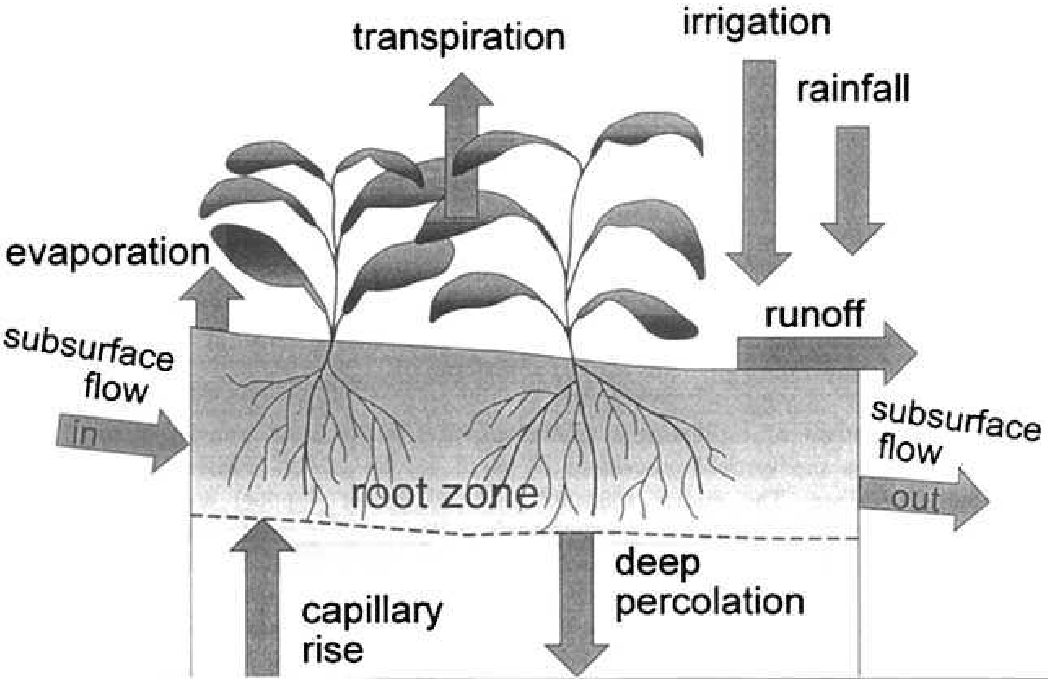


Figure 3.6: Evapotranspiration scheme. Source: [50].

Calculating the evapotranspiration of the cropland is not an easy process: several factors need to be taken into consideration and a few steps must be followed.

The reference evapotranspiration (ET_0), defined as the evapotranspiration of a hypothetical well irrigated grass surface, is required to obtain the actual evapotranspiration. This parameter only depends on climatic conditions, and the FAO Penman-Monteith method is going to be used as recommended in [50] due to the fact that it explicitly incorporates both physiological and aerodynamic parameters. Figure 3.7 shows a scheme of the reference evapotranspiration.

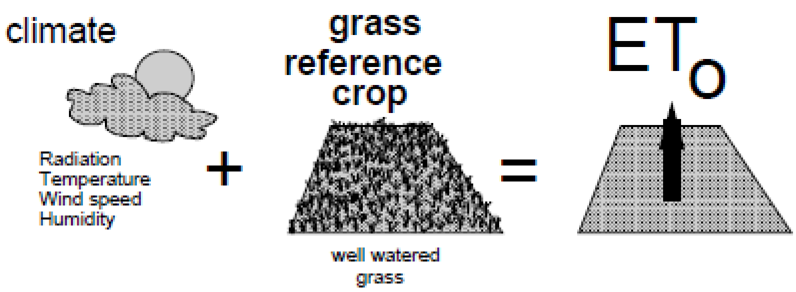


Figure 3.7: Reference evapotranspiration scheme. Source: [50].

Although this parameter should be obtained for every day, due to the data availability it is going to be obtained monthly. The climatic factors affecting reference evapotranspiration and the way to calculate them are:

- **Atmospheric parameters**: The calculation of some atmospheric parameters is a prerequisite to obtain the climatic factors. First of all, the atmospheric pressure- which depends on the elevation- is obtained for every point in the map with:

$$P = 101.3 \left(\frac{293 - 0.0065z}{293} \right)^{5.26} \tag{3.13}$$

  Being:

  - P: atmospheric pressure [kPa].
  - z: elevation, obtained with the elevation layer [m].

  With this parameter, the psychrometric constant, factor which will be used when obtaining the reference evapotranspiration and necessary as it relates the absolute vapor pressure with the saturation one. It can be calculated with Equation 3.14:

$$\gamma = \frac{c_p P}{\epsilon \lambda} = 0.665 \times 10^{-3} \tag{3.14}$$

  Where:

  - γ: psychrometric constant [$\frac{kPa}{^{\circ}C^{-1}}$].
  - P: atmospheric pressure [kPa].
  - λ: latent heat of vaporization, assumed as 2.45 [$\frac{MJ}{kg}$].
  - c_p: specific heat at constant pressure, 1.013 10-3 [$\frac{MJ}{kg^{\circ}C}$].

- **Air humidity**: being the water vapor contained in the surrounding air of the cropland, air humidity is the factor that determines the vapor removal in this area. Consequently, hot dry arid regions will consume more water than humid regions as the removal power will be higher. In the quest of calculating the evapotranspiration, vapor pressure is used as it is related to the air humidity. The vapor pressure is obtained from its homonym QGIS layer. The air has a limited capacity to contain water vapor. In a certain content, the water vapor that precipitates from the air is equal to the water vapor that is being absorbed by it. This value is named saturated vapor pressure, which depends on the air temperature and is obtained using Equation 3.15:

$$e^o(T) = 0.6108 \times exp\left(\frac{17.27T}{T + 237.3}\right) \tag{3.15}$$

  Where:

  - $e^o(T)$: saturation vapour pressure at the air temperature T [kPa].
  - T: air temperature [°C].

  The slope of the relationship between vapor pressure and temperature will be needed to obtain the evapotranspiration. It is calculated with:

$$\Delta_{month} = \frac{4098 \times 0.6108 \times exp\left(17.27 \times \frac{T_{avg,month}}{T_{avg,month}+237.3}\right)}{(T_{avg,month} + 237.3)^2} \tag{3.16}$$

- **Air temperature**: the air temperature is required for obtaining radiation parameters, as well as the saturation water pressure. The monthly minimum and maximum temperature were obtained from the layer mentioned in Table 3.1

- **Solar radiation (R_s)**: solar radiation is the energy that reaches the surface in a period of time. The evapotranspiration is a process that requires energy, and solar radiation is the main energy source. Thus, higher radiation implies higher evapotranspiration in the region. However, not all the solar radiation is absorbed by the crop and the soil, some of it is reflected by them or by the clouds. Thus, the net solar radiation absorbed by these elements has to be calculated. Starting from the solar radiation layer introduced in QGIS, the steps that needs to be followed are:

1. Clear-sky solar radiation (R_{so}): solar radiation that would reach the surface if there are no clouds in the sky. Due to the unavailability of data to obtain it, it was assumed that $R_{so} == R_s$.

2. Net shortwave radiation (R_{ns}): Given by Equation 3.17, the net shortwave radiation is the solar radiation that is not reflected by the soil and the grass.

$$R_{ns} = (1 - \alpha)R_s \tag{3.17}$$

Where:

   – R_{ns}: net solar or shortwave radiation in $[\frac{MJ}{m^2\ day}]$.
   – α: albedo or canopy reflection coefficient, which is 0.23 for the hypothetical grass reference crop [dimensionless].
   – R_s: the incoming solar radiation in $[\frac{MJ}{m^2\ day}]$.

3. Net longwave radiation (R_{nl}): longwave radiation is the energy emitted by a surface as a consequence of temperature. Hence, it can be understood as energy that is being lost by the crop and the soil. Equation 3.18 is used to calculate the longwave radiation:

$$R_{nl} = \sigma \left[\frac{T^4_{max,K} + T^4_{min,K}}{2}\right] (0.34 - 0.14\sqrt{e_a}) \left(1.35\frac{R_s}{R_{so}} - 0.35\right) \tag{3.18}$$

Where:

   – R_{nl}: net outgoing longwave radiation $[\frac{MJ}{m^2\ day}]$.
   – σ: Stefan-Boltzmann constant $[4.903 \times 10^{-9} \frac{MJ}{K^4 m^2 day}]$.
   – $T_{max,K}$: maximum absolute temperature during the 24-hour period [K = °C + 273.16].
   – $T_{min,K}$: minimum absolute temperature during the 24-hour period [K = °C + 273.16].
   – e_a: actual vapor pressure [kPa], provided by the QGIS layer mentioned in 3.1.
   – $\frac{R_s}{R_{so}}$: relative shortwave radiation (limited to 1.0). As it has been assumed that $R_{so} == R_s$ this coefficient will be 1.
   – R_s: measured solar radiation $[\frac{MJ}{m^2 day}]$.
   – R_{so}: calculated clear-sky radiation.

4. Net radiation (R_n): the net radiation is the difference between the incoming and the outgoing radiation. In this case, the incoming

radiation is the shortwave radiation and the outgoing radiation, the longwave one:

$$R_n = R_{ns} - R_{nl} \tag{3.19}$$

Where:

- R_n: net radiation $[\frac{MJ}{m^2\ day}]$.
- R_{ns}: net shortwave radiation $[\frac{MJ}{m^2\ day}]$.
- R_{nl}: net longwave radiation $[\frac{MJ}{m^2\ day}]$.

Afterwards, the soil heat flux (G) is then obtained with Equation 3.20. G is the energy absorbed by the soil, if G is greater than 0, or emitted by it if it is lower than 0.

$$G_{month,i} = 0.07 \times (T_{month,i+1} - T_{month,i-1}) \tag{3.20}$$

Where:

- $T_{month,i}$: mean air temperature of month i [°C].
- $T_{month,i-1}$: mean air temperature of previous month [°C].
- $T_{month,i+1}$: mean air temperature of next month [°C].

- **Wind speed**: wind speed affects the capacity of the air to remove vapor from the soil and crop. If the wind is quiet, then humidity cannot be removed, whereas high wind speeds favor the absorption of humidity as the saturated air is constantly replaced. Thus, high wind speeds increases evapotranspiration. Wind speed was obtained and introduced in QGIS. In this layer, this parameter was measured at a 10 meters height. However, the FAO methodology requires the wind speed to be measured at 2 meters above the ground level. Then, the values have to be adjusted with Equation 3.21, as wind speed decreases when closer to the ground:

$$u_2 = u_z \times \frac{4.87}{ln(67.8z - 5.42)} \tag{3.21}$$

Where:

- u_2: wind speed at 2m above ground surface $[\frac{m}{s}]$.
- u_z: measured wind speed at z m above ground surface $[\frac{m}{s}]$.
- z: height of measurement above ground surface, in this case 10m.

With all these previous calculations, the monthly reference evapotranspiration can be obtained with Equation 3.22:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{3.22}$$

Where:

- ET_0 reference evapotranspiration $[\frac{mm}{day}]$
- R_n net radiation at the crop surface $[\frac{MJ}{m^2\ day}]$
- G soil heat flux density $[\frac{MJ}{m^2\ day}]$
- T air temperature at 2m height $[^oC]$
- u_2 wind speed at 2m height $[\frac{m}{s}]$
- e_a actual vapor pressure $[kPa]$
- e_s saturation vapor pressure deficit $[kPa]$
- Δ slope vapor pressure curve $[\frac{kPa}{^oC}]$
- γ psychrometric constant $[\frac{kPa}{^oC}]$

Notice that the reference evapotranspiration is obtained for every square kilometer, according to the resolution used in QGIS for this project. As the reference evapotranspiration is obtained daily, the values are multiplied by the number of days of every month.

Once this is done, the standard evapotranspiration (ET_c) can be estimated. The standard evapotranspiration is the crop evapotranspiration under standard conditions, it is, when the crop is well-watered, well-fertilized, disease-free and under optimum soil conditions[50]. Figure 3.8 schematizes the standard evapotranspiration.

