

Article

A GIS-Based Approach to Inform Agriculture-Water-Energy Nexus Planning in the North Western Sahara Aquifer System (NWSAS)

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Abstract: The North Western Sahara Aquifer System (NWSAS) is a vital groundwater source in a notably water-scarce region. However, impetuous agricultural expansion and poor resource management (e.g., over-irrigation, inefficient techniques) over the past decades have raised a number of challenges. In this exploratory study, we introduce an open access GIS-based model to help answer selected timely questions related to the agriculture, water and energy nexus in the region. First, the model uses spatial and tabular data to identify the location and extent of irrigated cropland. Then, it employs spatially explicit climatic datasets and mathematical formulation to estimate water and electricity requirements for groundwater irrigation in all identified locations. Finally, it evaluates selected supply options to meet the electricity demand and suggests the least-cost configuration in each location. Results indicate that full irrigation in the basin requires ~3.25 billion million m³ per year. This translates to ~730 GWh of electricity. Fossil fuels do provide the least-cost electricity supply option due to lower capital and subsidized operating costs. Hence, to improve the competitiveness of renewable technologies (RT) (i.e., solar), a support scheme to drop the capital cost of RTs is critically needed. Finally, moving towards drip irrigation can lead to ~47% of water abstraction savings in the NWSAS area.

Keywords: NWSAS; GIS; water; energy; agriculture; nexus

1. Introduction

1.1. Context

The 2030 Agenda, set forth by the United Nations for sustainable development, aims, among other things, at achieving zero hunger. This is the second Sustainable Development Goal (SDG2) that targets doubling the agricultural productivity and income of small scale farmers (SDG2.3) [1]. This ambitious goal cannot be achieved by relying only on land resources or agricultural activities; it will also require other resources such as water and energy. Therefore, SDG6.3 calls for implementing integrated water resources management, including through transboundary cooperation and SDG7, which focus on

access to affordable, reliable and sustainable energy [1]. The interdependencies between these systems, which are known as water-energy and food nexus, are complex [2], and the situation might be even more complex if coupled with climate change, droughts, floods, water quality and transboundary water management in water-scarce regions. Therefore, to meet these challenges, more efficient resource management, infrastructure investments and technologies, as well as better governance of water resources, are needed [3]. This, in turn, requires access to reliable data and information, which must then be translated into a detailed analysis of social, technical, economic and political aspects to inform the decision-making process at different levels.

Different frameworks have been developed in recent years to address the complex interlinkages between water-energy and food-nexus, such as the 'Climate-Land use-Energy and Water strategies, CLEWs' [4] and UNECE Transboundary River Basins Nexus Approach (TRBNA) [5]. These methodologies have been modified recently to account for groundwater as well [6]. The TRBNA uses 'nexus dialogues' between different stakeholders in the study area in the form of workshops, bilateral meetings and online exchanges of information between representatives from water, energy, agriculture and environment sectors coming from ministries, Non-Governmental Organizations (NGOs) or utilities [7]. This study is based on these two frameworks.

To capture the spatial dimension of complex natural resource interactions, Geographic Information Systems (GIS) and remote sensing techniques are useful. The implementation of such techniques, which are becoming openly available, has scaled in recent years to provide a range of site-specific information. However, utilizing GIS data and associated analytical tools to conduct strategic energy planning remains at an early stage [8]. This extends to GIS-based nexus studies and integrated resource planning.

1.2. Background of the NWSAS

Among the many challenges in the Middle East and North Africa (MENA) region, the greatest threat and the crisis least prepared for is associated with water. It is the most water-scarce region in the world, with about 60% of the region's population living in areas with high or very high surface water stress [3] (high or very high water stress implies that water withdrawals make up 40 percent or more of surface water resources availability). The agricultural sector is the main water consumer in the region, as shown in Figure 1.

NWSAS is one of the largest groundwater sources in the MENA region and the world. It extends over an area of more than 1 million km² shared between Algeria, Libya and Tunisia, as shown in Table 1 [9]. NWSAS is the main source of water for all socio-economic activities, such as agriculture, industry and domestic use. The aquifer is formed by continental deposits and encloses two large aquifer layers. The first layer is called the Continental Intercalary (CI) and is the deepest and largest layer, covering a surface area of 1,000,000 km². The second layer is the Complex Terminal (CT), which has a relatively shallow depth and covers an area of 600,000 km² (see Figure 2) [10].

Table 1. Extension of the North Western Sahara Aquifer System (NWSAS) [9].

Parameter	Algeria	Tunisia	Libya
Country area (km ²)	2,381,741	163,610	1,759,540
Country area in the basin (km ²)	700,000	80,000	250,000
Share of the national territory in the NWSAS (%)	29	49	14
Share of NWSAS (%)	68	8	24

Water abstractions in the NWSAS basin have seen a substantial increase in the last decades, jumping from around 0.6 billion cubic meters (BCM) in 1970 [11] to 3.2 BCM in 2018 [12]. The average annual recharge rate is only about 1 billion m³/year [13], which is much lower than the abstraction rate. Several issues have resulted from overexploitation of the groundwater over time, such as the depletion

of natural springs, water table drawdown, seawater intrusion, and deterioration of water quality level in different parts of the aquifer system [11].

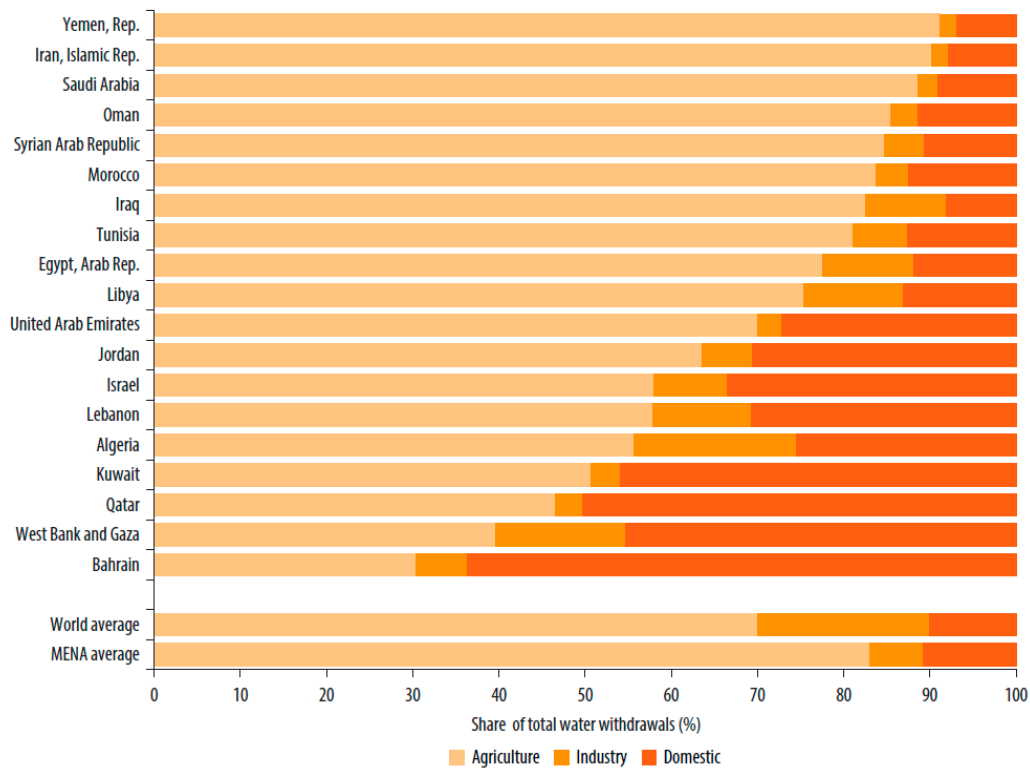


Figure 1. Water withdrawal in the Middle East and North Africa (MENA) countries as shared by sectors [3].



