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Water use efficiency in agricultural irrigation in Egypt

A qualitative study on the complexities of utilising fossil groundwater resources in the face of water scarcity

by

Johannes David Huber
jo4448hu-s@student.lu.se

Abstract: This study examines the adaptive capacity of desert farming in Egypt to imminent water scarcity and discusses the sustainability of fossil groundwater extraction. Through qualitative semi-structured expert interviews, the study identifies clear research and data gaps related to the Nubian Sandstone Aquifer System (NSAS) and highlights the need for a nuanced approach to fossil groundwater extraction that focuses on water use efficiency improvements. Economic-technological improvements in water use efficiency as well as socio-behavioural aspects of water scarcity adaptation are further identified to be vital for successfully adapting to water scarcity constraints in desert farming in arid regions.

Keywords: Water scarcity, water use efficiency, agricultural irrigation, desert farming, sustainability, groundwater extraction, Nubian Sandstone Aquifer System (NSAS)

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1 Introduction

Freshwater resources, while indispensable for human well-being, sustainable development, and environmental preservation, are finite in nature (Gleick, 1993; Wolf, 1999). Unfortunately, the prevailing perception of unlimited freshwater exacerbates the detrimental effects of water scarcity, including soil desertification, biodiversity loss, and ecosystem disruption. While there is agreement on the environmental challenges posed by water scarcity, there is less consensus on potential solutions and their implications for different groups and communities (IPCC, 2022). Globally, approximately four billion people face water shortages, with half experiencing physical water scarcity. These shortages stem from governance failures and inefficient water management. Rapid population growth, urbanisation, and industrialisation further contribute to water scarcity, disrupting natural systems, livelihoods, and human health. The extraction of groundwater from fossil aquifers has been an adaptive response as they present a reliable source of fresh water, but it risks overexploitation and proves to be unsustainable in the long term (FAO, 2020; IPCC, 2022).

Egypt, in its pursuit of food security, faces growing challenges of water shortages and scarcity due to rapid population growth, urbanisation, and agricultural expansion. With an annual freshwater availability of 560 cubic metres per capita, Egypt is among the most water-scarce countries globally (FAO, 2020, 2023). The North African country relies almost entirely on the Nile River, which provides approximately 97 percent of its water demand, as well as groundwater from aquifers, and regional precipitation along the Mediterranean coastline, averaging approximately 80 millimetres annually. However, the Nile River experiences increasing volatility due to upstream riparian activity and precipitation changes due to its transboundary nature, which adds to the uncertainty in Egypt’s water availability (Gohar & Ward, 2011; Satoh & Aboulroos, 2017). Furthermore, groundwater resources are increasingly involved in solving Egypt’s water scarcity; particularly in meeting the water demand of agriculture, which consumes approximately 85 percent of Egypt’s total water resources. Given the high water demand in the agricultural sector, Egypt has been focusing on improving water use efficiency by implementing water-efficient irrigation systems such as drip, centre pivot or sprinkler irrigation (Gohar & Ward, 2011; Karajeh et al., 2011; Osman, Ferrari & McDonald, 2016). Despite water efficiency improvements, per capita water consumption already exceeds available freshwater resources, highlighting the need for additional solutions to address escalating water scarcity (FAO, 2020).

In this context, Egypt's groundwater resources are part of the strategy to develop new agricultural land (MWRI, 2017). However, the fossil nature of its groundwater resources is problematic and might result in overexploitation as well as unsustainable and inefficient water use, particularly in agricultural irrigation as Egypt primarily relies on irrigation-fed farming due to extremely limited precipitation. Insufficient sustainable water resource management could subsequently lead to resource depletion and the occurrence of the tragedy of the commons (Ostrom, Gardner & Walker, 1994, p.5; Satoh & Aboulroos, 2017). Hence, this study aims to discuss the following research questions:

> *How can desert farming in Egypt adapt its agricultural water use to imminent water scarcity under climate variability?*
>
> *What are the challenges for groundwater exploitation in desert farming in the Bahareya Oasis in Western Egypt vis-à-vis sustainability?*

This study aims to enhance understanding regarding the sustainability of fossil groundwater withdrawals in the context of desert farming, considering the local conditions necessary for ensuring food security and meeting the needs of a rapidly growing population. It focuses on a pilot irrigation project located in the Bahareya Oasis in Egypt's Western Desert. The study explores the challenges and implications associated with the sustainability of fossil groundwater extraction, given that the oasis relies on non-renewable water resources from the Nubian Sandstone Aquifer System (NSAS).

To analyse the research questions, a qualitative study was conducted on-site in Egypt utilising semi-structured qualitative expert interviews. The interviewees consisted of experts directly involved in the pilot irrigation project as well as water resource and water management experts from governmental and international organisations, and academia. The findings of the study are presented through a thematic analysis of the expert interviews, with the aim to extract valuable insights for water-stressed countries in arid regions that depend on desert farming.

The contribution of this study is two-fold. First, it applies the social-ecological systems (SES) framework by Ostrom (2009) to the analysis of a non-renewable resource. This application enhances the understanding of how the SES framework can be utilised and provides valuable insights into examining the sustainability of common-pool resources (CPRs). Secondly, by employing the SES framework to investigate the fossil NSAS within the context of desert farming in Egypt, this study identifies context-specific factors that need to be considered in determining the adaptative capacity of communities in the face of water scarcity.

The outline of this study is as follows. Section 2 presents previous literature by discussing the limits and impacts of global water scarcity with a focus on food security and emphasises the complex nature of biophysical as well as societal considerations of water scarcity adaptation. The study continues to explore previous literature on sustainable groundwater use in agriculture as well as water use efficiency in irrigation methods and discusses the sustainability of non-renewable groundwater resource extraction. Section 3 presents the theoretical framework utilised to analyse the research problem of this study and provides an overview of the common-pool resource problem. Section 4 explains the methodology applied and explains the data collection process of conducting qualitative expert interviews during the on-site field research in Egypt. Sections 5 and 6 analyse and discuss the results in the context of the theoretical framework and by connecting them to previous literature. Section 7 concludes by providing future research suggestions.