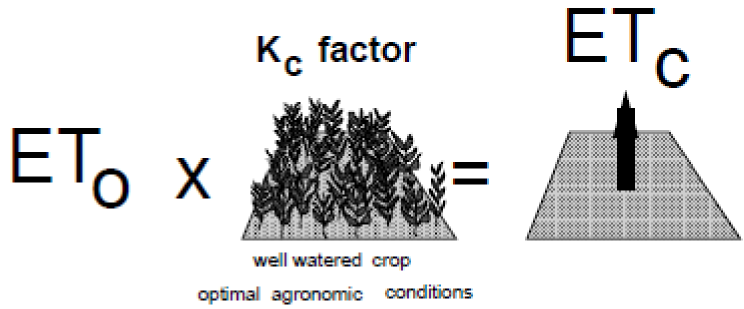


Figure 3.8: Standard evapotranspiration scheme. Source: [50].

Two methods appear in [50] for this purpose: the single crop coefficient approach, which applies just one factor known as crop coefficient (K_c) to the reference evapotranspiration to obtain the standard one; and the dual crop coefficient approach, in which the crop coefficient is the sum of the basal crop coefficient and the soil water evaporation coefficient. The former will be used here, as [50] recommends this approach when the calculation period is longer than one week and is simpler than the latter.

The crop coefficient depends on the crop type and the stage of development. As aforementioned, in the cropland layer the division of the crop type was already estimated. Hence, the next step is to obtain the crop calendar, which provides the needed information to know the development stage of every crop depending on the month. Four development stages are identified and depend on the growth of the crop: initial, crop development, mid-season and late season. The evolution of the crop coefficient with the development stage is shown in Figure 3.9.

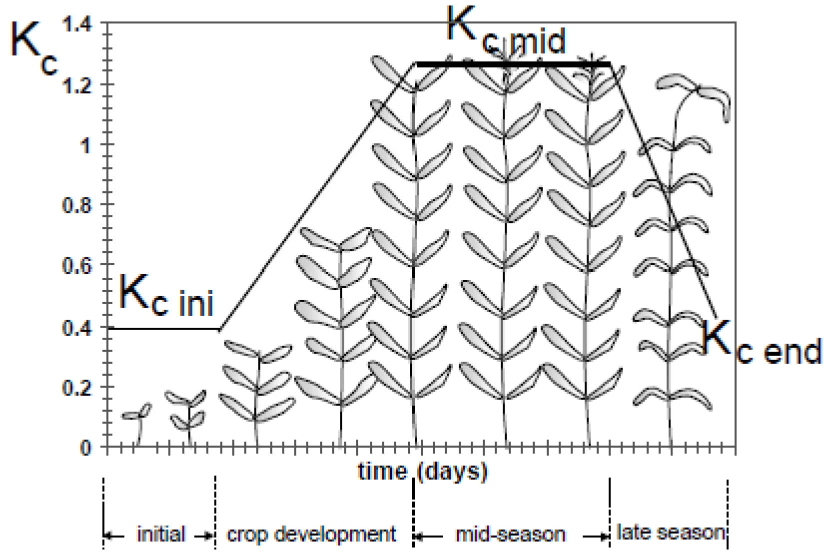


Figure 3.9: Crop coefficient curve for the different development stages. Source: [50].

In [51], some crop calendars of the most important crop types developed in the JV are specified. However, there are not many crops defined in this document. For the rest crop types, [50] specifies almost all the rest of the crops. Furthermore [50] provides the crop coefficient for every crop type and for every development stage. For the few cases that are not defined in either document, an average value of crop coefficient is used for every stage. So, the monthly standard evapotranspiration for every point is calculated with:

$$ET_{c,x} = \sum K_{c,i,x} \times ET_{0,x} \times AreaCrop_{i,x} \tag{3.23}$$

Where:

- $ET_{c,x}$: the standard evapotranspiration in point x.
- $K_{c,i,x}$: the crop coefficient of crop i in point x.
- $ET_{0,x}$: the reference evapotranspiration in point x.
- $AreaCrop_{i,x}$: the area occupied by crop i in point x.

The evapotranspiration can be obtained more specifically for a certain area with the crop evapotranspiration under non-standard conditions (ET_{cadj}), which takes into account factors such as water stress conditions, management practices, etc. However, a survey should be performed in the cropland areas to obtain the required information to know which factors should be applied to every point in the map. Therefore, for the estimation of water consumption in agriculture for this thesis the standard evapotranspiration was assumed as it is a good enough approximation.

Water consumption and supply

The evapotranspiration makes it possible to calculate the irrigation water demand. A water balance has to be applied to obtain the irrigation demand. This balance can be appreciated in Figure 3.6, having as incoming water rainfall, irrigation, subsurface flow and capillary rise and as outgoing water evaporation, transpiration, runoffs, deep percolation and subsurface flow. In [52], an easier balance is used to obtain the demand, with incoming water the precipitation and irrigation and as outgoing, evapotranspiration and water losses in the crop field, as appears in Equation 3.24:

$$W_{n,i} = \sum_{j=1}^{12} ET_{c,i,j} + W_{rs,i,j} - P_{e,i,j} \tag{3.24}$$

Where:

- $W_{n,i}$: net irrigation water requirements in point i [mm].
- $ET_{c,i,j}$: obtained standard evapotranspiration in point i in month j [$\frac{mm}{month}$].
- $W_{rs,i,j}$: water losses from crop field [$\frac{mm}{month}$].
- $P_{e,i,j}$: precipitation in point i in month j [$\frac{mm}{month}$].

To simplify the model, the water losses were neglected. The precipitation was obtained from the layer in Table 3.1.

The water supply differs from the water demand for irrigation due to the water efficiency of the different irrigation technologies explained in Section 2.5. Thus, to obtain the water supply for agriculture, the average water efficiency of irrigation per governorate was obtained with the information from [26] and the efficiencies defined in Section 2.5 using Equation 3.25:

$$\epsilon_x = \sum \frac{Area_{i,x}}{Area_{irrigated,x}} \times \epsilon_i \tag{3.25}$$

Where:

- ϵ_x: the irrigation efficiency in governorate x.
- $Area_{i,x}$: area irrigated with technology i in governorate x [dunums].
- $Area_{irrigated,x}$: total irrigated area in governorate x [dunums].
- ϵ_i: efficiency of irrigation technology i.

Then, the water supplied for agriculture is:

$$Supply_i = \frac{\sum W_{n,i,x}}{\epsilon_x} \tag{3.26}$$

Where:

- $Supply_i$:water supplied for agriculture in point i.
- $W_{n,i,x}$: net irrigation water requirements in point i in governorate x [mm].
- ϵ_x: average irrigation efficiency in governorate x.

3.5 Water supply by source

When the water consumption in domestic and agriculture sector is estimated, it is possible to obtain, considering the gathered information in the literature review, to estimate the provenience of the water resource. As aforementioned, three main water sources are employed in Jordan nowadays: groundwater, treated wastewater and surface water. In this section, the way it was estimated geographically which source is being used in every point will be explained.

3.5.1 Treated wastewater

As explained, 90% of the treated wastewater is reused for irrigation. In order to estimate the cropland that is being irrigated with this source, an AHP is performed. In this case, two different considerations needs to be taken into account: whereas the treated wastewater coming from most of the WWTP are reused for local cropland, that water treated by As-Samra is poured in Zarqa river and stored in KTD, where is then sent to the JV. Thus, two different comparison matrices are employed: for As-Samra, the distance to KTD will be considered whereas for the other WWTP the distance to the respective plant will be used as criterion. Apart from these criteria, it has been considered that the cropland close to wells and to surface water resources will be more unsuitable for being irrigated with this source, as it seems more likely to be irrigated by groundwater or surface water. Thereby, the comparison matrix for this process is:

Table 3.7: Comparison matrix for obtaining cropland irrigated with treated wastewater.

Parameter	Distance to KTD/WWTP	Distance to surface water	Wells density	Weight
Distance to KTD/WWTP	1	2	5	0.58
Distance to surface water	1/2	1	3	0.31
Wells density	1/5	1/3	1	0.11

The CR of this matrix is 0.003, so the matrix is consistent and can be used. The accuracy is set at 0.1 and the calibration value, the daily inflow shown in Table B.1 for every WWTP multiplied by 90%. However, when applying this algorithm, a problem arose as in the first attempt the algorithm would not converge. For some reason that, after an analysis, was not found, the process needed to be applied twice to obtain a proper result. Thus, a function could not be created to run the process for all the WWTPs and it had to be run individually, which required much more time. This fact and convergence problems with the smallest WWTPs obliged to run the algorithm with the 9 greatest plants, which were: As-Samra, Irbid center, South Amman, Wadi al Arab, Aqaba Mechanical, Baq'a, Shallaleh, Ramtha and Salt. This will not suppose a big error as these plants supposed more than the 95% of the total treated wastewater in 2015.

3.5.2 Groundwater

For the groundwater consumption in agriculture, to the total water supply those areas that were estimated to be irrigated with treated wastewater were removed. Then, an AHP was used, considering in this occasion that groundwater will be used as a water source in those areas where most wells are located and are far away from surface water sources such as rivers and dams. The comparison matrix for this case is:

Table 3.8: Comparison matrix for obtaining agriculture groundwater supply.

Parameter	Distance to rivers	Distance to dams	Wells density	Weight
Distance to rivers	1	1/0.7	1/2	0.26
Distance to dams	0.7	1	1/3.5	0.17
Wells density	2	3.5	1	0.57

With a CR 0.004 and an accuracy of 0.15. The calibration values were obtained from [53], paper in which the groundwater consumed in every basin was divided by sector. However, this document considered the consumption in 2004. Hence, the percentage that supposed every sector for every basin was considered and the consumption per basin was updated with the values in [14], taking into account in the case of the Disi aquifer the groundwater used in the Disi-Amman conveyance.

In the case of domestic consumption, it was considered that in every basin the groundwater supply for this sector was equally distributed. Therefore, the Equation X was used to obtain the groundwater supply for domestic consumption:

$$GW_{domestic,i,x} = DomSup_{i,x} \times \frac{Dombasin_x}{\sum DomSup_{i,x}} \tag{3.27}$$

Where:

- $GW_{domestic,i,x}$: groundwater supply for domestic sector in point i in basin x.
- $DomSup_{i,x}$: domestic water supply in point i in basin x.
- $Dombasin_x$: total groundwater used for domestic purpose in basin x.
- $\sum DomSup_{i,x}$: total domestic water supply in basin x.

In the case of Amman, the Disi-Amman conveyance was taken into account, adding the corresponding groundwater coming from the Disi aquifer.

3.5.3 Surface water

As there was not regional statistical data regarding surface water consumption neither for agriculture nor for domestic sector, this source was estimated by removing from the total water supply per point the water supplied by the groundwater in the case of the domestic sector, and removing the cropland areas irrigated with treated wastewater and with groundwater in the case of the agriculture sector.

3.6 Energy consumption in the water sector

The energy consumption in water sector can now be calculated as the water consumption has been divided per source and sector. Four different categories of energy consumption have been considered according to the scope of the project and the data availability: energy for wastewater treatment, energy for groundwater pumping, energy required in the Disi-Amman conveyance and energy for water distribution. In the following sections, the way these consumptions have been obtained is going to be explained.

3.6.1 Energy for wastewater treatment

Different ways exist to calculate the energy required for wastewater treatment. The one that seems more accurate is taking into account both the water inflow and the Biochemical Oxygen Demand (BOD5). However, as mentioned in Section 1.3, water quality has not been considered in this model and, thereby, this method is discarded. Another simpler approach is just considering the energy consumption depending exclusively on the water inflow. In [54], average energy consumptions values of different treatment technologies are estimated. Thus, the energy consumption for every WWTP was estimated with Equation :

$$E_{WWTP} = Q_{WWTP,i,t} \times X_t \tag{3.28}$$

Where:

- E_{WWTP}: Energy consumed by the WWTP in kWh/year.
- $Q_{WWTP,i,t}$: annual inflow in the WWTP for year i using technology t in $\frac{m^3}{year}$.
- X_t: average energy consumption of technology t in $\frac{kWh}{m^3}$.