Figure 2. The boundaries of the NWSAS showing the extension of the Continental Intercalary (CI) and the Complex Terminal (CT) aquifers.

This significant change in water abstraction has been mainly driven by the growth of the agricultural sector and the proliferation of wells [11]. In the past years, the irrigated area has seen consistent growth reaching about 470,000 ha in 2014 [9] of which 270,000 ha are irrigated by NWSAS water (consultation with Sahara and Sahel Observatory (OSS)). This, coupled with the use of inefficient irrigation systems, has exacerbated water withdrawal. Surface irrigation is the dominant technique that accounts for 72% of irrigated land, sprinkler irrigation covers 26%, and the rest (2% or less) is drip irrigated. This means that less than half of the water abstracted is actually utilized [14].

Fossil fuels are the main source of electricity supply in the three countries [15–17]. The energy sector in the three countries is heavily subsidized. In 2018, Algeria spent 17,080 million USD on subsidies for energy products. Similarly, Libya spent 4698 million USD in the same year [18], while in Tunisia, energy subsidies peaked at 1318 million USD in 2013, then dropping significantly to only 70 million USD in 2016 due to the government's measures to reduce energy subsidies [19].

1.3. Previous Studies

The main studies on the NWSAS were conducted in the form of joint efforts between the three countries. In 1999 a multi-phase project, led by the Sahara and Sahel Observatory (OSS) was launched to ensure control over potential impacts of transboundary water resources [20]. In the first phase (ended in 2002), a 'hydraulic model' was developed, and a consultation mechanism for joint water management was initiated [10,20]. In the second phase (started in 2003), new case studies highlighted the inefficiency of irrigation, the inadequate valorization of water, and the degradation of soil quality in the NWSAS [11]. The third phase (started in 2009) focused on water valorization and sustainable development in the NWSAS. About 3,000 farmers were surveyed, and "demonstration pilots" were conducted in six locations to implement technical innovations and test their feasibility and social acceptance [21].

Although the joint efforts of the three countries and the OSS were substantial and key to understanding the complexity and vulnerability of the NWSAS system, the components of the research were heavily driven towards water issues with a lesser focus on other sectors like energy. Another limitation is that most of the pilot studies covered certain areas, and no study considered the entire NWSAS area, especially when it comes to energy and water aspects.

GIS-based methods are useful for evaluating activities that interact with natural resources and physical conditions that are dependent on location, but they can be scaled to large areas. In a study by [22], spatially distributed and temporally averaged meteorological data and crop distributions were used to estimate irrigation requirements in the country of Greece. Furthermore, [23] studied the water demand and energy footprint of irrigated production in the Mediterranean region. The study investigates the water-energy-food nexus in the region and highlights trade-offs between strategies to save water, reduce CO₂ emissions and/or intensify food production. Additionally, [24] developed electrification pathways for Kenya using the Open Source Spatial Electrification Tool (OnSSET) [25] and the Open Source Energy Systems Modeling System (OSeMOSYS) [26] to capture the spatial and temporal dynamics of the system. Different energy demand scenarios were analyzed to find the optimal energy generation technology mix.

GIS modelling of the interaction between water, energy and food for the entire NWSAS area, we suggest, is key to inform sustainable development in the region. Furthermore, the use of open-source tools should encourage transparency, reproducibility and support researchers and policymakers to build robust decision-making tools. Therefore, the goals of this paper were to: (1) develop an open-source GIS-based model that addresses selected Water-Energy-Food (WEF) nexus questions, (2) estimate the crop water requirement for selected crops in the region and the associated irrigation and pumping requirements, and (3) study the competitiveness of different electricity supply technologies under different conditions (namely solar Photovoltaics (PV), small-scale wind turbine and diesel gen-sets). It is worth mentioning that this study can be considered as an exploratory modelling activity, which means it is not intended to conduct any site-specific sampling or study a specific area in a detailed

manner. Rather, we aim to fill the WEF nexus gap in the NWSAS region by looking at the entire area, exploring different scenarios and studying the synergies and tradeoffs.

2. Materials and Methods

An overview of the methodology of this study is shown in Figure 3, and Sections 2.1–2.5 briefly describe each step shown in this figure. Wherever possible, the official data provided by local authorities were used to validate the inputs, assumptions and modelling results, as will be discussed in the relevant sections. A more detailed description of each method is given in the Supplementary Material. Additionally, the code developed for this study is available in a [Github repository](#).

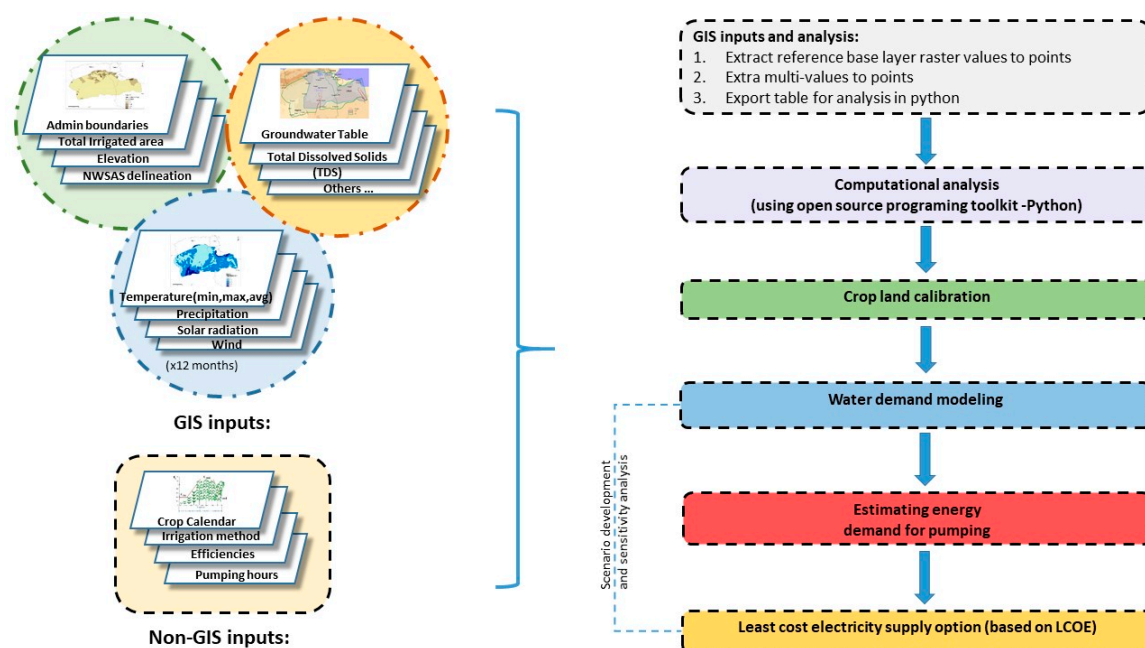


Figure 3. Schematic representation of the methodology used for estimating the electricity demand of groundwater irrigation in the NWSAS.