2 Previous literature

2.1 Global water scarcity

2.1.1 Limits and impacts of global water scarcity

Global freshwater resources are limited, with only 2.5 percent of the total water covering the planet being consumable. The majority of freshwater is inaccessible, frozen in polar caps, ice sheets, permafrost, and glaciers. Accessible freshwater is heavily relied upon, primarily stored underground in aquifers, soils, or wetlands, while surface water makes up a mere 0.3 percent (Chellaney, 2013, p.xii; Foster & Chilton, 2003; Global High-Level Panel on Peace and Water, 2017; World Bank, 2023). Water scarcity is particularly severe in regions with annual resource availabilities below 1700 cubic metres per capita, such as Western Asia and North Africa, where some countries are acutely water-stressed with average availabilities below 500 cubic metres per capita (Falkenmark, 1989; Gleick, 1993; Global High-Level Panel on Peace and Water, 2017). While over the past two decades, the annual amount of per capita available resources has declined by approximately 20 percent, Western Asia and North Africa have faced even more significant declines of over 30 percent, resulting in severe water stress and more frequent droughts (FAO, 2020).

However, water scarcity is not solely determined by physical limitations but is influenced by governance, institutions, security, and health considerations (Stringer et al., 2021). Consequently, water scarcity can arise from both lacking physical freshwater resources as well as challenges related to infrastructure, failures of governance, and wider socio-political aspects. While governance or infrastructure-related challenges may make countries struggle to provide their population with safe and dependable access to fresh water, even if physical scarcity is not given, Mehta (2007) argues that water scarcity must be assessed as a social construct and as a result of anthropogenic actions rather than accepting it as a natural condition. Anthropogenic and social-institutional impacts, such as societal status, historical legacies, gender, and affluence, play a significant role in causing water scarcity and shortages. Hence, scarcity experienced by locals can be a result of physical water shortages, while socially constructed scarcity is generated by processes that benefit the privileged or powerful (Mehta, 2007).

Population growth, economic and industrial development, poverty reduction and climate change intensify physical water scarcity resulting in a six-fold increase in global freshwater withdrawals since 1900 (Christoforidou et al., 2023; Dlamini, Senzanje & Mabhaudhi, 2023; FAO, 2020; Gleick, 1993; Ritchie & Roser, 2017; World Bank, 2016). Currently, around 4 billion people face water scarcity annually, and this number is expected to rise with a 2°C global temperature increase, potentially affecting at least 800 million people (IPCC, 2022; Mekonnen & Hoekstra, 2020).

Climate change, along with changes in land use and water pollution, is a key driver behind the loss and degradation of freshwater ecosystems. Consequently, agricultural production is strongly impacted by climate change-related water scarcity coupled with rising crop water demand (IPCC, 2022). Excessive use and pollution of freshwater resources by the agricultural and industrial sectors, as well as the alteration of water courses for electricity production and other navigational purposes, further contribute to the decline of global freshwater resources (Orlando, 2015). Less developed countries in arid and semi-arid regions, already experiencing high temperatures, will be disproportionally affected as they heavily rely on agricultural production for their national income. The pressure on these governments will increase as evapotranspiration and decreasing precipitation lead to additional water losses (Mertz et al., 2009). To address the crisis, one response has been the extraction of freshwater from aquifers as surface water from lakes and rivers dwindles (Siebert et al., 2010).

2.1.2 Food security under water scarcity

Global water scarcity driven by population growth, economic development, and climate change, poses significant challenges for ensuring food security. While global water resources are adequate to ensure food security, the problem lies in distribution. Regions and countries grappling with water scarcity are increasingly unable to achieve self-sufficiency in food production, creating a distribution problem rather than a scarcity problem (Christoforidou et al., 2023).

Before the global financial crisis, combining domestic agricultural production with food imports was a strategy to ensure food security in water-scarce regions. However, the crisis led to rising food prices, exposing the risks of this global trade strategy, particularly for low-income countries reliant on food imports. In response, less-developed countries shifted their focus to improving self-sufficiency in food production to reduce dependence on global markets and price volatility (Christoforidou et al., 2023; Molden, 2013). However, countries in semi-arid and arid regions, constrained by limited water resources and population growth, face challenges in meeting the growing demand for food and achieving economic development (Abdelkader & Elshorbagy, 2021). Furthermore, their reliance on food imports exposes them to price hikes, volatility, and geopolitical turmoil, leading to export restrictions by food-producing countries and negatively affecting global food prices (Cardwell & Kerr, 2014).

North Africa and Western Asia, the most water-scarce regions globally, continue to heavily rely on cereal imports. Declining domestic water resources put their self-sufficiency to meet food demands under pressure, forcing them to rely on food imports and subsequently causing budget constraints, particularly in countries that are water-stressed and lack a strong export sector, making them vulnerable to both efforts to increase self-sufficiency and reliance on trade (Christoforidou et al., 2023).

2.2 Inclusive adaptation to water scarcity

Water scarcity requires countries and communities to adapt to new circumstances as water resources continue to decline. Adaptation refers to the ability of different groups of people, organisations, communities, or nations to adjust to climate change and its effects (IPCC, 2014). However, as with the multi-layered experiences of water scarcity, adaptation to diminishing water resources is a complex process, encompassing not only climatic and technological aspects but also cultural environments and institutions (Vincent & Cundill, 2022). Behavioural and cultural forces, including individual self-interest and collective initiatives, can play a role in governing and conserving water resources (Schofield & Gubbels, 2019).

While it is commonly assumed that farmers are responsible for maladaptation to water scarcity, Ghazouani et al. (2015) argue that research primarily focuses on income maximisation through technological innovations and crop choice rationalities. However, the response to reduced water availability is influenced by multiple factors, including cultural skills, traditional knowledge and cumulative experiences of farmers (Liwenga, 2008; Pereira, Cordery & Iacovides, 2002).

Farmers’ resistance to adopting more water-efficient technologies may be stronger when organised associations have more negotiation power compared to smaller farmers with less influence. Financial success also plays a role, as financially secure farmers have easier access to knowledge and resources to mitigate the impacts of water scarcity. For instance, the Jordanian government plans to increase its wastewater treatment from 30 to 80 percent by 2050 requiring not only large infrastructural investments but also the willingness of farmers to utilise treated wastewater for irrigation (Tawfik et al., 2023).