In the case of As-Samra, there is information regarding its energy consumption that is going to be used as this data is more accurate for this WWTP scope. The data was obtained from [55].

3.6.2 Energy for groundwater-pumping

To obtain the energy required for groundwater pumping, it has been assumed that groundwater is being pumped where the water is being consumed. Then, considering the layers of depth to water table and groundwater supply for agriculture and domestic sectors, the first thing that has to be obtained for calculating the energy for groundwater pumping is the the total pressure required [52]:

$$H_{tot,i} = Lift_i + H_{opp,i} + F_{loss,i} \tag{3.29}$$

Where $H_{tot,i}$ is the total pressure required for pumping and applying water in meters, $Lift_i$ is the height water has to be lifted in point i, in this case the depth to water table ; $H_{opp,i}$ is the operating pressure required,which will depend on the irrigation technology as explained in Section 2.5 in the case of agriculture, and assumed as 0 for domestic consumption as the water is being consumed where abstracted; and $F_{loss,i}$ the friction loss, assumed in this case as 0 as the pumping distance is short [52] and, thereby, the losses can be neglected. As a layer had been obtained in which the percentage that represent each irrigation technology per square kilometer was estimated, the operating pressure can be obtained as follows:

$$H_{opp,i} = \sum \%technology_i \times H_{opp,t} \tag{3.30}$$

Where $H_{opp,i}$ can be understood as the mean operating pressure in point i in meters, $\%technology_{t,i}$ is the percentage of irrigation technology t in point i and $H_{opp,t}$ is the operating pressure of technology t and explained in 2.5. With these previous considerations, it is possible now to obtain the energy consumption for groundwater abstraction with:

$$E_i = \frac{Q_i \times H_{tot,i} \times \rho \times g}{3.6 \times 10^6 \times \mu} \tag{3.31}$$

Being E_i the energy consumption in point i in kWh, Q_i the groundwater supply in point i in m^3, $H_{tot,i}$ the total pressure in meters, ρ the density of water equal to 1,000 $\frac{kg}{m^3}$, g the gravity (9.81 $\frac{m}{s^2}$), 3.6×10^6 the conversion factor from J to kWh and μ the pumping electric efficiency, considered as the mean efficiencies of groundwater pumps in Jordan reported by [33].

3.6.3 Other energy consumptions in water sector

As aforementioned, the Disi-Amman conveyance is a huge energy-intensive project as a huge quantity of water has to be pumped through almost 400km of pipes. According to [34], this consumption implies the 4% of the total energy consumption in Jordan. Then, as an approximation, the energy consumption of this system is calculated as the 4% of the total energy obtained from [31].

Finally, the rest of the energy consumed by the water sector was assigned to the water distribution. As it was not clear in the data from MWI if the energy consumption in [14] referred to all the consumption in water sector or only was the consumption for water pumping to households, the data coming from MEMR was considered. Although with GIS it would have been possible to obtain a more accurate data to perform a deeper analysis, for example considering the distance to the surface water sources and the elevation, due to time constraints and data availability this approximation had to be employed.

3.7 Scenarios

The last stage of this thesis is the construction of three scenarios. Due to time constrains, these scenarios are meant to serve as a proof of how a GIS model can be useful for a water-energy nexus analysis, although more detailed scenarios can be created in the future to obtain the full potential of such tool. Three scenarios were built, using the National Water Strategy (2016-2025) as a case study:

In the Business As Usual (BAU) scenario, it has been considered that none improvements nor policies are applied in the water sector. Then, according to the projections provided by [7] and [56] are used in this scenario.

The second scenario considers some improvements of water efficiency, proposed by the National Water Strategy. These improvements consist of the replacement of surface irrigation systems, as it is the most inefficient irrigation technology, and a decrease of the NRW to 30% by 2025, as one of the main objectives of the National Water Strategy, with the aim of drastically reducing the water supplied for domestic consumption.

Lastly, the third scenario consists of the increase of non-conventional water sources, such as an increase of wastewater treatment and reuse for irrigation and the completion of phase I of the RSDSP project by 2021 and phase II in 2025.

Table 3.9 summarizes the assumptions considered in every scenario.

Table 3.9: Assumptions considered in the three scenarios.

Scenarios	**BAU**	**Increase water efficiency**	**Non-conventional water sources**
Population	Increase according to [56]	Same as BAU	Same as BAU
Water demand	Growth rate according to[7]	Same as BAU	Same as BAU
Wastewater treatment	Increased taking into account 63% of people is connected to sewage system until reaching the maximum capacity of the WWTPs	Same as BAU	**Increase of percentage of people connected to sewage system until reaching 80% by 2025**
Irrigation	There are no changes in irrigation systems	**Progressive replacement of surface irrigation systems by, equally, the other two technologies**	Same as BAU
RSDSP	Not completed	Same as BAU	**First phase completed by 2021 and second phase completed in 2025**
NRW	Remains the same (53%)	**Progressively reduced to 30%**	Same as BAU
Groundwater table	Decrease of groundwater table at a rate of 1 meter per year as average according to [23]	**Groundwater table decrease updated with the decrease of groundwater supply**	**Groundwater table decrease updated with the decrease of groundwater supply**
Cropland	Remains the same, as well as crops water demand	Same as BAU	Same as BAU

To calculate year by year the water consumption and supply by source, the algorithms explained along this section were used. As some of the AHPs did not converge in the first attempt, the procedures had to be performed year by year and individually for every WWTP, so simulating the scenarios was a very time-intensive process. When increasing non-conventional water sources and when decreasing NRW, it has been considered that both groundwater and surface water consumption are decreased in the same proportion.

To calculate the energy consumption in every scenario, some considerations have to be taken into account:

- The energy consumption of the wastewater treatment plants increase at the same rate as the water consumption as they are directly related.
- The groundwater table decrease in scenarios 2 and 3 has to be updated every year as it is expected that, by applying their respective improvements, the groundwater consumption will decrease. Then, it has been assumed that the reduction of groundwater table will be mitigated in the same proportion as the decrease of groundwater consumption in every basin.
- As groundwater consumption in Amman increases, it has been considered that the water and energy consumption of the Disi-Amman conveyance increase at the same rate.
- To obtain the RSDSP desalination energy consumption, the energy consumption per m^3 of desalinated water proposed by [57] is considered $(3.31\frac{kWh}{m^3})$.

Chapter 4

Results and discussion

4.1 GIS model

Along this section, the GIS layers obtained with the procedure explained in Section 3 are going to be shown and analysed to prove its validity.

4.1.1 Population and domestic water consumption

The calibrated population layer is shown in Figure 4.1. Due to Jordan's unevenly distributed population, a logarithmic scale is required to appreciate the different levels of population density. Here it can be easily noticed the great concentration of population in the north-western part of the country, highlighting the north-west of Amman's governorate, where the capital of the governorate and the country, Amman, is found. The higher annual precipitation and proximity to water resources make this area the most suitable for human development. Although in a lesser extent, the rest of the western part of the country is also relatively densely populated when compared to the east, where the desert area can be in this layer easily appreciated. The scarce rainfalls and water sources together with a harsh climate hinder the expansion of urbanization.

The importance of this layer lies in its potential, as it allows the estimation of water consumption and supply, depicted in Figure 4.2a and 4.2b respectively. Comparing both figures, it can be noticed the difference between the supply and the consumption due to the NRW. The greatest water consumptions are located, logically, in the most populated areas, mainly in Amman, Zarqa, which is attached to Amman in the north-east; and Irbid, in the north-westernmost corner of the country.

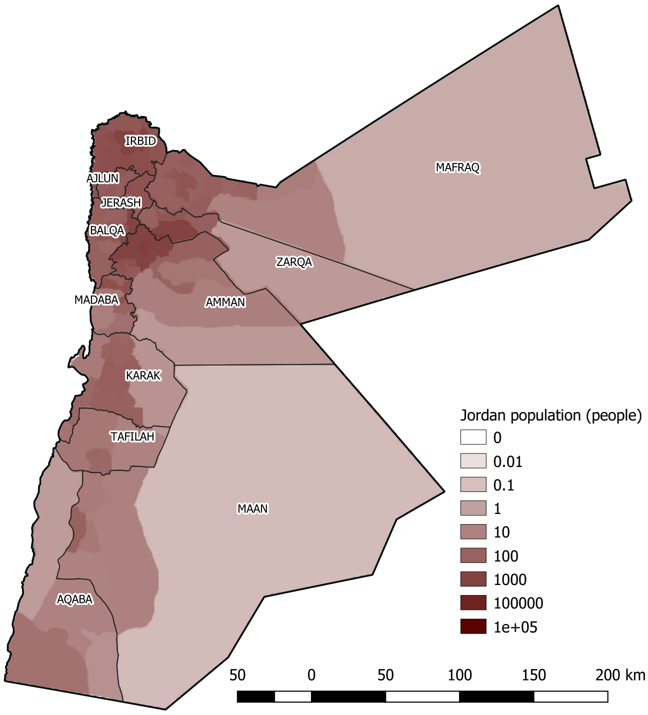
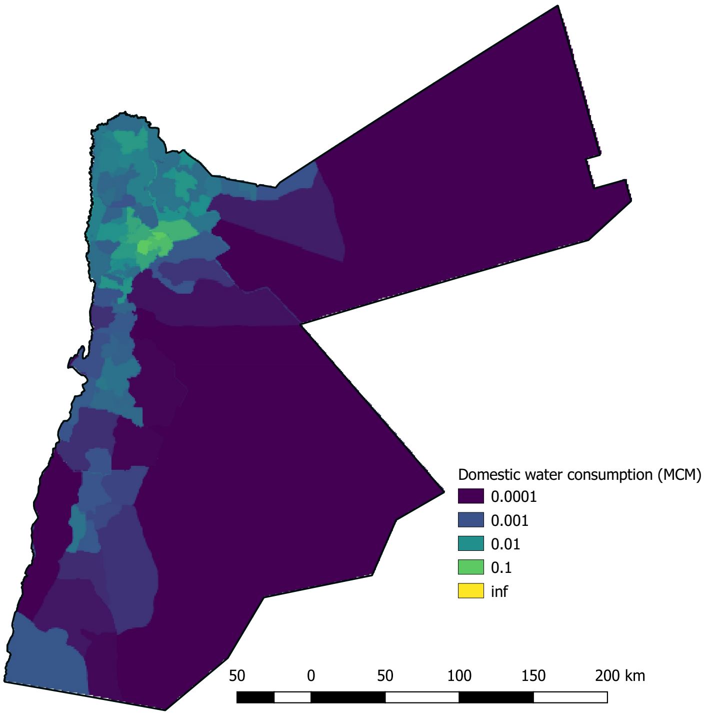
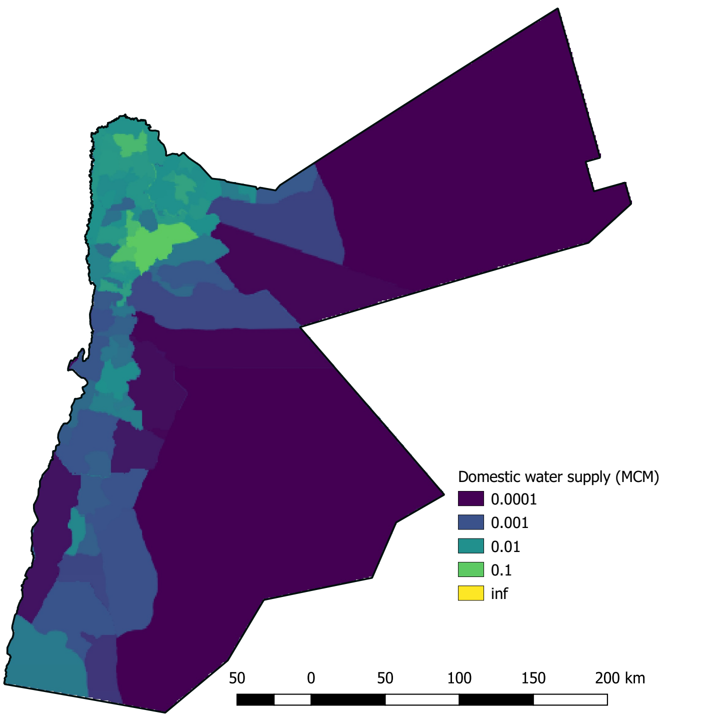


Figure 4.1: Calibrated Jordan population layer.