2.1. GIS Data Collection

The first step of the analysis consisted of data rendering and cleaning. Climatic datasets such as temperature, wind speed, solar irradiance and precipitation were collected for every month. Other biophysical characteristics such as elevation, water table and ground properties were collected on an aggregated annual basis. Table S1 (in the Supplementary Material, Section 1.1) provides a more detailed description of the characteristics of the dataset.

2.2. Cropland Calibration

GIS land cover data can be used as a proxy for identifying cultivated and/or irrigated areas. There are several options available for GIS land cover and cropland data [27–29]. The European Spatial Agency’s (ESA) Climate Change Initiative (CCI) land cover S2 prototype for Africa dataset [30] provides a fine spatial resolution throughout the entire NWSAS region. Using ESA CCI, the total cropland area in the NWSAS was estimated at 860,000 ha. However, national statistics indicated only about 270,000 ha of irrigated land (using NWSAS groundwater). In consultation with local stakeholders in OSS, a calibration methodology was developed to eliminate misclassification errors and identify croplands using groundwater, based on Multi-Criteria Decision Analysis (MCDA). Three (potential) sources of misclassification in the ESA CCI were identified. They included sparse vegetation, rain-fed crops and irrigated crops using surface water. Following an Analytical Hierarchy Process (AHP) [31],

the decision criteria were ranked and weighted by local experts. The AHP process has been previously used, proving its effectiveness for GIS applications and assisting the creation of land suitability for farming maps [32,33], landslide susceptibility maps [34] and assessment of groundwater potential zones [35].

2.3. Estimation of the Irrigation Water Requirement

This part of the study builds on previous work by [36], which was mainly adopted from FAO Irrigation and drainage paper 56- Guidelines for computing crop water requirements [37] and FAO's Irrigation Water Management; Training Manual for small-scale pumped irrigation [38]. The following paragraphs explain the main steps of this method.

Modelling reference crop evapotranspiration (ET₀). The FAO-56 Penman-Monteith [37] method was used to estimate reference crop evapotranspiration based on monthly climate data. The Python library "Pyeto" [39] was used to calculate meteorological parameters from climate data, which are then used to calculate the reference evapotranspiration.

Crop calendar modelling. Since the crop water requirement varies with each growing season, the monthly crop calendar and crop coefficient (K_c) for each crop modelled were collected from the literature as shown in Table 2. The distribution of crops in each province was based on consultation with local experts. The data were then spatially and temporarily (monthly and yearly) aggregated to represent the variation in K_c values in each growing season and the resulting change in crop water requirement.

Table 2. Crop calendar and crop distribution in the NWSAS region.

Growing Cycle		Dates	Vegetable	Olives
Planting	init_start	01/11	01/11	01/03
	init_end	30/03	25/11	30/03
	Kc ini	0.56	0.5	0.45
	dev_start	31/03	26/11	31/03
Growing	dev_end	04/05	31/12	30/06
	mid_start	05/05	01/01	01/07
	mid_end	30/09	07/02	31/08
	Kc mid	0.7	1	0.55
Harvesting	late_start	01/10	08/02	01/09
	late_end	31/10	28/02	30/11
	Kc end	0.56	0.8	0.6
Sources		[40,41]	[37]	[42]
Distribution in the NWSAS provinces (% of irrigated cropland area) Based on consultation with local experts from countries.		In most provinces: Date Palm (50%) and Vegetables (50%) except: Gharyan (Libya): Olives (70%) and vegetables (30%) Jufrah (Libya): Dates (70%) and Vegetables (30%)		

Irrigation water demand modelling. Knowing the reference crop evapotranspiration (ET₀) and crop coefficient (K_c), the water requirements for each crop in each month were calculated [37]. The effective rainfall, which represents the amount of rainwater that can be retained in the root zone and can be used by a plant, was then calculated based on monthly precipitation data [43]. The difference between effective rainfall and the monthly crop water requirements provide an estimate of the monthly crop water needs. This crop-specific factor can then be used to estimate the monthly irrigation water demand of a certain crop, taking into consideration the total area irrigated each month and the irrigation efficiency applied.

2.4. Estimation of the Electricity Requirement for Pumping

Based on irrigation requirements throughout the year, the electricity required to pump groundwater at each location of the aquifer system was calculated (energy for conveyance is not considered in

this estimation). Electricity demand depends on the efficiency of the pump, the pipeline diameter, pipe material roughness or friction factor, the volumetric demand for water, and the water table depth (the latter was taken from [44]). Since information about the distribution of irrigation methods could not be found for each province, it was agreed with stakeholders to assume the same irrigation technique for all provinces. Three different scenarios were examined, as will be explained later.

2.5. Estimation of the Least-Cost Electricity Supply Option

Different supply options were compared based on the Levelized Cost of Electricity (LCOE) following a similar approach to [45]. This calculation maps the cheapest option available for the farmer at each location to produce electricity for pumping. In Libya all pumps are electric and connected to the grid while in Algeria and Tunisia a mix of diesel and electric pumps are used. However, due to lack of publicly available maps of the medium and low voltage grid network, it was difficult to know the actual distribution of the electric pumps in Algeria and Tunisia. Hence, we assume that all pumps in Algeria and Tunisia are running with diesel generators and in Libya all pumps are powered by the national grid. This assumption was also verified through the consultation with local experts of the three countries [12]. These options were compared to stand-alone PV and small-scale wind turbines as shown in the following Table 3.

Table 3. Summary of the energy supply technologies compared in each country.

#	Country	Technologies Compared
1	Algeria	Diesel pumps, stand-alone PV and small-scale wind turbines.
2	Libya	Electric pumps (grid-connected), stand-alone PV and small-scale wind turbines.
3	Tunisia	Diesel pumps, stand-alone PV and small-scale wind turbines.

3. Scenarios and Nexus Questions

The ‘nexus dialogues’ with stakeholders identified a number of key challenges in the NWSAS [46] underlining the need to quantify the actual water and energy requirements associated with irrigation. The following questions emerged from this dialogue and guided the development of the model:

1. What is the monthly irrigation requirement in each province?
2. What would be the impact of improving the efficiency of irrigation systems? Three levels of efficiency were investigated based on data obtained from literature [47] and consultation:
 - Scenario 1: Surface irrigation—low efficiency (45%).
 - Scenario 2: Surface irrigation—enhanced efficiency (65%).
 - Scenario 3: Drip irrigation (85%).
3. What is the electricity requirement associated with pumping?
4. What would be the least-cost electricity supply option in each location to meet the estimated energy requirements?
5. What changes in technology cost and subsidy levels would be needed to make renewable technologies more competitive in the region?

4. Results and Discussion

The following section presents and discusses the results of this exploratory modelling work in light of each nexus question above. Before diving into irrigation related questions however, it should be highlighted that prior to this study, no accurate GIS map of irrigated cropland in the NWSAS was available. Hence, assembling existing spatial data and generating such a map for the first time are the key contributions of this study. Together with the results, they help fill the information gap in the region and pave the road for more detailed analysis in the future.

What is the total irrigated cropland area?