Climate change adaptation measures are often designed as technological top-down approaches by governments without considering local knowledge or context (i.e., drought resistance crops). However, these approaches fail regularly due to a lack of support, understanding and inclusion of the local community’s technological and behavioural changes required, such as adjusting irrigation cycles (Caretta & Morgan, 2021; Pahl-Wostl & Knieper, 2014). Successful adaptation is more successful when traditional knowledge is considered and when local stakeholders, particularly those most vulnerable to climate change impacts, are involved (Caretta & Morgan, 2021; IPCC, 2019). These cultural considerations are also supported by institutional theory as Rodrik (2000) emphasizes the importance of local knowledge and understanding in formal as well as informal institutional settings.

Finally, values play a significant role in water scarcity and climate change adaptation. However, they are often narrowly defined in monetary or relative terms, focusing on fair returns or exchanges. O’Brien and Wolf (2010) advocate for a broader understanding of values that takes into account the meaning of climate change and water scarcity impacts and considers different perspectives and contexts in assessing effective adaptation approaches. The perceived value of an adaptation approach can vary across contexts, as people may have different opinions about what is worth preserving and achieving. Therefore, it is essential to understand and discuss the limits of adaptation, which can be biophysical, economic, technological, or societal in nature, including ethics, knowledge, attitudes to risks, and culture (Adger et al., 2009).

2.3 The sustainability of groundwater

2.3.1 Groundwater availability and utilisation

Groundwater is a crucial natural resource stored beneath the Earth's surface in soils, wetlands, and aquifers. It meets over a third of global freshwater demands, supporting the daily water needs of more than half of the global population (Famiglietti, 2014; World Bank, 2023). However, there is an unequal distribution of underground and surface water resources globally, resulting in higher groundwater utilisation in arid and semi-arid regions (UN, 2022). These regions suffer from surface water depletion and often rely on groundwater as their sole source of freshwater (Frappart, 2020; OECD, 2017a). Climate change exacerbates groundwater management challenges, with projections indicating further declines in renewable surface and groundwater resources in certain regions, intensifying water competition (OECD, 2017a). Changes in precipitation patterns, increased evapotranspiration, extreme weather events and rising sea levels further impact groundwater recharge and water quality such as saline intrusion in coastal aquifers (IPCC, 2014; OECD, 2017a). According to Frappart (2020), the current global overexploitation of groundwater exceeds recharge by 3.5 times leading to reduced recharge and increased exploitation as climate change is expected to worsen. Furthermore, groundwater resources, serving as a reliable and constant water source, are gaining in importance as they can play a crucial role in mitigating droughts, floods, and runoff, thus contributing to food security and poverty alleviation (Siebert et al., 2010; World Bank, 2023).

Groundwater resources consist of stocks, describing the stored volume, and flows, depicting the rate of renewal (OECD, 2017a). Usually, the most important factor for quantifying groundwater levels is the flow rather than the stock as renewable groundwater sources have inflows and outflows of water that determine their recharge rate (Giordano, 2009; Margat & Van der Gun, 2013). However, some aquifers are fossil or non-renewable groundwater resources since it can take several hundreds of millennia to recharge them. The highest density of fossil aquifers can be found in North Africa and the Arabian Peninsula which have formed centuries ago and are deep and large groundwater storages (OECD, 2017a). According to the OECD (2017a), extracting water resources from those aquifers can be compared to irreversible mining and is associated with rising extraction costs for energy and drilling since increasing withdrawals result in further declining water levels, which will disadvantage small-scale actors without the necessary financial means to access water resources at deeper levels (OECD, 2016, 2017a; Scanlon et al., 2022).

One significant challenge with underground water resources, particularly aquifers, is the lack and uncertainty about the data on the available and accessible quality and quantity of those resources. The lack of data about storage volumes and depletion rates is particularly present in less-developed countries with weaker governance systems (MacDonald et al., 2012; OECD, 2017a; Siebert et al., 2010). The 6th Assessment Report of the IPCC acknowledges that these limitations in the spatial-temporal coverage of groundwater monitoring networks continue to constrain the understanding of climate change-related impacts on groundwater (IPCC, 2022). Comprehensive mapping and monitoring of deep underground aquifers are necessary to understand and assess sustainable withdrawal regimes and their role in climate change and water scarcity mitigation (OECD, 2017a).

With diminishing surface water availability, climate change-induced variability in precipitation, and higher evapotranspiration, the focus on ensuring water security continues to shift further towards groundwater resources, particularly in water-stressed arid and semi-arid regions, which are largely relying on groundwater resources already (Foster et al., 2011; OECD, 2017a). Consequently, groundwater has become the most extracted resource globally, with projections indicating a significant increase in withdrawals for agricultural irrigation to ensure food security (Chellaney, 2013, p.8; Rosa et al., 2020). Its overexploitation has led to deteriorating benefits, reduced agricultural production, and declining water quality (IPCC, 2022). Anthropogenic activities such as urbanisation, population growth, increased agricultural activity, and the lack of proper sewage and irrigation drainage systems have resulted in considerable deterioration of groundwater quality (Masoud & El Osta, 2016). Major aquifer systems, particularly low-lying coastal aquifers, are facing excessive overexploitation and increased salinity due to various factors, including land use change, rising sea levels, reduced stream flows, and increased storm floods. Furthermore, groundwater storage has declined in the 21st century due to intensified agricultural groundwater-fed irrigation, with projections indicating continued depletion due to increased evapotranspiration caused by increasing global temperatures (IPCC, 2022).

2.3.2 Management of non-renewable groundwater

Achieving groundwater sustainability is a formidable challenge given the global depletion of groundwater resources, especially in arid and semi-arid regions, which has resulted in serious pollution and water supply problems due to inadequate management (Mays, 2013). In this context, the concept of non-renewable groundwater highlights the inherent unsustainability of utilising aquifers with low rates of average annual renewal and large storage capacity (Maliva & Missimer, 2012). Margat and Van der Gun (2013) define non-renewable groundwater as a resource available for extraction over a finite period, characterised by minimal current renewal rates. Strict biophysical definitions deem the use of non-renewable groundwater as unsustainable, although socio-economic sustainability, including the adaptive capacity to water scarcity and societal needs and goals related to exploiting non-renewable resources, is vital when it comes to assessing sustainability in fossil groundwater extraction (Abderrahman, 2002; UNESCO, 2006), including considerations of existing trade-offs between exploiting water resources and achieving improvements in areas such as jobs, education, food security, and hunger reduction, as the choice of crops and water use efficiency directly impact yield and sales, influencing value creation (Ahmed, 2020).