Groundwater and surface water supply are derived from these layers, represented in figures 4.3b and 4.3a respectively. It is remarkable that surface water consumption is concentrated in the north-west of the country, which seems coherent when considering that the greatest rivers are located in that area as the closer the consumption the lower the water losses and the energy consumption for water pumping. In this way, the JV is remarkable as the groundwater consumption is negligible whereas the surface water consumption is noticeable. The southern part of the country also consumes a notable amount of surface water. This is due to the fact that Wadi Araba is used for water consumption in that area, where the city Aqaba is located and the groundwater resource in that region, the Wadi Arab Sout Basin, is considerably low, of only 5.5MCM per year. But although these regions have a great surface water contribution, groundwater arises as the main source for the domestic sector. As Amman receives groundwater not only from its own basin but also from the Disi aquifer, its groundwater consumption is considerably greater than the other governorates and surpasses by far its surface water consumption. What is more, it can be seen that groundwater consumption is more distributed in the most populated areas, reaching those regions far away from surface water.

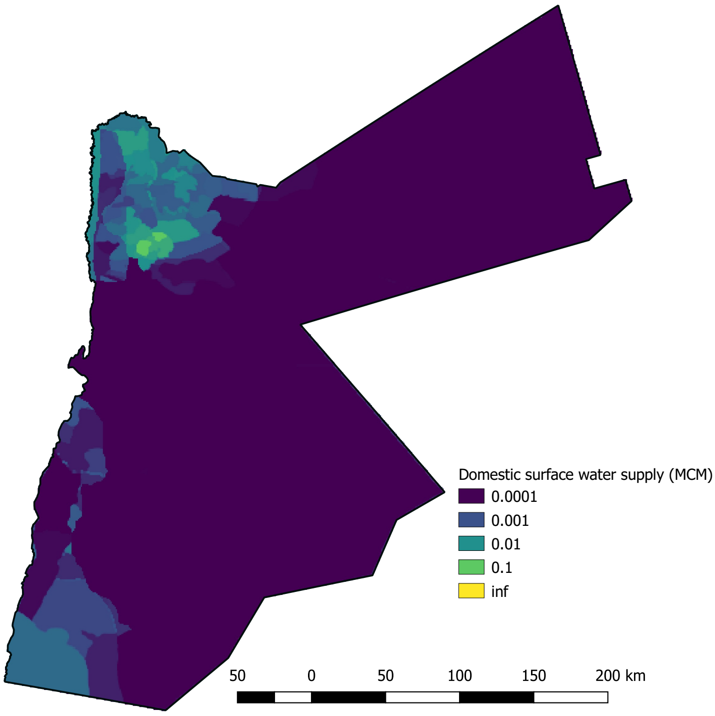


(a)

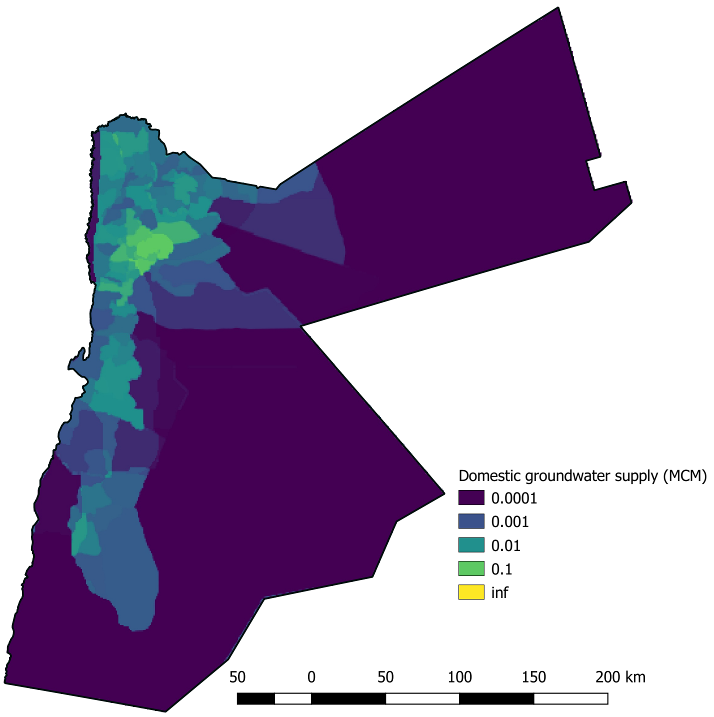


(b)

Figure 4.2: Domestic water consumption (a) and supply (b).



(a)



(b)

Figure 4.3: Domestic groundwater and surface water consumption.

4.1.2 Cropland and irrigation water consumption

The obtaining of the agriculture consumption begins with the raw cropland dataset depicted in Figure 4.4. According to this layer, Jordan has 5,668,503.8 dunums of agriculture land. This value is far above the actual data obtained from [26], which asseverates that the actual cropland area in the country is 2,665,964 dunums. Figure 4.5 shows the cropland area per governorate according to the layer and the actual value. It is noticeable that in most of the governorates, and especially in those where cropland is more developed, the values greatly differs from the DoS data. A calibration is required as an accurate cropland layer is essential to obtain the water consumption for irrigation. The procedure to obtain the water consumption for irrigation requires the precise location of the cropland as it hugely depends on data such as the climatic conditions, which, as explained in Section 2.2, varies considerably with the location in Jordan. A simple rule of three is not appropriate for this purpose in this case as it was identified that most of the cropland areas in this layer corresponded to land where agriculture was unsuitable.

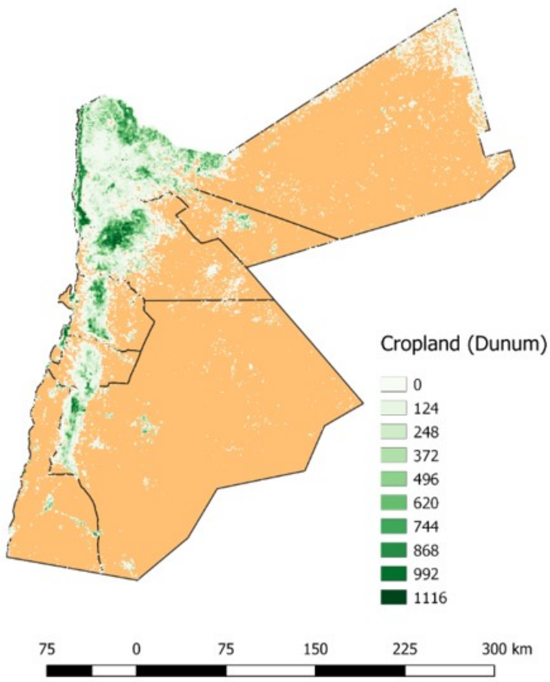


Figure 4.4: Initial cropland layer.

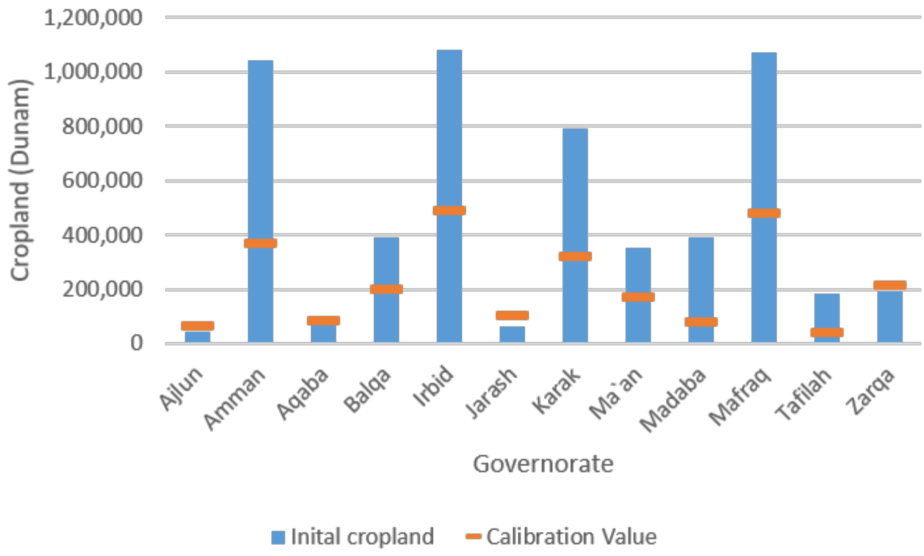
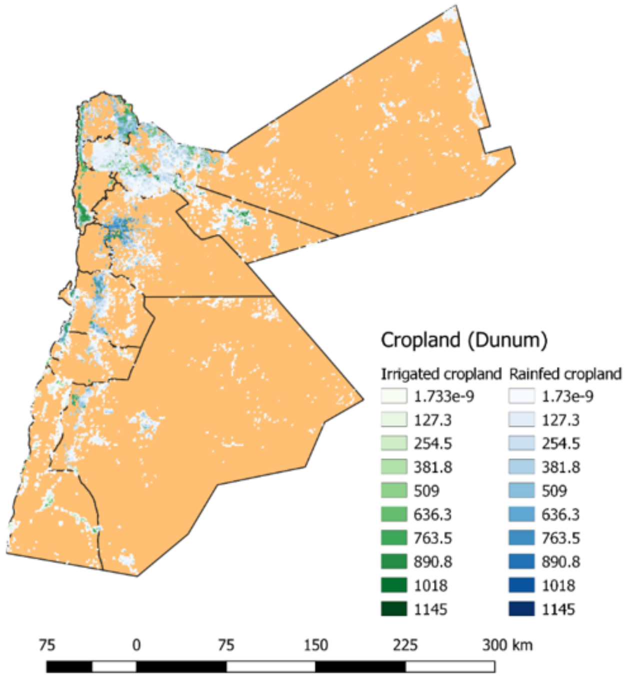


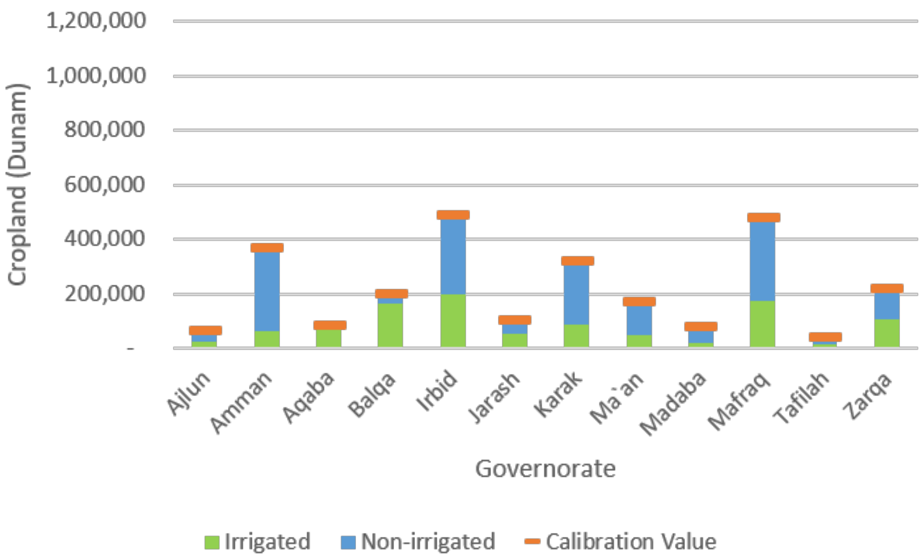
Figure 4.5: Initial cropland layer statistics.