Calibration of the cropland layer derived from the ESA CCI land cover dataset produced a new layer showing cropland density in the region at 1 km spatial resolution (ha/km^2). The process succeeded in removing croplands from possible error sources such as sparse vegetation, croplands irrigated with surface water and rain-fed croplands. The discrepancy in terms of total irrigated cropland area between the national statistic and the ESA CCI map was reduced in all provinces by the selected $\pm 15\%$ tolerance range. Nonetheless, the calibrated layer is certainly not free of error and uncertainty. It may carry uncertainty and errors from the original ESA CCI map, the selected GIS layers for the AHP process and potential bias error from the ranking and weighting process by local experts (see Section 1.2 of the supplementary material for more detail on the AHP process). A comparison between the original ESA CCI dataset, the national statistic and the calibrated cropland layer is presented in Figure 4.

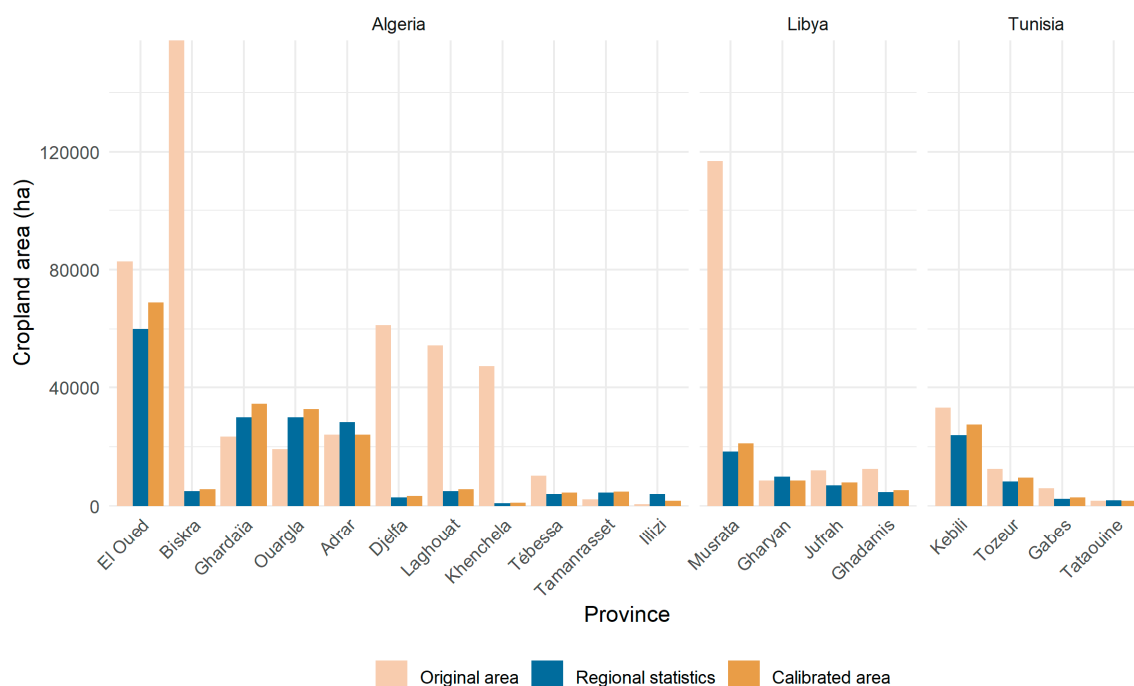


Figure 4. European Spatial Agency’s (ESA) Climate Change Initiative (CCI) original cropland area, national statistics and calibrated area by province.

4.1. What is the Irrigation Requirement in Each Province of the NWSAS Region?

Modelling results indicate that the total annual irrigation water requirement in the entire NWSAS is about 3.25 billion m^3 (or 11,700 m^3/ha). These values are close to the local statistics for water abstraction reported by OSS and local experts [12]. Figure 5 shows the estimated annual water demand (m^3/ha) based on the selected crops for each province (Table 2). It can be observed that Adrar, Illizi, Tamanrasset and Jufrah exceed the level of 14,000 (m^3/ha), whereas other provinces are between 10,000–12,000 (m^3/ha), and only Musratah is below the 10,000 (m^3/ha) threshold. Different parameters affect the irrigation water requirement such as evapotranspiration, which depends on wind speed, temperature and solar radiation. Areas like Adrar have high solar irradiance and wind speed (see Figures S2 and S3 in the Supplementary Materials), which result in higher evapotranspiration and, accordingly, irrigation needs. Another important parameter is the type of crops cultivated in each province, which influences different water requirements (see Table 2).

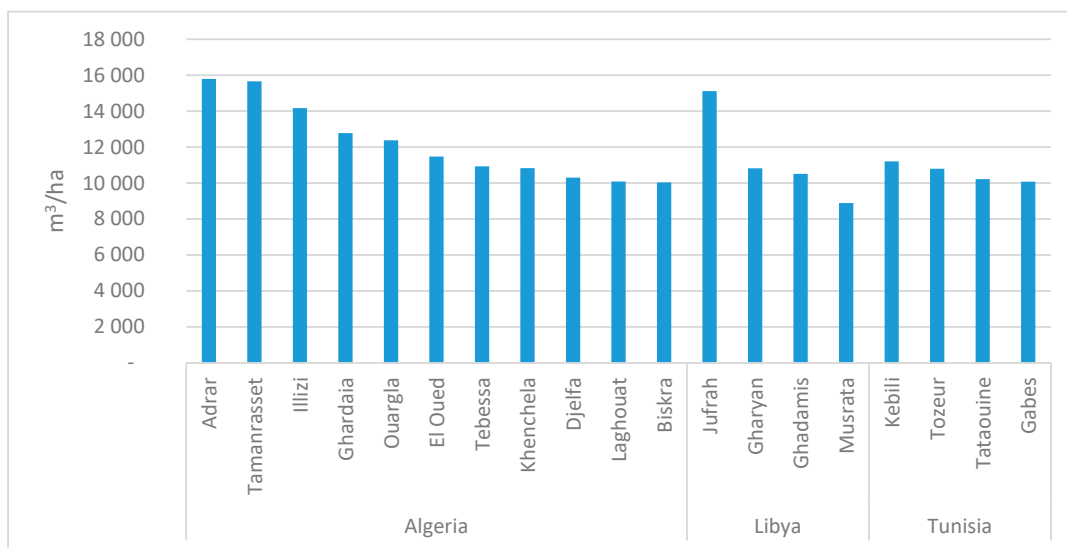


Figure 5. Estimated annual water demand level (m³/ha) in each province based on the selected crops modelled in each province.

4.2. What is the Impact of Improving the Irrigation System on Water Demand Level?

The savings from water abstraction in each province due to improved efficiency are shown in Figure 6. It can be noticed that investing in improving the efficiency of the irrigation system has the potential to save up to 47% of water abstraction in the NWSAS area, which in terms of volume can save on average 5500 m³/ha and even more than 7000 m³/ha in Adrar (Algeria) and Jufrah (Libya) (see Table S7).