Therefore, sustainable groundwater extraction necessitates a comprehensive approach that considers the local context, technological advancements, and the inclusion of social, economic, and environmental factors. Balancing socio-economic development, efficient water use, and the preservation of groundwater resources is crucial. While carefully planned intensive use of non-renewable groundwater resources can support short-term socio-economic development, it is imperative to recognize the limitations and potential risks associated with such practices. Achieving sustainable groundwater management requires a holistic strategy that integrates these considerations to ensure its long-term viability (Ahmed, 2020; Maliva & Missimer, 2012; Mays, 2013; UNESCO, 2006).

2.4 Agricultural water utilisation

The agricultural sector is the largest consumer of water globally, and as a result, makes it particularly sensitive to the effects of climate change, highly impacting food security (Christoforidou et al., 2023; Liu et al., 2022). Agriculture is increasingly at risk due to water shortages, floods, extreme weather events and declining water quality, impacting production, markets, trade, and food security (OECD, 2017b). Climate-driven water scarcity and rising water demand pose additional challenges to agricultural production, with varying water-related risks specific to each region. Regions most prone to water stress (i.e., North Africa, Central and West Asia) are projected to face limitations in expanding agricultural production due to existing water stress, changes in water availability, and ongoing groundwater depletion from excessive irrigation (IPCC, 2022).

The impacts of climate change on the agricultural sector can be both direct, affecting agricultural potential through changes in precipitation, and indirect, influencing world market prices of agricultural products (Mertz et al., 2009). Therefore, ensuring sustainable water management in agriculture becomes crucial for securing food production, mitigating risks, and promoting resilience in the face of climate change, particularly in countries with limited water resources and heavy reliance on agriculture. With 3.2 billion people living in agricultural areas experiencing water stress or severe water scarcity, the frequency of droughts in rainfed cropland or high water stress in irrigated areas is alarmingly high, with climate change exacerbating the situation (FAO, 2020; Mertz et al., 2009). Furthermore, countries with overall limited water resources tend to allocate larger amounts of their water resources for agricultural production and seem to particularly focus on water-intensive crops such as wheat, rice, cotton or sugarcane due to conducive climatic conditions as well as the high cash value of such crops (Chellaney, 2013, pp.8–9; Mekonnen & Hoekstra, 2020).

2.4.1 Increasing Water Use Efficiency

Water use efficiency, defined as the ratio of the volume of water used productively to the weight of crop water loss to the atmosphere, plays a key role in optimizing water utilisation (Stanhill, 1986). Recognizing the importance of water efficiency, the Sustainable Development Goals (SDGs) emphasise the need to enhance water-use efficiency across all sectors and ensure sustainable withdrawals (FAO, 2020). With declining water availability for agriculture due to increased demand from other sectors, improving water productivity becomes imperative (Patle et al., 2023). Enhancing water productivity, measured as the ratio of crop yield to water consumption, not only reduces the need for additional water resources but also contributes to global water safety and food security, considering the significant water use in agriculture globally (Patle et al., 2023; FAO, 2020). Improving irrigation efficiency through better soil and water management practices and the adoption of efficient irrigation technology is essential to promote sustainable water use (FAO, 2020; OECD, 2017b). These measures can significantly increase productivity, enhance food security, and reduce vulnerability to climate variability.

Sustainable intensification of irrigated food systems offers a viable approach to meet growing demands in an equitable, environmentally sustainable, and economically viable manner (Dlamini, Senzanje & Mabhaudhi, 2023; Kaini et al., 2022). However, climate change presents challenges to food production by negatively affecting irrigation systems and reducing yields in certain regions. Current limitations, such as poor irrigation management, water scarcity, and inadequate infrastructure, contribute to the gap between potential and actual yields (Kaini et al., 2022).

In addition to these challenges, subsidies for energy used in groundwater pumping, as well as subsidies from other sectors, can create incentives for overexploiting groundwater resources, resulting in falling water levels, wetland degradation, and land subsidence. Addressing these issues and promoting sustainable groundwater management practices are essential for ensuring the long-term availability and quality of groundwater resources (Margat & Van der Gun, 2013; OECD, 2017b).

Therefore, achieving sustainable and productive water use in agriculture requires efficient groundwater management, improved irrigation practices, and the enhancement of water use efficiency. By adopting these measures, it is possible to increase productivity, strengthen food security, and mitigate the impacts of climate variability on agricultural systems. Furthermore, addressing subsidies and external costs associated with groundwater pumping can contribute to the sustainable management of water resources and the preservation of ecosystems (OECD, 2017b; Margat & Van der Gun, 2013).

2.4.2 Water-efficient irrigation approaches

To address water stress and scarcity in agriculture, it is crucial to make more productive use of irrigation water by increasing crop yields and reducing evapotranspiration. Water productivity varies significantly across countries, with access to modern agricultural inputs, efficient irrigation systems, and better soil and water management playing vital roles in achieving higher productivity. Despite these improvements, yield gaps still exist with agricultural water management coming under increased scrutiny due to a projected decrease in effectiveness caused by warmer temperatures. Closing these gaps can contribute significantly to improved food security, nutrition, livelihoods, and resilience to climate variability (FAO, 2020; IPCC, 2022).

Irrigation is a common adaptation response to stabilise yields against variations in moisture availability. Projections indicate a substantial increase in agricultural water needs driven by factors like population growth, increased irrigated agriculture, cropland expansion, and the higher demand for bio-energy crops for climate change mitigation. With water resources expected to decrease and climate variability significantly impacting water availability in semi-arid regions, optimising water usage according to crop needs becomes essential for sustainable irrigation. While population growth, land use change, and irrigation expansion contribute to this increase, significant amounts of it can directly be attributed to climate change (Abou Ali et al., 2023; IPCC, 2022).