By applying the AHP explained in the methodology, and after applying the second AHP to divide the irrigated and rain-fed cropland, Figure 4.6a is obtained. In this layer, the irrigated and rain-fed croplands are distinguished, symbolised with a range of greens and blues respectively. The rain-fed area is located mainly in the highlands, where it was said that rainfall is more abundant, and in disperse areas where small cultivated areas are found. Regarding irrigated area, the algorithm correctly assigned this area to great part of the JV, as is the region with more abundant surface water resource. But irrigated land is also found in other parts of the country. To verify the validity of this layer, these other areas were compared to the development of irrigation areas identified by [20] in Figure C.1. It was then considered that the greatest irrigated areas of the layer matched the regions identified as irrigated land in this document.

A region that should be analysed is found in the middle of the desert. According both to Figure 4.6a and C.1, in the Azraq basin an irrigated area is found- difficult to notice in the first figure as it is surrounded by disperse rain-fed crops. A research was performed to verify if it was actually irrigated land. It was discovered then that, according to [58], in that basin, an oasis was located some years ago. Agriculture land was developed surrounding it and using its water, but it was exhausted in the 80s and nowadays groundwater is used to irrigate this area.



(a)



(b)

Figure 4.6: Rain-fed and irrigated cropland layer (a) and stats (b).

With the calibrated cropland, the evapotranspiration of the crops can be obtained. This layer is depicted in Figure 4.7. As evapotranspiration depends on climatic parameters, among them temperature and radiation, it can be noticed that in areas closer to the desert, where these parameters are higher, the evapotranspiration is also higher. In the JV for example, where temperature and radiation along the year are lower, the values are also lower although crop density was high in that region.

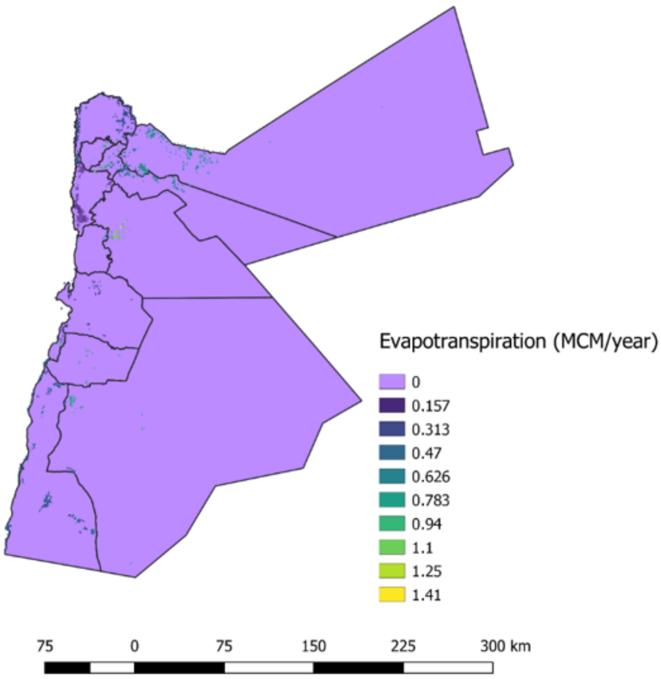


Figure 4.7: Standard evapotranspiration layer.

Afterwards, applying the water balance, the crops water demand was obtained. It was then noticed that the obtained agriculture demand was higher than the actual one, as represented in Figure 4.8. Here it should be remembered that agriculture sector was suffering water shortages of around 200MCM, being the real demand around 700MCM. With the FAO methodology, the total water demand from the crops was estimated to be 742.86MCM, relatively close to the data. Taking into account that with the standard methodology specific conditions of crops and the management techniques are not considered, this approximation seems extremely accurate. Assuming that all the cropland in

Jordan was affected by water shortages, a factor was applied to match the water consumption layer and the actual consumption. Then, taking into account the irrigation efficiency depending on the governorate, the layer shown in Figure 4.9a was obtained. In this layer, the values are quite lower than in the previous layer. This is due to the fact that this layer is obtained by subtracting to the evapotranspiration the rainfall. Furthermore, the aforementioned water shortages reduce the values of the dataset.

Lastly, the water supply for agriculture was divided per source with the steps previously explained. In order to perform a proper analysis, it was considered interesting to focus on the north-western region of Jordan, in the JV and part of the Highlands, where most of the irrigated cropland is found. Figure 4.9b depicts this zone. This figure also shows the important spots for this analysis, finding on it the WWTPs of this region, the main rivers, the KAC and the KTD. Here it is important to remember the explanation of agriculture consumption in Section 2.5. In concordance with the reported information, the middle of the JV is irrigated with the treated wastewater coming from As-Samra and stored in KTD. Furthermore, most of the area surrounding this dam is also irrigated with this water. Regarding the other WWTPs, it is noticed that most of their treated water is, indeed, being used to irrigate its local area except in the case of Salt and Wadi Al Arab, which are not surrounded by cropland and its water is being considered to irrigated other close areas. In relation to the other water sources, as the focused area is the north-west, where the surface water sources are located, most of the rest of the cropland is being irrigated with water coming from the rivers and the KAC.

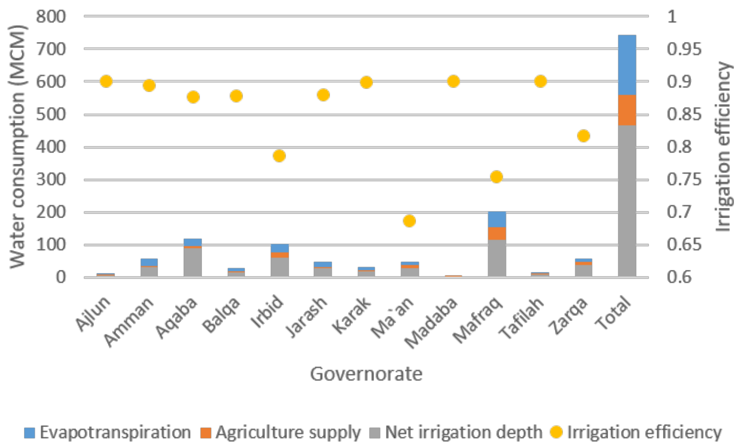
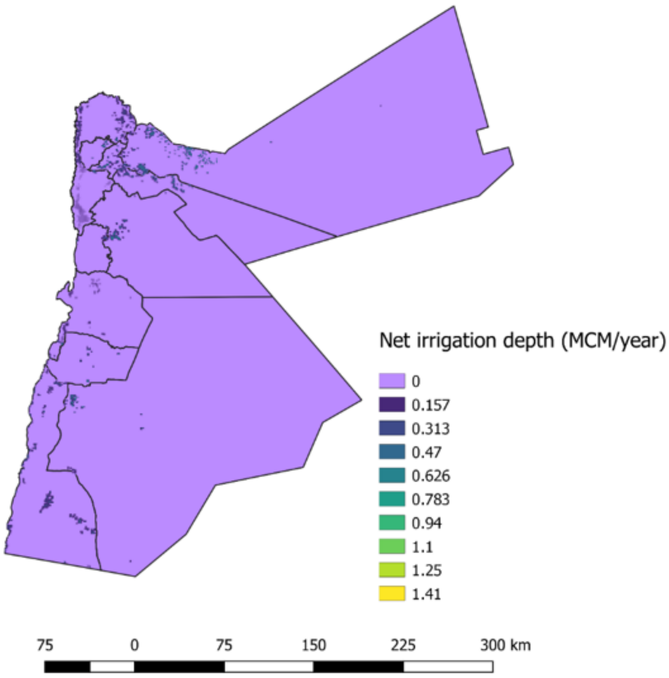


Figure 4.8: Results of total cropland water demand and the data from [14].



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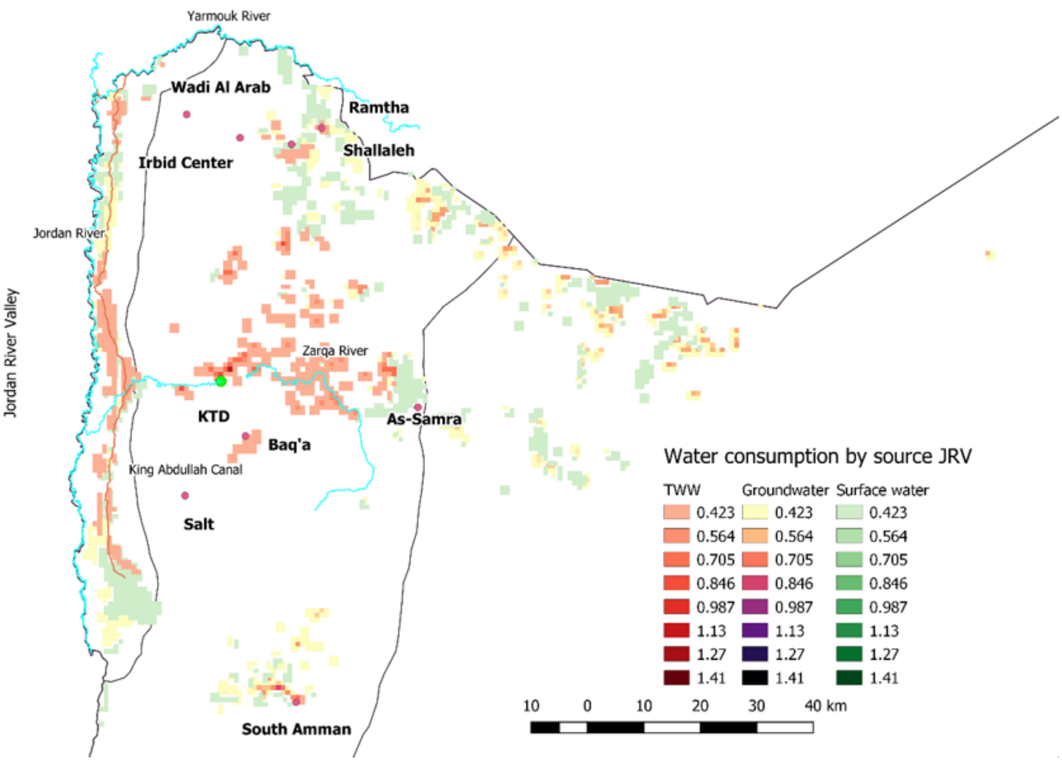

(b)

Figure 4.9: Irrigation demand and irrigation per source in the JV.

4.1.3 Comparison of the results with the MWI data

The resulting datasets were compared to the MWI data in order to check their validity. Figure 4.10 shows that most of the obtained layers are considerably close to the MWI data. Of course, those rasters obtained by applying a rule of three match perfectly the values of [14]. However, it is remarkable the alarming difference between the agriculture groundwater consumption obtained and the real one. The error was identified as the obtained water consumption for irrigation in the Disi aquifer was 28.41MCM per year, whereas the value of agriculture groundwater consumption that appeared in [53] was 58.31. Therefore, it is possible that, as the source is relatively old, in the last years a great part of the agriculture land in that area has disappeared and that portion of groundwater has been reallocated and, apart from the water that is being pumped to Amman for domestic water consumption, more water is being pumped for agriculture in areas close to the aquifer.