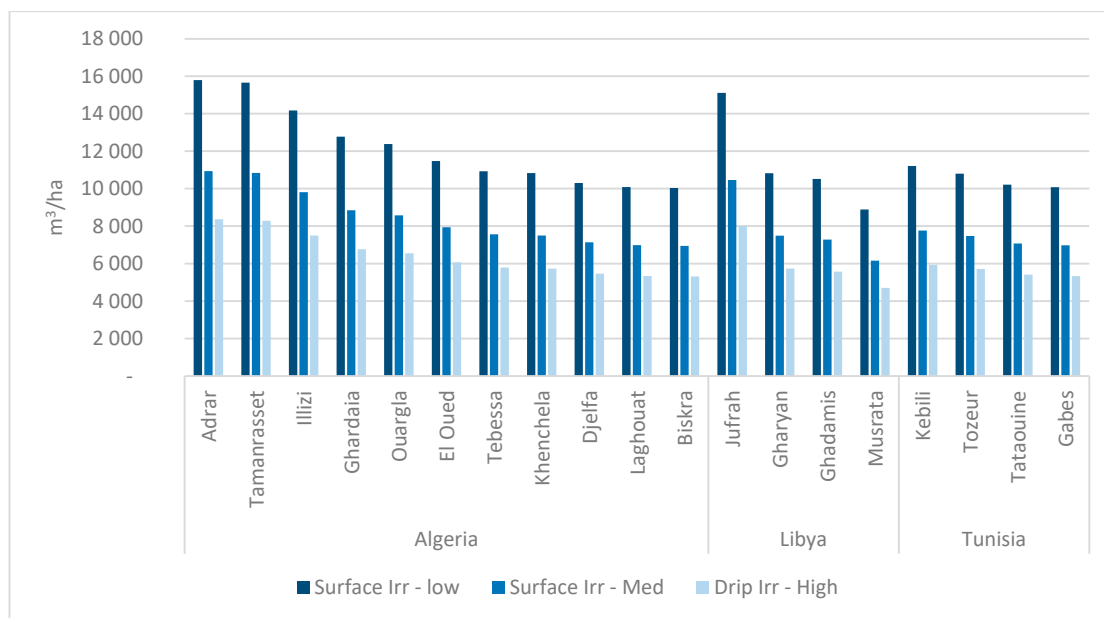


Figure 6. Comparison of water demand in (m³/ha) for each province under three scenarios: a. (Surface Irr–Low): Surface irrigation with low efficiency 45%; b. Surface Irr–Med: Surface irrigation with low efficiency 65%; and c. Drip Irr–High: Drip Irrigation with high efficiency 85%.

4.3. What is the Electricity Required for Pumping?

The total annual electricity demand reached 730 GWh for the entire NWSAS area. Algeria accounts for 70%, then Libya 21% and only 9% in Tunisia. Figure 7 shows the annual energy requirement in

each province. Eloued, Adrar and Ghardaia (all in Algeria) contribute to about 55% of the total energy demand. This directly reflects the high volumes of water being pumped in these locations (Figure 8). In Libya and Tunisia, the provinces with the highest demand are Musratah and Touzer, respectively. Comparing water and energy demands again, it can be noted that although the annual amount of water being pumped in Kebeli is higher than in Touzer, the associated energy requirement is higher in Touzer, probably due to the average depth of the water table level, which reaches 43 m in Touzer and 26 m in Kebeli (See Table S3).

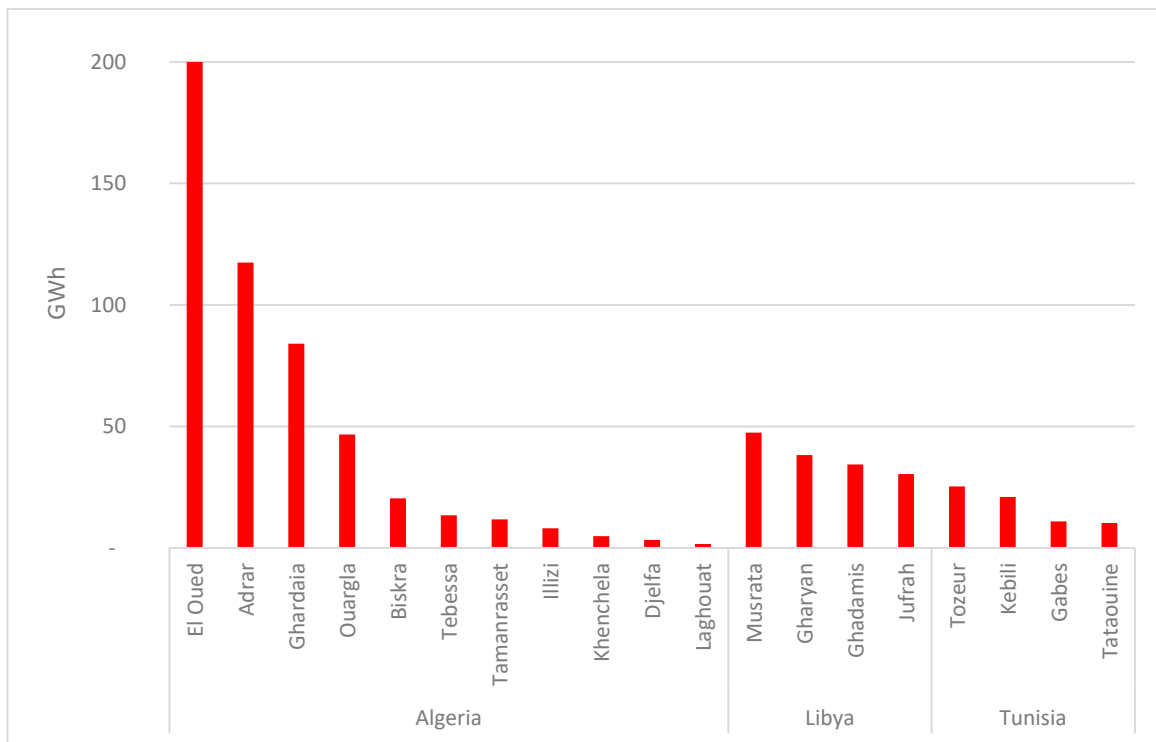


Figure 7. The estimated electricity demand (GWh) for pumping in each province.

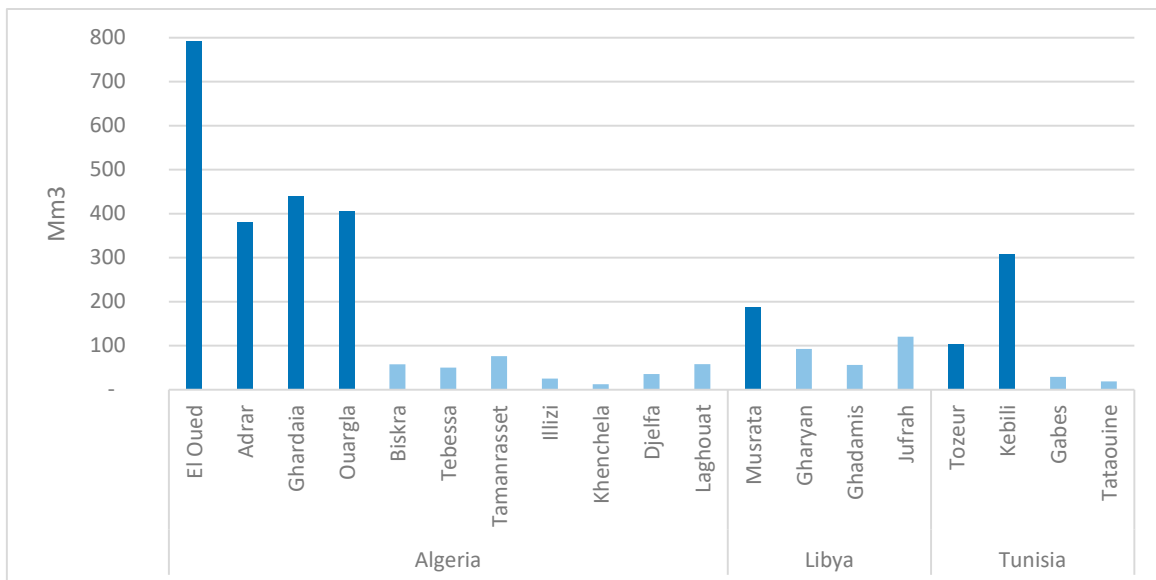


Figure 8. Annual water demand (Million m³) in each province.