The implementation of efficient irrigation methods, such as drip irrigation, offers several advantages, including improved fertiliser efficiency, environmental preservation, and higher water use efficiency. However, it is crucial to control water flow to minimise losses through percolation (Abou Ali et al., 2023). Evapotranspiration, the process of water movement from plants and soil to the atmosphere as vapor, is a key factor in determining irrigation requirements and varies depending on factors such as weather, crop type, crop variety, and soil properties (Abou Ali et al., 2023; IPCC, 2022).

In addition, solar-powered irrigation systems have emerged as a viable alternative to diesel-powered systems, especially in less developed countries with a high dependence on irrigated agriculture. These systems offer reliable and affordable energy for irrigation while also reducing greenhouse gas emissions compared to diesel-powered systems. However, it is important to consider potential challenges, as solar-powered systems may lead to unsustainable exploitation of water resources due to the lack of operating costs once installed. Hence, governmental policies and subsidies to promote photovoltaic systems for groundwater exploitation might have unwanted detrimental effects (Hartung & Pluschke, 2018).

Furthermore, improving water use efficiency in agriculture is no trivial task as it involves optimizing multiple steps rather than focusing on a single aspect, as even modest improvements in various stages can lead to significant overall efficiency gains (Hsiao, Steduto & Fereres, 2007).

3 Theoretical Framework

Groundwater resources and aquifers face institutional and sustainable management challenges. Hydrological assessments often lack crucial information, such as water tables and well depths, leading to unintended mismanagement of potentially depleted aquifers. Neglecting hydrogeological conditions and traditional ecosystem knowledge can render ongoing management efforts ineffective (OECD, 2017a). Decentralised extraction of groundwater complicates monitoring making the exclusion of actors difficult. Hence, groundwater resources resemble common pool resource (CPR) characteristics that create competition for water units, depletion of stocks, and socio-physical issues relevant to local water scarcity analyses due to the subtractability of CPRs (OECD, 2017a; Ostrom, Gardner & Walker, 1994, p.5).

This chapter presents a theoretical framework for analysing and discussing the research conducted in this study. The first section explores the CPR problem and the tragedy of the commons, focusing on theoretical approaches to prevent and mitigate it. The second section introduces Elinor Ostrom's (2007, 2009) theory of social-ecological systems (SES), emphasizing the interconnectedness of natural resources and providing insights into the conservation challenges associated with exhaustible groundwater resources.

3.1 The Common-Pool Resource Problem

The theoretical framework of this study centres on a specific type of resource that possesses two crucial characteristics: exclusion and subtractability. Once the resource is naturally provided or offered by others, the act of excluding potential beneficiaries from accessing and benefiting from it becomes prohibitively costly. The aspect of physical exclusion also entails legal and economic considerations, as well as basic constitutional rights when it comes to limiting potential beneficiaries from utilising the resource. Additionally, the yield of the resource is subtractable, meaning that when one actor extracts a certain quantity, it becomes unavailable to others (Ostrom, 2015; Ostrom, Gardner & Walker, 1994, p.6).

These two distinct characteristics of exclusion and subtractability enable the differentiation of four broad types of goods: private goods, public goods, toll goods, and common pool resources (CPR), as illustrated in Table 1. Although the variations and characteristics within each type may differ extensively, these broad types fundamentally differ from each other. Public goods involve high costs for excluding actors and do not allow for subtractability (e.g., weather forecast), whereas private goods possess opposite characteristics to public goods as outlined in Table 1. Toll goods share the relative ease of exclusion found in private goods but lack subtractability (e.g., online streaming service). CPRs are characterized by costly exclusion and high subtractability (e.g., ocean fish populations or underground water resources) (Ostrom, Gardner & Walker, 1994, pp.6–7).

		Subtractability	
		Low	High
Exclusion	Difficult	Public Goods	Common Pool Resources (CPR)
	Easy	Toll Goods	Private Goods

Table 1: Classification of different types of goods
Source: Illustration based on Ostrom, Gardner and Walker (1994: p.7)

Considering that this study focuses on groundwater aquifers, the theory primarily centres on CPRs due to the complexities associated with managing these resources. The combination of limited exclusion possibilities to avoid overexploitation and simultaneously the high subtractability makes CPR management intricate and highly susceptible to overuse and exploitation (Ostrom, 2015). When such overexploitation occurs, either due to the absence of regulatory frameworks and institutions for fair and sustainable resource management or because resource actors are unaware of the depletion rate due to unavailable data, it results in the tragedy of the commons (Ostrom, Gardner & Walker, 1994, p.5), as originally coined by Garrett Hardin (1968). Resource actors tend to deplete a natural resource assuming the absence of institutional norms and regulations against overexploitation since they focus on their personal benefit while disregarding costs inflicted on others (Hardin, 1968; Ostrom, Gardner & Walker, 1994, p.5). Hardin (1968) argued that individuals would always deplete CPRs until degradation led to the tragedy of the commons, as long as governing authorities fail to assume management responsibilities. While Ostrom, Gardner and Walker (1994: p.5) agree with Hardin (1968) on the tragedy of the commons, they have discovered numerous instances that contrast Hardin's findings, showing that the tragedy of the commons is not an inevitable outcome. In many cases, individuals who jointly utilize CPRs have successfully averted resource depletion by engaging in communication, reaching agreements on rules and regulations, and enhancing mutual benefits. There are instances where government regulations incentivise the overexploitation of CPRs rather than preventing depletion, despite local efforts to manage resources sustainably (Basurto & Ostrom, 2019; Ostrom, 2009).

CPRs are generally categorized into resource systems and resource units. Resource systems establish the conditions necessary for the existence of a stock of resource units, while resource units represent the available flow of the CPR that can be withdrawn and subtracted over time. For instance, extracted cubic meters of water from a groundwater aquifer, as well as harvested fish from fish stock, serve as examples of a CPR system and its resource unit. While appropriating resource units from resource systems can be undertaken by multiple appropriators simultaneously or sequentially, the resource units themselves, such as fish or water, are not subject to joint appropriation, meaning that once appropriated by one individual or entity, they are no longer available for others to use, demonstrating that the resource system is subject to joint use, but the resource units are not. The distinction between stock and flow becomes significant for renewable resources where a regeneration rate can be determined. As long as the appropriation of resource units from a CPR does not exceed the regeneration rate, the resource stock will not be depleted. However, if a resource lacks natural regeneration, any utilisation will ultimately lead to exhaustion (Ostrom, 2015; Ostrom, Gardner & Walker, 1994, p.8; Schlager, Blomquist & Tang, 1994).