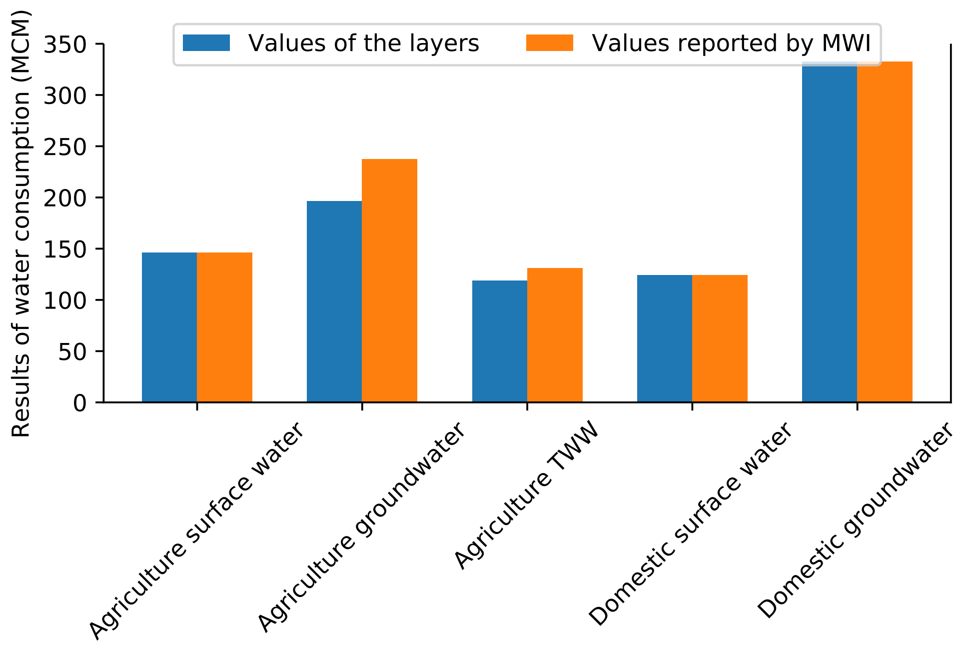

Figure 4.10: Comparison of the obtained water consumption and the data reported in [14].

4.1.4 Energy consumption in the water system

Finally, the energy consumption of the water sector is obtained and represented in Figure 4.11. The most water-consuming portion is represented by water distribution, with 1827GWh. As previously told, water distribution in Jordan is hugely water-intensive due to the topographic characteristics of the country, together with low efficient pumping systems. Whereas the former cannot be assessed, the latter can be mitigated by improving the pumps in the water system and reducing the water losses. The Disi-Amman conveyance represents the second largest energy consumption. 323GWh are needed every year to increase the Amman water supply with this groundwater source. Wastewater treatment requires a huge amount of energy, 110GWh, and it is expected to increase in the next years with the increase of population and people connected to the sewerage system. Although with the methodology 110GWh of energy consumption for wastewater treatment were obtained, it should be mentioned that it does not take into account the energy needed both for pumping the water to the WWTPs and the required energy for pumping and reuse it. Finally, the lowest energy consumptions were obtained for domestic and agriculture groundwater pumping. Domestic groundwater pumping has a higher energy consumption as this sector consumes more groundwater. What is more, while cropland is located in the areas where the depth to water table is lower, as these areas are more suitable for agricultural development [59] due to the fact that boreholes are installed were this level is estimated to be lower in order to minimize the energy cost. However, cities are not constructed following this criteria.

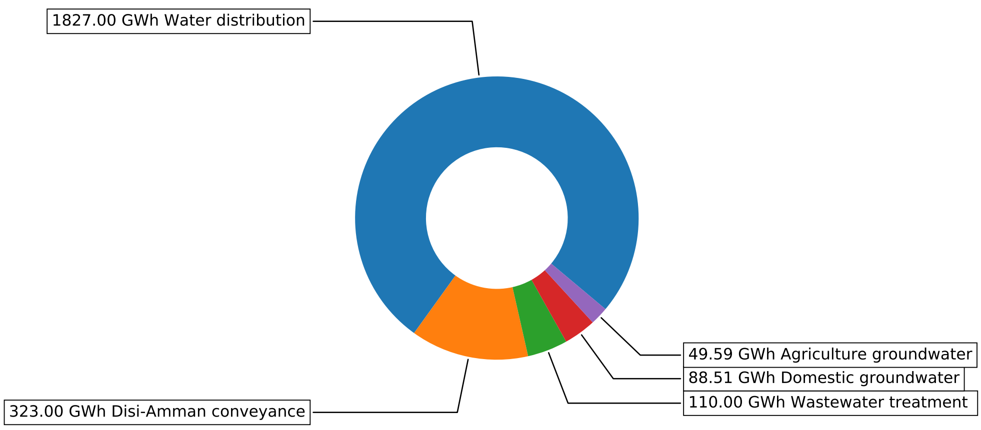

Figure 4.11: Energy divided by consumption in the water sector.

4.2 Scenarios

Finally, the results of the scenarios are shown and analysed in this section. It must be mentioned beforehand that in all the scenarios, the water consumption exhibits a step from 2015 to 2016. This is due to the errors introduced in the calibration processes, causing this inaccuracy. However, as the objective of these scenarios is to analyse the trends of the consumption of different sources in the following years as a result of the application of improvements in the water system, this error is not critical.

4.2.1 Business As Usual

In the BAU scenario, the water consumption trends if no policy is applied in Jordan are analysed. The result is depicted in Figure 4.12. Due to the increase of population in Jordan, water consumption in the domestic sector is expected to increase. Both groundwater and surface water consumption increase at the same pace as it was assumed that both sources are still going to be consumed in the same proportion. The increase of domestic water consumption leads to an increase of wastewater. Therefore, treated wastewater for irrigation is increased and, as the agriculture water consumption is supposed to remain the same, groundwater and surface water consumption decrease in this sector.

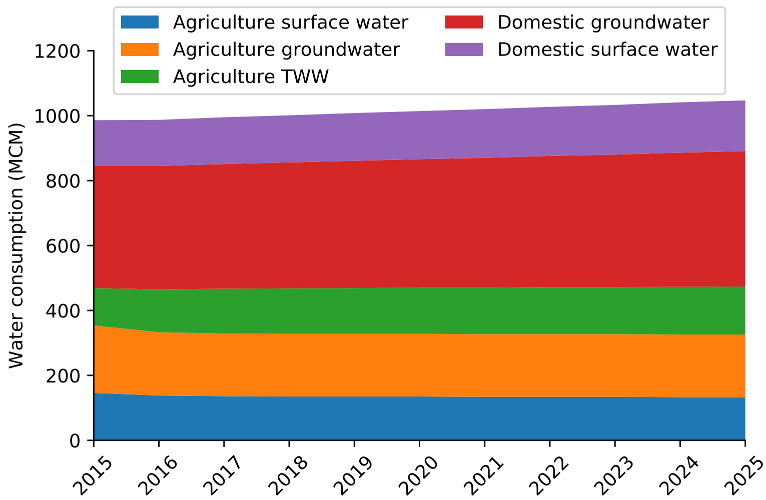

Figure 4.12: Evolution of water supply in the BAU scenario.

The increase of water consumption implies an increase of energy consumption. This same trend is appreciated in Figure 4.13. Water distribution increases as the domestic consumption increases. The Disi-Amman conveyance energy consumption shows also an increase of consumption as water consumption in Amman is expected to increase and, as it was assumed that the water consumed by the capital from this aquifer increased at the same rate as domestic consumption, the energy required to pump that huge amount of water also increases. Energy for wastewater treatment will also increase, as well as groundwater pumping for domestic consumption. Regarding groundwater pumping for irrigation, although the water consumption is decreased every year with the increase of wastewater treatment, due to the yearly decrease of groundwater table it is expected that the more energy will be required to compensate the increase of the Lift term in Equation 3.29.

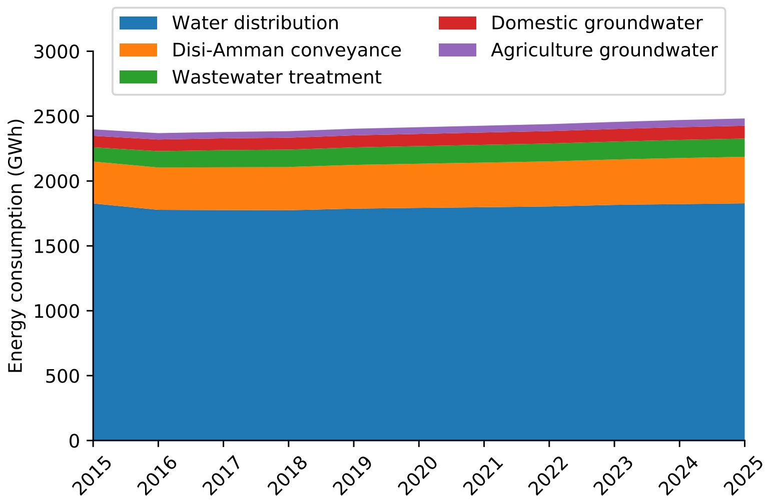

Figure 4.13: Evolution of energy consumption in the water sector in the BAU scenario.

4.2.2 Increase Water Efficiency

In this scenario, NRW is decreased until reaching a 30% of losses in 2025 and more water-irrigation efficient technologies are installed. Hence, in Figure 4.14 the first thing that stands out is the huge reduction of water supply in the domestic sector, both in surface and groundwater. This drastic reduction may mean a reduction of water shortages for this sector, as the water that is being saved may be reallocated and increase the frequency of the water supply in the cities. Additionally, as the reduction is located only in the supply side and the consumption remains the same as in the BAU scenario, the amount of wastewater available for reuse in irrigation remains the same as in the previous case. Therefore, and added to the increase of water-efficiency in irrigation, groundwater and surface water consumption are further reduced in this scenario.

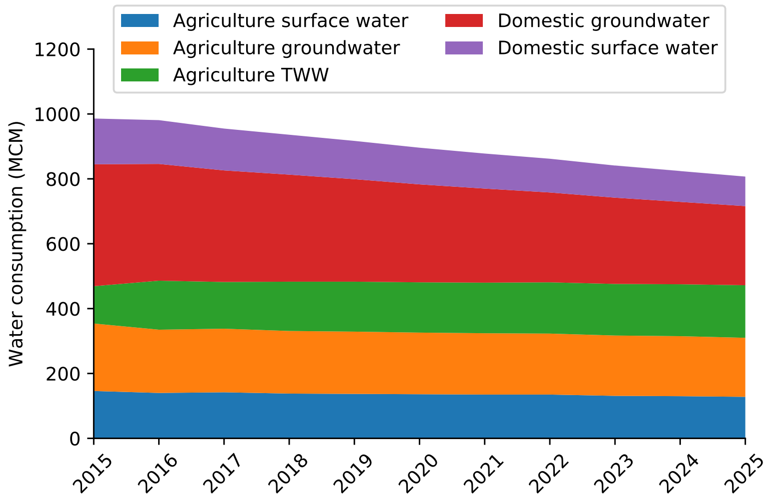

Figure 4.14: Evolution of water supply in the increase of water efficiency scenario.

This huge reduction of water consumption is reflected in the energy consumption of the water sector. The most noticeable reductions found in Figure 4.15 belong to the two greatest energy consumptions, which are water distribution and the Disi-Amman conveyance. Energy for domestic groundwater pumping is reduced as well. These reductions are direct consequences of the severe reduction of domestic water consumption. As aforementioned, wastewater treatment increases at the same growth rate as in the BAU scenario and, hence, the energy consumption of the WWTPs keeps increasing every year. The reduction of groundwater consumption entails the slows down or even stops the reduction of groundwater table. As a result, although on the one hand energy consumption for groundwater pumping should increase as more efficient irrigation technologies involves higher pressure supply and, thus, higher energy for pumping, on the other hand this increase of energy consumption is surpassed by the reduction of consumption due to the higher groundwater table. For instance, in this scenario, as groundwater consumption is reduced every year with the increase of wastewater reuse, energy consumption for agriculture groundwater pumping is being reduced year by year.

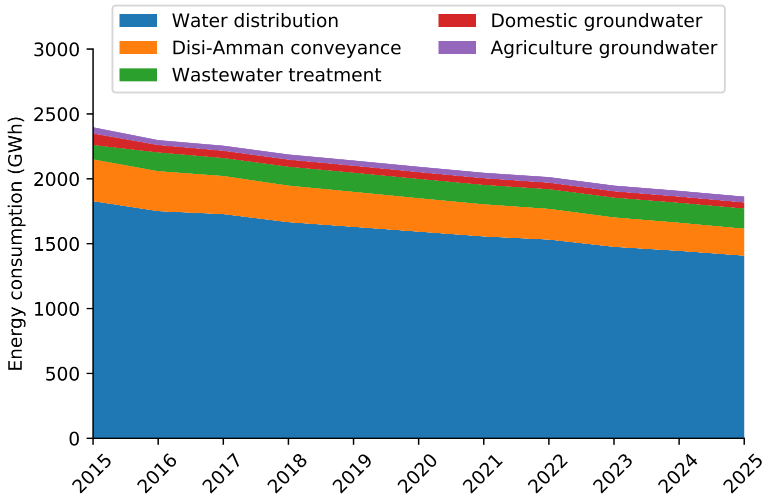

Figure 4.15: Evolution of energy consumption in the water sector in the increase of water efficiency scenario.