4.4. What is the Least-Cost Electricity Supply Option at Each Location to Meet the Estimated Energy Requirements?

The following Figure 9 shows the most economical option based on the LCOE comparison of different technologies. It is noted that all locations are colored either by red or purple, which reflects the use of diesel generators in Algeria and Tunisia, and grid electricity in Libya which is coming from fossil fuel sources (in 2016, about 60% of the electricity generation in Libya came from Natural gas and the rest came from oil products [48]). This result indicates that the current, highly subsidized prices of fossil fuel in the region make the penetration of renewable energy, at the current technology cost, very challenging. To facilitate renewable energy deployment in the three countries, subsidy structures may need to be revised.

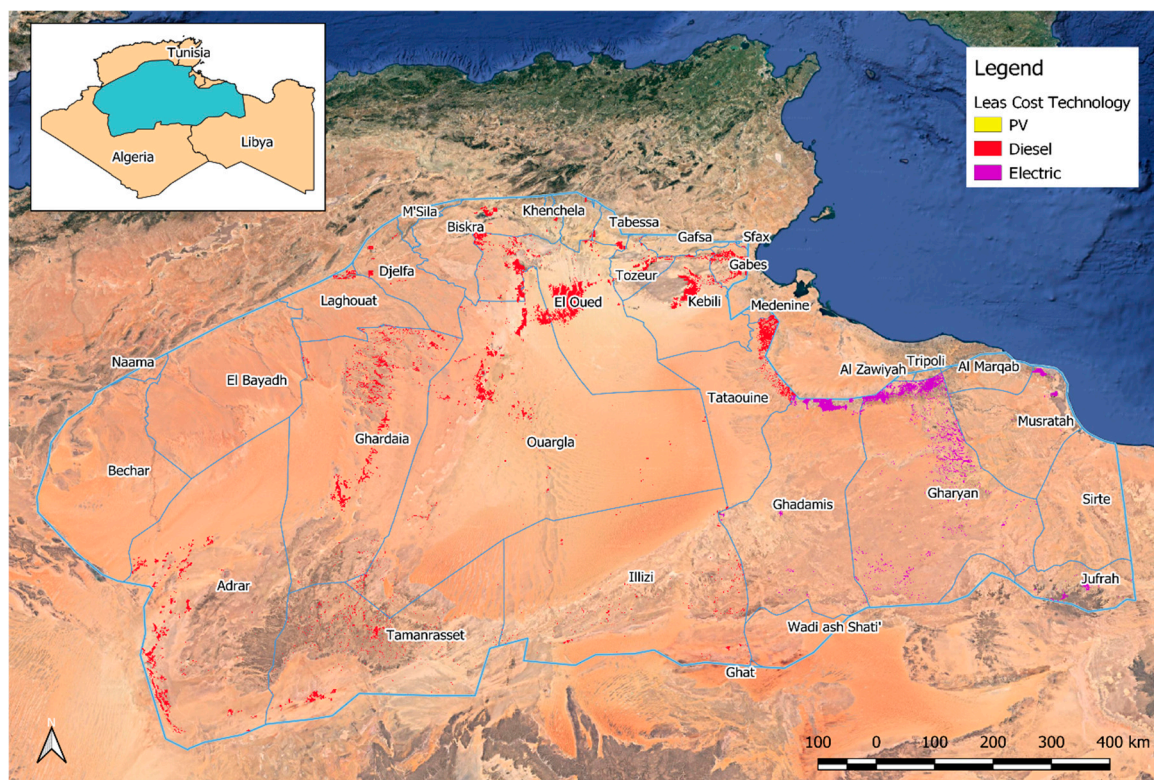


Figure 9. Least-cost electricity supply option for pumping irrigation in the NWSAS region.

4.5. What Changes in Subsidy Levels Are Needed to Make Renewable Technologies More Competitive in the Region?

Sensitivity analysis was carried out to study the impact of two key factors of the LCOE calculation: (a) the capital cost (CAPEX) for the two renewable technologies considered, namely stand-alone solar PV and small scale wind turbines; and (b) fossil fuel subsidy level, which, in the case of Algeria and Tunisia, is the diesel price and in the case of Libya is the electricity price as shown in Table 4. A step increase of 25% and 50% was assumed for both diesel and electricity prices at sensitivity levels 2 and 3, respectively, to reflect a decrease in subsidies. Additionally, a drop in solar PV and Wind CAPEX due to learning curves was assumed at 15% and 30% to represent levels 2 and 3, respectively. This is a conservative assumption if compared to the International Energy Agency (IEA) World Energy Outlook (WEO) 2018. Which projects a decline in solar PV cost in the Middle East to about 44% by 2030 compared with the 2017 cost under the new policy scenario and 54% by 2030 under the Sustainable Development Scenario (SDS) scenario [49].

Table 4. Summary of the sensitivity analysis inputs.

Technologies	Parameter	Units	Sensitivity Levels			Source
			1	2	3	
Diesel Gen sets	Capital Cost (CAPEX)	USD/KW	938	938	938	
	O & M	USD/KWh	0.1	0.1	0.1	[50]
	Life Time	Years	10	10	10	[51]
	Fuel Cost (Diesel, Algeria)	USD/Litre	0.17	0.21	0.26	
	Fuel Cost (Diesel, Tunisia)	USD/Litre	0.62	0.78	0.93	
Electric Pump	Capital Cost (CAPEX)	USD/KW	845	845	845	
	O & M	USD/KWh	0.1	0.1	0.1	[50]
	Life Time	Years	10	10	10	[52]
	Fuel cost (Electricity, Libya)	USD/KWh	0.168	0.21	0.252	
Wind	Capital Cost (CAPEX)	USD/KW	1300	1105	910	
	O & M	USD/KWh	0.02	0.02	0.02	[53]
	Life Time	Years	20	20	20	
PV	Capital Cost (CAPEX)	USD/KW	1140	970	680	
	O & M	USD/KWh	0.01	0.01	0.01	[54,55]
	Life Time	Years	15	15	15	

CAPEX level 1:

As mentioned earlier, with the current subsidized levels of fossil fuels and high CAPEX of renewables (level 1), renewable energy generation is simply not the most cost-effective option (Figure 10a). Removing 30% of fossil fuel subsidies will allow for PV to start being competitive in Jufrah (Libya) (Figure 10b), and 50% subsidy removal will see PV being part of the mix in Gharyan (Libya) as well, especially in the northern part where the intensity of irrigated croplands is higher (Figure 10c). This can be explained by the fact that solar radiation in those two provinces is very high (it reaches 2000 kWh/m² per year (See Table S2)) and by the high irrigation water demand in these provinces, which means more energy for pumping and therefore a lower LCOE value for PV. In all cases, the competitiveness of wind turbines is very low due to high capital cost and relatively low wind speed at the locations considered.