While the challenges associated with exploiting different CPRs vary depending on the specific resource being utilised, the differentiation between appropriation and provision problems generally applies to all CPR situations. Appropriation problems concern finding the efficient level of resource appropriation, which involves balancing the marginal costs of appropriation with the marginal returns. Appropriation problems pertain to the flow aspect of CPRs. When actors extract resource units from a CPR, they create appropriation externalities because increased appropriation by one actor reduces the average return received by others from their investments in appropriating CPRs. Resolving appropriation problems can be achieved through agreements on the level and method of appropriation and the allocation of outputs (Ostrom, 2015; Ostrom, Gardner & Walker, 1994, pp.9–12).

On the other hand, provision problems concentrate on the resource stock or resource facility and can be further divided into demand-side provision problems and supply-side provision problems. Demand-side provision problems address the impacts of appropriation on the productive capacity of the resource stock, while supply-side provision problems focus on individual incentives to free-ride on the provision activities of other actors. For example, when groundwater is overexploited from an aquifer near the ocean, saline water intrusion may occur, potentially compromising the capacity of the resource facility to hold extractable water resources, creating a demand-side externality. Investing in maintenance to prevent such a situation could result in individuals free riding because it is challenging to identify the beneficiaries of such investments, leading to supply-side externality (Ostrom, 2015; Ostrom et al., 1999; Ostrom, Gardner & Walker, 1994, pp.12–14).

In practice, actors encounter a complex interplay of appropriation and provision problems. To prevent the depletion or destruction of CPRs due to overuse, it is necessary to address both aspects effectively. The provision problem involves ensuring that the CPR is adequately provided or that investments are made on the demand side to make appropriation feasible and economically viable. The resolution of the provision problem directly impacts the appropriation problem, which relates to the efficient allocation and use of the resource. The success of solving the provision problem significantly influences how well the appropriation problem can be managed (Ostrom, Gardner & Walker, 1994, p.15).

Furthermore, organizing collective action among actors in CPR situations is typically a complex and uncertain task. A significant factor contributing to this uncertainty is the lack of knowledge regarding the precise structure of the resource system, including its boundaries and internal characteristics, which must be determined. However, uncertainties resulting from this lack of knowledge can be gradually reduced over time through the integration of scientific knowledge and local contextual knowledge. It is important to note that reducing uncertainty is a costly endeavour and rarely achieved completely. Furthermore, even with considerable knowledge about the resource system, uncertainties persist due to strategic behaviour exhibited by appropriators. Within any group, there will always be individuals who disregard established norms and act opportunistically when presented with an opportunity. Additionally, certain situations may offer such high potential benefits that even committed individuals may be tempted to violate norms. Consequently, dealing with opportunistic behaviour is a crucial consideration for all appropriators seeking to address CPR challenges (Ostrom, 2015).

Having examined the fundamental characteristics and classification of types of goods in relation to exclusion and subtractability, we now turn our attention to the specific framework utilised in this study: social-ecological systems (SESs) centred around groundwater aquifers. Groundwater aquifers fall within the category of common pool resources (CPRs), characterised by the challenges of limited exclusion possibilities and high subtractability (OECD, 2017a). The management of CPRs presents intricate complexities, as overuse and exploitation can lead to the tragedy of the commons. However, contrary to the notion of inevitability put forth by Garrett Hardin (1968), empirical evidence showcases instances where individuals have successfully averted resource depletion through effective communication, rule-making, and cooperation. Balancing appropriation and provision problems is crucial in sustaining CPRs since resulting externalities might affect the efficient allocation and use of resources. By addressing both aspects, we can work towards the preservation and responsible management of social-ecological systems (Basurto & Ostrom, 2019; Ostrom et al., 1999). In the upcoming chapter, we will delve further into the dynamics of SESs, exploring the theoretical solutions for sustainably managing groundwater aquifers within the framework of CPRs.

3.2 The Social-Ecological Systems Framework

Complex social-ecological systems (SESs) comprise a wide array of resources utilised by humans and are composed of various subsystems and internal variables functioning at different levels. Until recently, the prevailing belief was that actors would not proactively engage in preserving their resources but instead depend on solutions imposed by the government. However, interdisciplinary research has challenged this notion, uncovering instances where government policies contribute to resource destruction while actors actively invest in achieving sustainability (Ostrom, 2009). Although predictions of resource collapse hold in large, valuable, open-access systems where communication among diverse harvesters is lacking and management rules are absent, cases exist where self-organisation and effective resource management defy these dire forecasts. Experimental studies, including those with open discussion options, have also refuted these predictions (Berkes, 2000; Ostrom, Gardner & Walker, 1994, p.5).

The core subsystems of an SES are as follows: resource systems such as groundwater aquifers; resource units illustrated by available units of water in the groundwater aquifer; actors such as farmers that utilise the water for agriculture; and governance systems that include the government and other institutions responsible for managing the groundwater resource, along with the specific rules governing its use and how these rules are formulated. Each core subsystem comprises multiple second-level variables, such as the size of the resource system, mobility of resource units, level of governance, and actors' knowledge of the resource system. To comprehend complex systems, it is crucial to analyse the specific variables and their interrelationships, rather than simplifying the complexity (Ostrom, 2007, 2009, 2015). Figure 1 provides an overview of the framework, illustrating the relationships among the core subsystems of an SES. These subsystems mutually influence each other and are interconnected with social, economic, and political contexts, as well as related ecosystems (Ostrom, 2007, 2009).