4.2.3 Non-conventional water sources

The last scenario considers an increase of non-conventional water sources as a result of more people connected to the sewage system and the completion of the RSDSP. The results of the evolution of water consumption are shown in 4.16. In this scenario, no improvements in the water distribution system were applied. Therefore, the water consumption remains the same as in the BAU scenario. But focusing firstly on the increase of treated wastewater, it can be noticed the higher increase of this source to the detriment of the consumption of the other sources in agriculture when compared to the other scenarios. Regarding the RSDSP, the steps that the completion of every phase implies, firstly in 2021 and secondly in 2025, are remarkable. With the first step, the domestic groundwater and surface water consumptions are decreased in a total amount of 65MCM, whereas these very same sources are decreased more than the 20MCM that this project is going to supply to the agriculture sector. This is due to the fact that treated wastewater remains the same. But the second step is considerably more noticeable, as the second phase will increase the water supplied to Amman with an extra amount of 150MCM, reducing the other consumptions of the domestic sector. In this year, the evolution of the supply in the agriculture sector is not affected by the RSDSP.

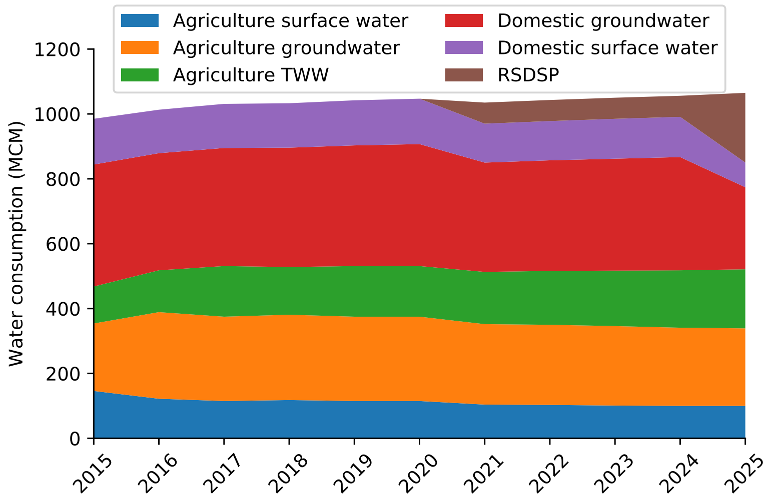

Figure 4.16: Evolution of water supply in the increase of non-conventional water sources scenario.

This scenario is the one in which energy consumption is most affected. In Figure 4.17 it can be seen the huge consumption that implies the desalination in the RSDSP. Although the surface water consumption is reduced, which is the main contributor to the energy consumption for water distribution, as the consumption of the RSDSP considers only the desalination process, the energy that is not being used for water distribution due to the decrease of surface water consumption has been considered to be consumed for pumping the water from the conveyance to Amman. But not only this project increases the energy consumption. The increase of treated wastewater is also increasing the energy consumption for such purpose. Hence, this scenario is, by far, the most energy-consuming one.

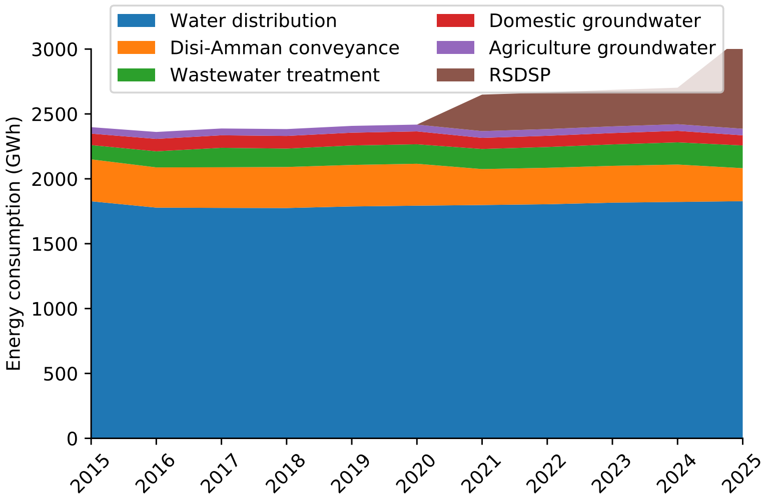

Figure 4.17: Evolution of energy consumption in the water sector in the increase of non-conventional water sources scenario.

4.2.4 Scenarios comparison and discussion

Lastly, a brief comparison of the consequences of the scenarios is performed. In Figure 4.18, the resulting groundwater abstraction per basin and scenario in MCM in 2025 is shown, with the mark of the safe yield of every basin. First, in the BAU scenario the over abstraction of the basins is very alarming. In the case of the Amman-Zarqa basin, for example, the abstraction could double the safe yield. The increase of water efficiency leads to great reductions of groundwater abstraction in every basin with the exception of those basins in which the great part of the groundwater is consumed by agriculture, such as Azraq, the Dead Sea, Jafr and Yarmouk. For instance, in the three last basins it seems to increase the groundwater abstraction when compared to the BAU scenario. This slight increase is due to the inaccuracies of the AHPs applied to obtain the treated wastewater and groundwater consumption. In the last scenario, some of the basins are affected by the increase of non-conventional sources when compared to the BAU scenario. On the one hand, basins such as the Jordan Side Valleys and the Jordan Valley, decreases their groundwater consumption as in these basins, the cropland irrigated with the treated wastewater coming from As-Samra is found. Thus, the increase of wastewater treated by this WWTP is reflected in the reduction of groundwater consumption of these basins. On the other hand, Amman is located both in the Amman-Zarqa and Azraq basins. Consequently, the water desalinated in the RSDSP decreases in these basins the groundwater consumption severely. It is worrying that, although in the scenarios 2 and 3 the water consumption in most of the basins has been reduced, the safe yield is still surpassed. Although the groundwater table reduction would be decelerated, the problem would still exist. However, as in these scenarios the use of surface water has been also reduced, this non-used water resource could be actually used to reduce even further the employment of groundwater. A further study on the evolution of the surface water source if these scenarios are applied could tell if this option is feasible.

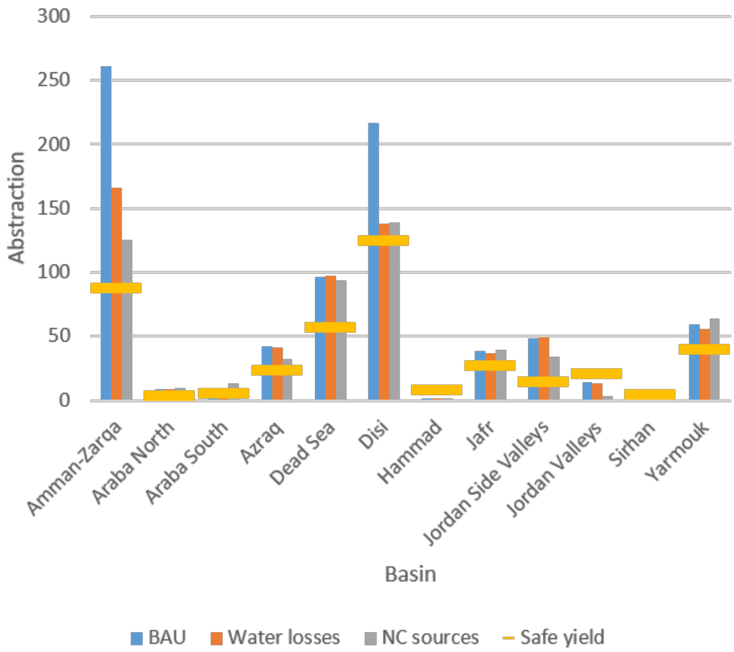

Figure 4.18: Abstraction of groundwater by basin and scenario in 2025.

The annual inflow of the WWTPs should be also analyzed. Although in scenarios 1 and 2 wastewater treatment is increased as a consequence of the growth of domestic water demand, in Figure 4.19 it is observed that in these scenarios upgrades in the WWTPs are not needed. However, in the third scenario, the increase of wastewater does require some upgrades in WWTPs. The most remarkable one is As-Samra, which suffers an increase of annual inflow of 30MCM. But, as said in Section 2.8, two projects to upgrade this WWTP are projected, adding in 2016- already completed- and in 2024 35MCM of capacity, more than enough to cover the projected inflow. The same happens with Aqaba WWTP, as in 2020 a project is expected to be finished, adding an extra capacity of 5.17MCM, also enough to treat the estimated inflow.

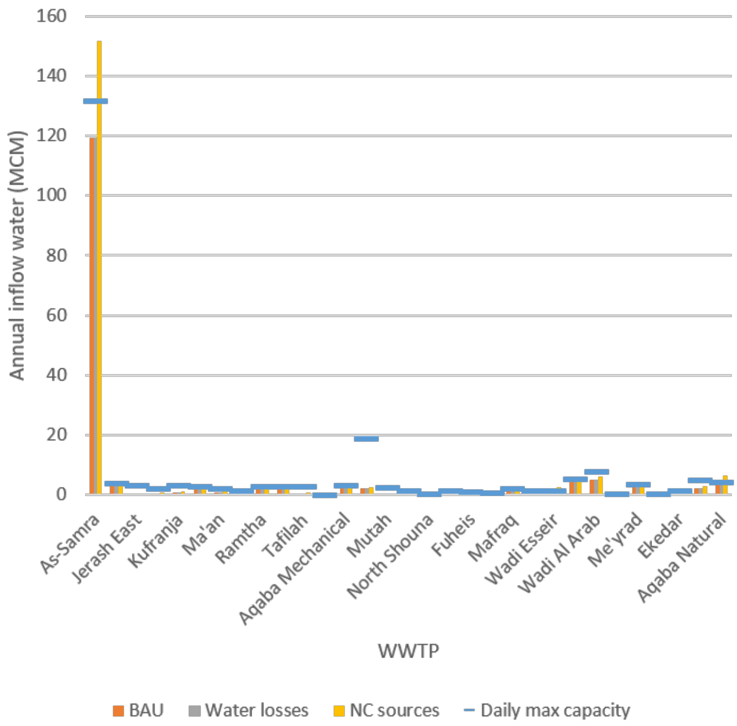

Figure 4.19: Wastewater annual treatment by WWTP and scenario in 2025.

So, mitigating water scarcity and its implications seem possible if some of the goals set in the National Water Strategy are met. However, a lot of work has to be done to achieve it, and further more ambitious targets might be needed as population and economy are expected to further grow in Jordan.

The addition of non-conventional water sources and the reduction of water losses lead to a reduction of the stress on natural water sources. However, these water savings may be used to reduce the gap between demand and supply, it is, the shortages. Furthermore, the assumption that water consumption in agriculture will not increase seem pretty optimistic. For instance, agriculture water supply increased from 514.4MCM in 2015 to 551.8MCM in 2017 [60]. What is more, according to the water demand projections of the MWI, domestic water consumption will increase at a growth rate of 1% annually, whereas according to [56] and as seen in Figure 2.11, population is expected to growth 2.2% annually in the following years. This may lead to a lesser water availability per capita. Nevertheless, as water shortages may be reduced with the increase of non-conventional water sources, the reduction of natural water availability can be surpassed with these new available sources.