CAPEX level 2:

A drop in technology cost by 15% will have the highest impact on the Tunisian side, which has the highest fossil fuel prices (lower subsidy) [51] of the three countries. With a technology cost of 970 USD/KW, PV will start being part of the mix in Tataween (south of Tunisia) as shown in Figure 11a. Tataween has higher solar radiation compared to other Tunisian provinces, which reach about 1900 kWh/m² per year (see Table S2). Further increase in fossil fuel cost by 30% will make PV the preferable option for most of Tunisia, as shown in Figure 11b. The Algerian part will require further removal of fossil fuel subsidies, up to 50%, before PV becomes competitive. Southern provinces like Adrar and Tamaneassat, which receive the highest solar radiations, are the first ones to see the penetration of solar technology on the Algerian side (Figure 11c). It is worth recalling that Adrar is one of the provinces that also has one of the highest annual irrigation water requirements (Figure 8).

CAPEX level 3:

Finally, a further drop in the CAPEX of renewable technologies down to 680 USD/KW for solar would make PV the least-cost supply option in almost the entire region of the NWSAS, even without the need to change the subsidy structure of fossil fuels (as shown in Figure 12). Based on the three scenarios, it can be concluded that the competitiveness of renewable technologies (mainly solar PV) is more sensitive to technology cost than fossil fuel subsidy. This means that supporting solar technology in the region is a key policy question for decision-makers to make renewable technologies affordable for middle- to low-income people like farmers in rural areas who are currently dependent on diesel gen-sets and/or fossil fuel-based electricity coming from the national grid.

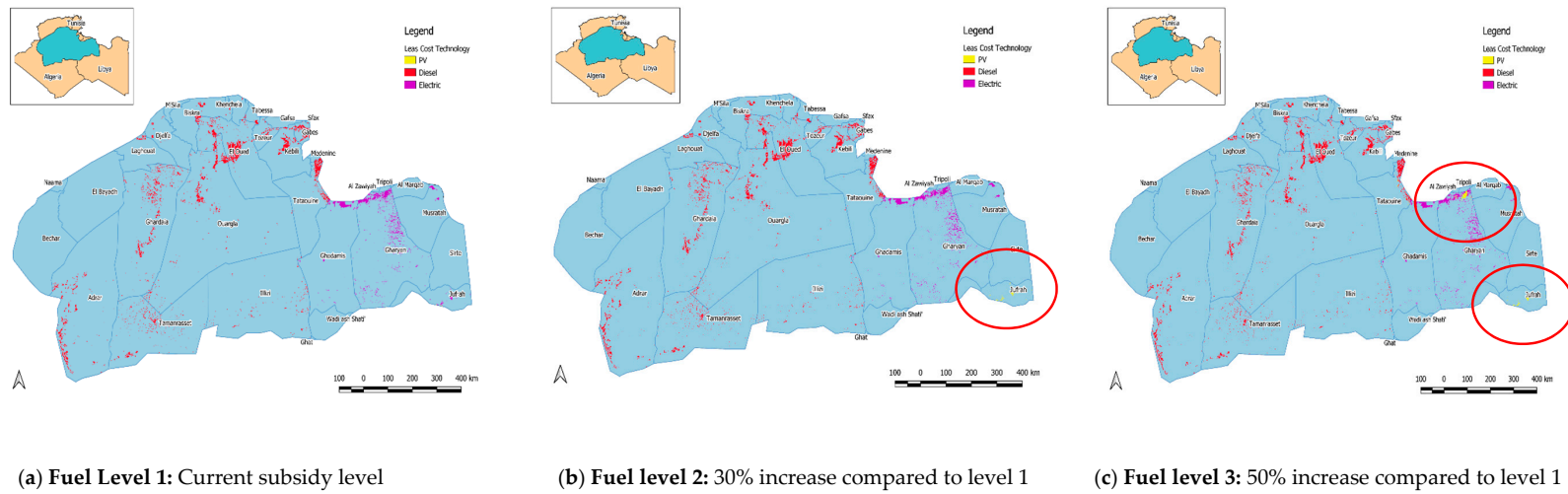


Figure 10. Comparison between the electricity supply options at CAPEX level 1 for three levels of fuel subsidy.

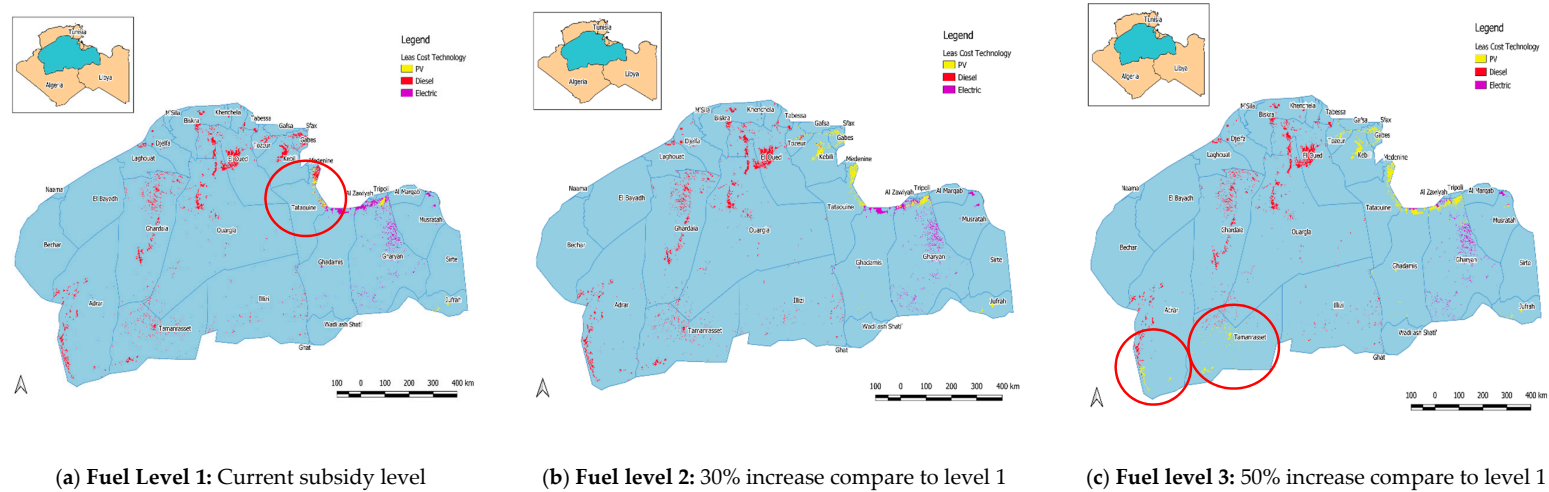


Figure 11. Comparison between the electricity supply options at CAPEX level 2 for three levels of fuel subsidy.