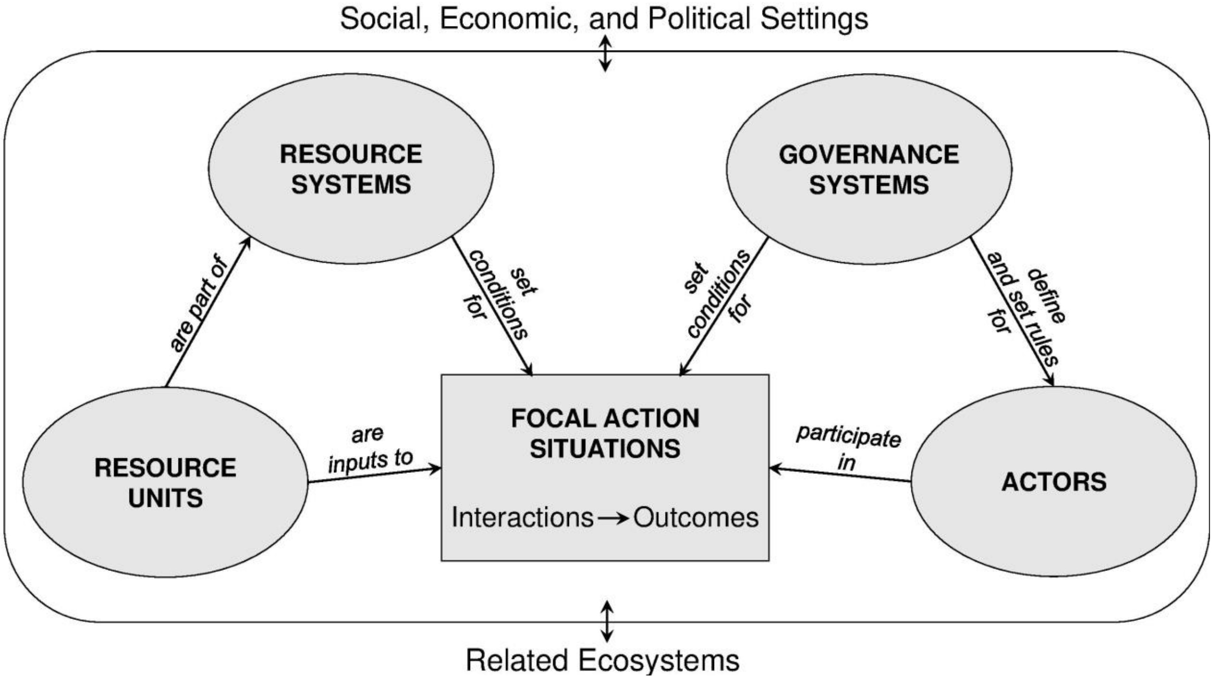

Figure 1: Core subsystems in a social-ecological framework (SES)
Source: own illustration adapted from McGinnis and Ostrom (2014) and Ostrom (2009).

Interactions and resulting outcomes, being part of action situations, jointly affect and are indirectly affected by the attributes of CPRs. While interactions can be described as activities that are initiated by actors involved and dependent on a CPR (e.g., harvesting, information sharing, conflicts or deliberation processes), outcomes are defined as resulting situations based on the particular set of interactions as well as the attributes of a particular CPR (i.e., efficiency, social and ecological sustainability, overexploitation or externalities to other CPRs). This framework also bears the opportunity to understand how CPRs may affect and be affected by the larger socioeconomic, political, and ecological settings in which they are embedded, as well as other related ecosystems (Ostrom, 2007).

Understanding the factors that influence the effectiveness of policy outcomes promoting sustainability is crucial, particularly when considering different types and sizes of resource systems. While some resource actors have made substantial investments in developing governance systems to ensure long-term sustainability, this is not universally applicable to all resources. Actors' decision to self-organise and implement effective rules and norms depends on weighing the expected benefits of resource management against the perceived costs of investing in such systems. However, the process of self-organising to sustain a resource can be time-consuming and may result in short-term economic losses. These costs, coupled with concerns about rule violations and overharvesting, can discourage actors from initiating costly changes and maintaining unsustainable practices (Ostrom, 2009, 2015).

Ostrom (2009) has identified certain variables that significantly influence the likelihood of actors engaging in collective action and self-organisation. Among these variables, the **size of the resource system** plays a key role, as large territories incur high costs in terms of defining boundaries, monitoring use patterns, and gaining ecological knowledge, making self-organisation unlikely. On the other hand, small territories do not yield substantial valuable outputs, making moderate territorial size the most conducive to self-organisation (Chhatre & Agrawal, 2008). For example, fishers who consistently harvest from moderately sized coastal zones, lakes, or rivers are more inclined to organise compared to those navigating the vast ocean in search of valuable fish (Berkes et al., 2006).

Furthermore, the **productivity of the resource system** also influences self-organisation since actors may not perceive the need for future management if a water source or fishery appears either depleted or highly abundant. Actors require a certain degree of scarcity to motivate their investment in self-organisation. The **predictability of system** dynamics represents another critical variable. Actors need a level of predictability in system dynamics to estimate the potential outcomes of implementing specific harvesting rules or establishing no-entry territories (Ostrom, 2007, 2009).

Resource unit mobility is a contributing factor as well. Self-organisation is less likely in systems with mobile resource units, such as ocean fish, due to the associated costs of observation and management. In contrast, systems with stationary units, like forests, are more conducive to self-organisation (Ostrom, 2009; Schlager, Blomquist & Tang, 1994). The **number of actors** also plays a role, with larger groups incurring higher transaction costs in terms of organising and reaching agreements on changes (Baland & Platteau, 2000). However, if managing a resource involves costly tasks like monitoring extensive forests, larger groups have an advantage in mobilising labour and resources. Therefore, the impact of group size on self-organisation depends on other SES variables and the nature of the management tasks (Ostrom, 2009). **Leadership** as well as **norms and social capital** exert significant influence as well. Self-organisation becomes more likely when actors possess entrepreneurial skills and are respected as local leaders. Actors who share moral and ethical standards, norms of reciprocity, and trust in one another to uphold agreements experience lower transaction costs in reaching agreements and monitoring (Baland & Platteau, 2000; Ostrom, 2009). **Knowledge** of the SES is crucial, with actors possessing common knowledge of relevant SES attributes, understanding how their actions impact each other, and being familiar with rules used in other SESs, perceiving lower costs of organising (Berkes, 2000). The **importance of the resource** to actors is a determining factor, with successful cases of self-organisation often arising when actors heavily rely on the resource system for their livelihoods or highly value its sustainability. Otherwise, the costs of organising and maintaining a self-governing system may not outweigh the benefits (Berkes, 2000; Chhatre & Agrawal, 2008). **Collective-choice rules** contribute to self-organisation, as actors having full autonomy in crafting and enforcing their own rules at the collective-choice level encounter lower transaction costs (Berkes et al., 2006)