Chapter 5

Conclusions and Future Work

With this thesis, a GIS model for water accounting in order to assess the water scarcity in Jordan was performed. The calibration process allowed to obtain accurate population and cropland layers that were difficult to find in open source datasets. These calibrated layers were essential to obtain water consumption in the domestic and agriculture sector. Although the first consumption was easy to obtain with regional statistics, a more complex methodology was employed to obtain, firstly, the evapotranspiration of the irrigated cropland. Is in this process when the usefulness of a GIS model shows its potential, as this process depends on the geographical location of the different crop types and on the climatic conditions. The proposed methodology provided accurate values that closely matched the regional statistics. But with this methodology not only water consumption could be estimated. The energy consumption of the water sector could be broken down in different components. All these results made it possible to create and simulate scenarios to analyse the policies Jordan is implementing in the water sector, giving some outcomes that can be used to guess the possible evolution of the water consumption in the country.

So, this model is intended to provide a tool to KTH and Jordan stakeholders for the development of the FAO project *Implementing the 2030 Agenda for water efficiency/productivity and water sustainability in NENA countries* and facilitate the progress of the project. However, some considerations will need to be taken into account and a few recommendations are given in this section, preceded by more detailed conclusions of the obtained results.

5.1 Conclusion

Summing up, a GIS model can be very useful for water scarcity assessment and interactions among nexus resources as the spots in which the different water sources are being used can be obtained. What is more, factors such as local rainfall and radiation can be taken into account to obtain the crops water consumption. Water pumping is high energy-intensive in Jordan, adding pressure to the energy system. The water distribution system in Jordan seems especially water-intensive. Applying some improvements such as the reduction of NRW can reduce this huge energy consumption. On the other hand, although the use of non-conventional water sources seems mandatory to reduce the natural water sources pressure, this would increase the energy consumption, as wastewater treatment and desalination are huge energy-intensive processes.

Extreme water scarcity in Jordan is a huge challenge, and more strict measures need to be implemented. An effort must be taken by Jordan to mitigate this problem, as it may imply severe consequences to the country in the future, such as extreme droughts, reduction of water quality and great water shortages. Further alternative ways to fight against water scarcity may be explored by the MWI to achieve a sustainable water system.

5.2 Future work

This model may be used in future works in dESA-KTH and Jordan's authorities and stakeholders. Here some suggestions are offered on how to continue with the work with this model:

- A scenario combining scenarios 2 and 3 may give further insights, as both scenarios can be combined. With this final scenario, groundwater depletion can be absolutely stopped as with scenarios 2 and 3 a notable reduction of this consumption was obtained.
- The model should be optimized as, aforementioned in the methodology, when using the AHP for the treated wastewater layer, the algorithm did not converge in the first attempt. As a consequence, when running the simulations of the scenarios, the algorithm had to be used twice for every WWTP consuming a lot of time and not allowing the simulation to be fully automatized.
- Modelling the surface water system, locating the pumping stations and the water networks in the map, will allow to perform an interesting anal-

ysis of the water system and to obtain more accurate energy consumptions and elements that can be optimized.

- More detailed data regarding Jordan's specific crops calendar and cropland management will allow a more detailed evapotranspiration calculation.

- Out of the scope in this thesis, the effects of the scenarios on the water quality should be assessed as, for example, the depletion of groundwater leads to increase of salinity and, then, an increase of energy consumption as that water would need a treatment.

- The inclusion of climate change in the scenarios as a sensitivity analysis may be also really useful as it will affect the groundwater recharge, the flows of the rivers and the water consumption of irrigated cropland.

- Finally, a techno-economic analysis will be also required to check the affordability of the scenarios. Applying improvements in the water system decreases the stress on water sources, but a huge investement will, for sure, be needed.

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Appendix A

Groundwater exploitation per basin

Basin		Safe yield	Abstraction	Deficit
Araba North		3.5	6.3	-2.8
Yarmouk		40	54	-14
Jordan Side Valley		15	46.7	-31.7
Disi		125	143	
Araba South		5.5	8.5	-3
Jafr	Renewable	9	35	-29
	Non-Renewable	18	1.7	
Azraq		24	52.5	-28.5
Hammad		8	1.9	6.1
Dead Sea		57	90	-33
Jordan Valley		21	17	4
Sirhan		5	1.7	3.3
Amman-Zarqa		87.5	166	-78.5

Table A.1: Groundwater safe yield, abstraction and deficit per basin.

Appendix B

Treated wastewater by WWTP in 2015.

Name	Design cap	Daily	Technology
As-Samra	360000	294862	Activated Sludge
Irbid Center	11023	8143	Trickling Filter + Activated Sludge
Jerash East	9000	0	Activated Sludge
Karak	5500	1408	Activated Sludge
Kufranja	9000	2506	Trickling Filter + Activated Sludge
Madaba	7600	6557	Activated Sludge
Ma'an	5772	2288	Activated Sludge
Jiza	4000	773	Activated Sludge
Ramtha	7400	4743	Activated Sludge
Salt	7700	7407	Activated Sludge
Tafilah	7500	1450	Trickling Filter
Shobak	350	92	Waste Stab Ponds
Aqaba Mechanical	9000	6699	Activated Sludge
South Amman	52000	5436	Activated Sludge
Mutah	7060	1228	Activated Sludge
Zaatari	3500	964	Trickling Filter + Activated Sludge
North Shouna	1200	777	Waste Stab Ponds
Abu Nuseir	4000	3201	Activated Sludge
Fuheis	2400	2719	Activated Sludge
Wadi Hassan	1600	1594	Activated Sludge
Mafraq	6050	3557	Waste Stab Ponds
Wadi Mousa	3400	2628	Activated Sludge
Wadi Esseir	4000	5040	Oxidation Ditch
Baq'a	14900	11862	Trickling Filter
Wadi Al Arab	21023	12280	Activated Sludge
Tal Mantah	400	358	Trickling Filter + Activated Sludge
Me'yrad	10000	6268	Activated Sludge
Lajoon	1000	595	Waste Stab Ponds
Ekedar	4000	1918	Waste Stab Ponds
Shallaleh	13750	6070	Activated Sludge
Aqaba Natural	12000	12745	Waste Stab Ponds
Total	**606178**	**416513**	

Table B.1: Wastewater Treatment Plants in Jordan 2015 [14].

Appendix C

Jordan irrigated agriculture development areas

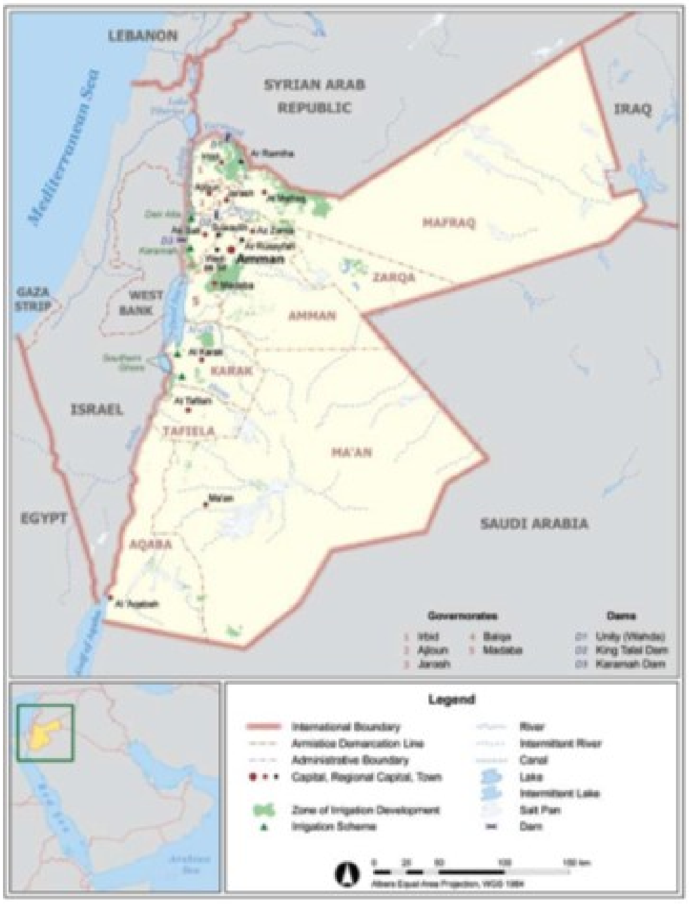

Figure C.1: Development of irrigated cropland areas from [20]

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Appendix D

Other layers

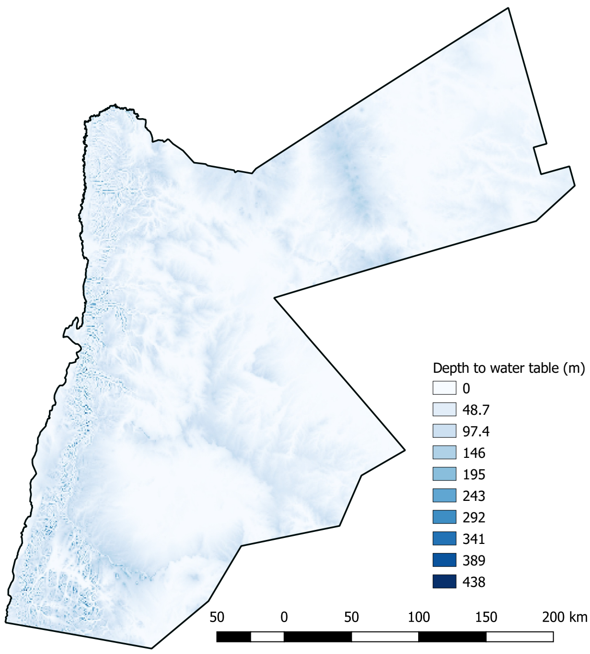

Figure D.1: Depth to water table in meters.

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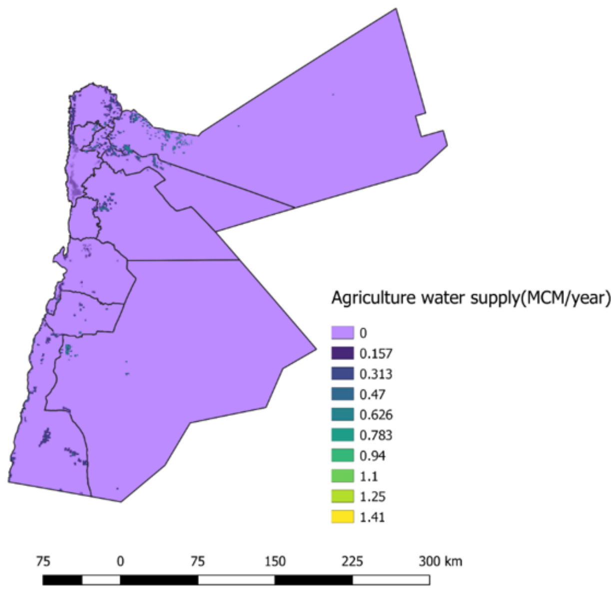

Figure D.2: Agriculture supply layer.

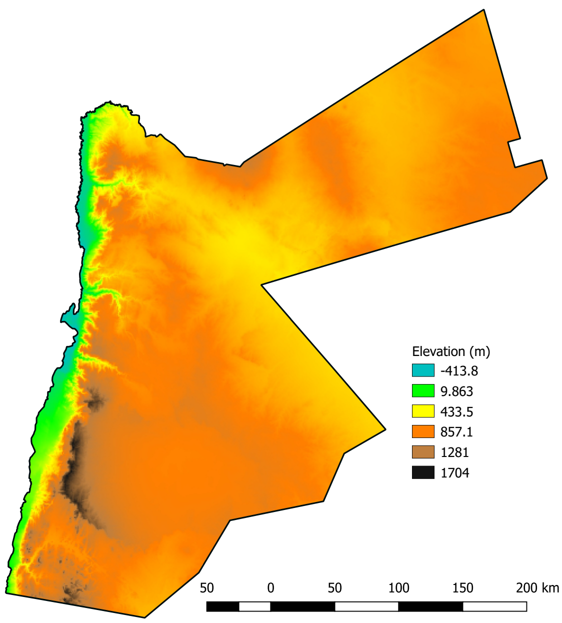

Figure D.3: Elevation in meters.