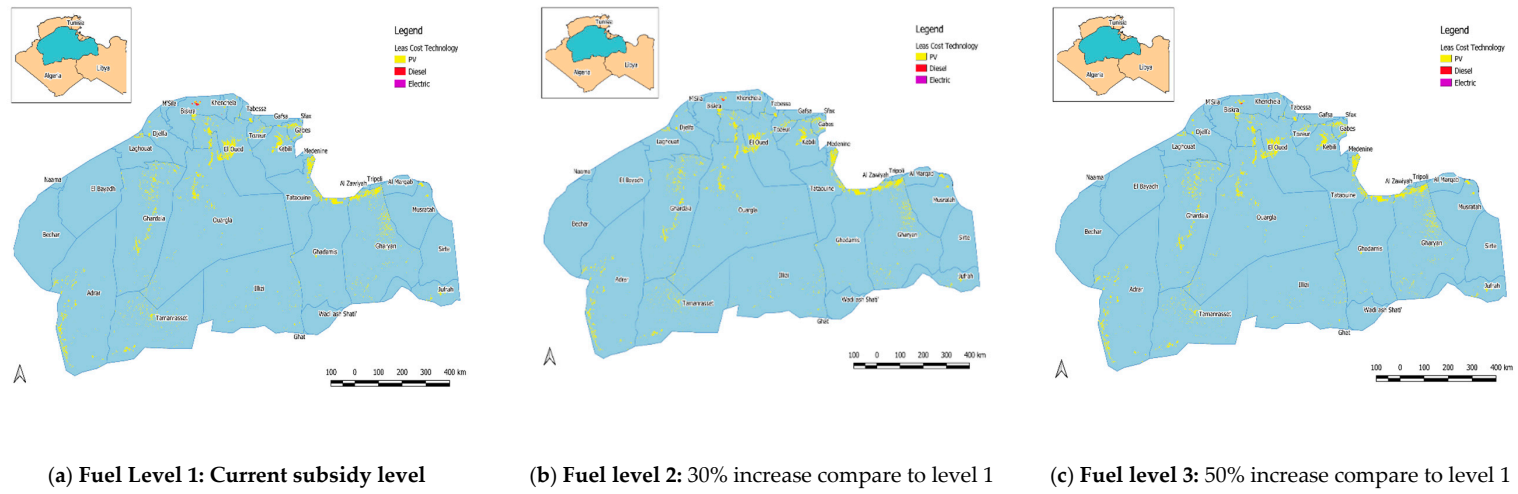


Figure 12. Comparison between the electricity supply options at CAPEX level 3 for three levels of fuel subsidy.

At this point, it is important to stress that the use of solar technology for irrigation comes with the significant risk of aggravating groundwater exploitation, particularly where abstraction limits are non-existent or difficult to impose, as in the case of the NWSAS. The problem is that, once the investment cost is made, PV pumps come with zero operation cost, which creates an incentive for the farmer to irrigate more. This is another key policy question that calls for a much closer collaboration among the agriculture, water and energy sectors to ensure sustainable deployment of solar technology in the region.

5. Conclusions

This study shows that the annual irrigation water requirement in the entire NWSAS reaches 3.25 billion m³. This translates in most provinces to 10,000–12,000 (m³/ha), while in areas with high evapotranspiration such as Adrar, Illizi, Tamanrasset and Jufrah, the irrigation requirements exceed the level of 14,000 (m³/ha). From a policy perspective, our analysis indicates that improvements to the irrigation system with the introduction of drip irrigation have the potential to reduce the water abstraction rate by up to 47%, which, in terms of volume, means an average saving of about ~5500 m³/ha per year. However, the estimated savings may be compromised if the net irrigation area is extended. This is a common “rebound” effect related to irrigation efficiency, which underlines the importance of employing water conservation measures beyond efficiency improvement.

Electrification of irrigation in the NWSAS region is estimated to account for an additional 730 GWh per year. On a country level, electricity requirements in Algeria seem to take the highest merit of total electricity needs (~70%) followed by Libya (21%) and Tunisia (9%) to a lesser extent. This is explained by the large share of the Algerian area and the intensity of agricultural activity. On a sub-national level, our study finds that the provinces of ALEoud, Adrar, Chardaia (in Algeria), Musrata (Libya) and Tozeur (Tunisia) indicate the highest levels of electricity needs for irrigation.

The least-cost approach indicates that fossil fuel-based (grid and off-grid) technologies dominate electrification. That is due to existing subsidies on fossil fuels as well as the high (upfront) capital costs of renewable-based technologies, which significantly reduce the competitiveness of the latter. Restructuring existing subsidy schemes (for fossil fuels) or introducing a new renewables support scheme to reduce the capital investment of renewable technologies, mainly PV, would make them more competitive when compared with diesel gen-sets or grid electricity. It should be highlighted, however, that support for solar-based irrigation must go hand in hand with water regulation, water-saving incentives, and awareness-raising to avoid groundwater depletion.

The results presented in this paper have the power to inform policy at regional, national, and sub-national levels. In fact, this paper has been part of a multilateral planning effort in the NWSAS region involving partners from several institutions active in the region representing agriculture, water, energy and environmental sectors in the three countries. Their contribution was important in providing information on a local level and helping to deal with existing data gaps and modelling limitations. Despite the high degree of collaboration, and as in any modelling exercise, our analysis has limitations, which we briefly describe below.

First, there is the issue of poor data lineage (e.g., poor information regarding the source and methods of derived data) and geo-semantic uncertainty. The authors have worked closely with local stakeholders to obtain and process the best available datasets to integrate water, agriculture and energy aspects. However, some important datasets were not available either in public online sources or in local databases. Examples include the grid network and the distribution of the pumping techniques in each province. To overcome this, the authors relied on the pool of experts during the nexus dialogues to develop sensible assumptions that fit the purpose of this study. Another example is the variation between satellite data sets versus local statistics. Although calibration was carried out to reduce mismatches, the process does induce uncertainty, which was not explicitly quantified in the results.

Secondly, there are limitations related to the design of the analysis per se. These may include the limited number of crops, crop calendar assumptions, proxy values for the crop coefficient (kc) factors,

technology specifications, generalizations over the irrigation techniques and water management methods (e.g., irrigation efficiency, pumping hours per day), among others. These were based on the value-laden judgements of the authors, in consultation with local experts, and should be taken into consideration when interpreting the results.

Third, the spatiotemporal resolution of the analysis was a compromise between computational complexity, resources, time and scope. This paper serves as a high-level policy support analysis rather than a detailed engineering analysis. That is, spatial aspects that require high information granularity (e.g., soil dynamics, high spatial resolution vegetation cover) but do not necessarily add value to the final objective, were not included. The monthly temporal resolution was selected for similar reasons. It should be noted, however, that different spatiotemporal granularity may have an impact on the results and thus should be explored in future research.

Finally, there is a dimension of political uncertainty in the three countries sharing the basin, which certainly has an impact on the development of agriculture and other water and electricity uses. This was also not explicitly captured in our analysis.

Based on the above, we suggest that future work in the NWSAS should aim at tackling these limitations. For example, updating the model with the grid network map can allow for a better understanding of farmers' proximity to the grid and the competitiveness of solar PV. Equally, the existing model can be used to explore different agricultural development pathways and quantify the impact on water and energy resources. This can be done with a high level of transparency due to the open-source nature of the model. The availability of the code on GitHub supports reproducibility and capacity building for both policy and academic purposes.

Despite its limitations, the suggested methodology, in our opinion, takes nexus analysis a step ahead, informs sustainable development strategies and motivates nexus dialogues across sectors and countries.

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