Obtaining measures for these aspects represents the initial step in analysing whether actors in an SES would self-organise. However, analysing the relationships between these variables is challenging, as the impact of one variable depends on the values of other SES variables (Ostrom, 2009). Furthermore, while the initial establishment of rules by actors or the government is crucial for the long-term sustainability of SESs, these rules alone may not suffice (Berkes, 2000; Dietz, Ostrom & Stern, 2003). If the initial set of rules is incongruent with local conditions, long-term sustainability may not be achieved. Matching the attributes of the resource system, resource units, and actors is essential for rules to foster long-term sustainability (Dietz, Ostrom & Stern, 2003). Moreover, the long-term sustainability of rules devised at the SES level depends on effective monitoring and enforcement, and the absence of overruling by larger government policies (Ostrom, 2009).

In conclusion, SESs encompass a diverse range of resources and subsystems, each with its variables and interrelationships. While the prevailing belief was that actors would rely on government-imposed solutions for resource preservation, interdisciplinary research has challenged this notion. Instances have been found where government policies contribute to resource destruction while actors actively invest in sustainability. Understanding the interplay between the variables of CPRs is complex but essential for analysing whether actors in an SES would self-organize. Additionally, the initial establishment of rules and their congruence with local conditions, effective monitoring and enforcement, and the absence of overruling by larger government policies are crucial for long-term sustainability. Overall, achieving sustainability in SESs requires a nuanced understanding of the relationships between variables and the effective implementation of appropriate rules and governance mechanisms.

4 Methodology

This chapter provides an overview of the research methods utilized in the present study, with a focus on promoting transparency in the approach and establishing a coherent link between the research findings, discussion, and conclusions. Firstly, the study site is described, incorporating information from internal reports and on-site field observations, which together offer a comprehensive understanding of the local context. Secondly, the qualitative and abductive research approach is introduced, and an explanation of the research design, including data collection and analysis, is provided. Lastly, the chapter concludes by acknowledging its limitations.

4.1 Study site and project description

The analysis in this study is based on a project by the development initiative Sekem and is situated in Wahat El Bahareya, in the Western Desert in Egypt. Sekem is a development initiative focusing on holistic sustainable development and social innovation initiatives in Egypt. It encompasses various organisations within its institutional system and undertakes diverse projects related to agriculture, textiles, education, and the environment (Sekem, 2023).

According to internal reports, the night irrigation project aims to enhance water use efficiency in irrigation by transitioning the irrigation schedule to night-time irrigation to minimise water losses through evaporation during peak sunlight hours. This involves constructing a levelled reservoir that would be charged with groundwater by the use of a 125 kW photovoltaic-powered pump system and a pumping capacity of 125 cubic metres per hour. Groundwater extraction will occur from a 78-meter-deep well. During the evening, night, and morning hours with lower solar radiation, the down-flow from the levelled reservoir will generate sufficient pressure to operate the centre pivot irrigation system. Additionally, the water's downward flow will power a turbine, producing the necessary electricity to operate the wheels of the centre-pivot irrigation system (see Appendix A for a detailed report of the on-site field visit).

As internal reports explain, this outcome is facilitated by lower ambient temperatures, which increase the water absorption capacity of the irrigated water. Evaporation is influenced by factors such as water droplet size from the sprinkler nozzles and plant canopy size (square meters of leaf surface per hectare of crops). Additionally, evaporation levels depend on temperature, humidity, and the water absorption rate of the specific soil type. The majority of evaporation occurs during hours with the highest temperatures and solar radiation, estimated to be approximately six hours per day at the farm in Wahat El Bahareya. Thus, night irrigation is anticipated to reduce both canopy and soil surface evaporation, enabling more effective water infiltration into the soil. Consequently, even with lower water volumes applied during night irrigation compared to daylight irrigation, a higher volume of water infiltration into the soil is expected. The estimation of a minimum 20 percent improvement in water use efficiency resulting from the switch to night irrigation is based on the substantial temperature difference between day and night at the farm in Wahat El Bahareya.

The Bahareya Oasis, situated in the Western Desert in Egypt (see Figure 2), experiences hyper-arid conditions with extremely low levels of annual rainfall, averaging 3-6 mm, and high evaporation rates (Masoud & El Osta, 2016; Sharaky et al., 2021; Shokr et al., 2022). Groundwater resources sustaining the El Bahareya Oasis originate from the Nubian Sandstone Aquifer System (NSAS). In Wahat El Bahareya, the sole water source is fossil groundwater from the NSAS, which comprises several interconnected aquifers separated by impermeable shale beds (El Hossary, 2013). Covering approximately 2.2 million square kilometres, the NSAS is the world's largest fossil water aquifer system, shared by Egypt, Libya, Chad, and Sudan. It is regarded as one of the most significant groundwater basins globally (Sharaky et al., 2021; UNESCO, 2006).

Within Wahat El Bahareya, the NSAS can be categorised into two major aquifer systems. The oldest and most extensive reservoir is known as the Nubian Aquifer System, which underlies the second Post-Nubian Aquifer System in the northern regions of the Western Desert of Egypt and north-eastern Libya. The two reservoir systems are separated by low permeability layers (Frappart, 2020; Sharaky et al., 2021; UNESCO, 2006). Comprehensive information regarding the NSAS, including the total water volume stored, groundwater flow rate, and annual extraction, remains uncertain. The water salinity gradually increases from freshwater in the southern part of the system to highly saline water, with a salinity level of 13.5 percent in the northern part. Accurate estimates of the groundwater volume vary significantly, and economically feasible extraction from depths of up to 4000 meters is not technologically possible at present. Moreover, the viability of groundwater extraction should be evaluated on a case-by-case basis (Sharaky et al., 2021).

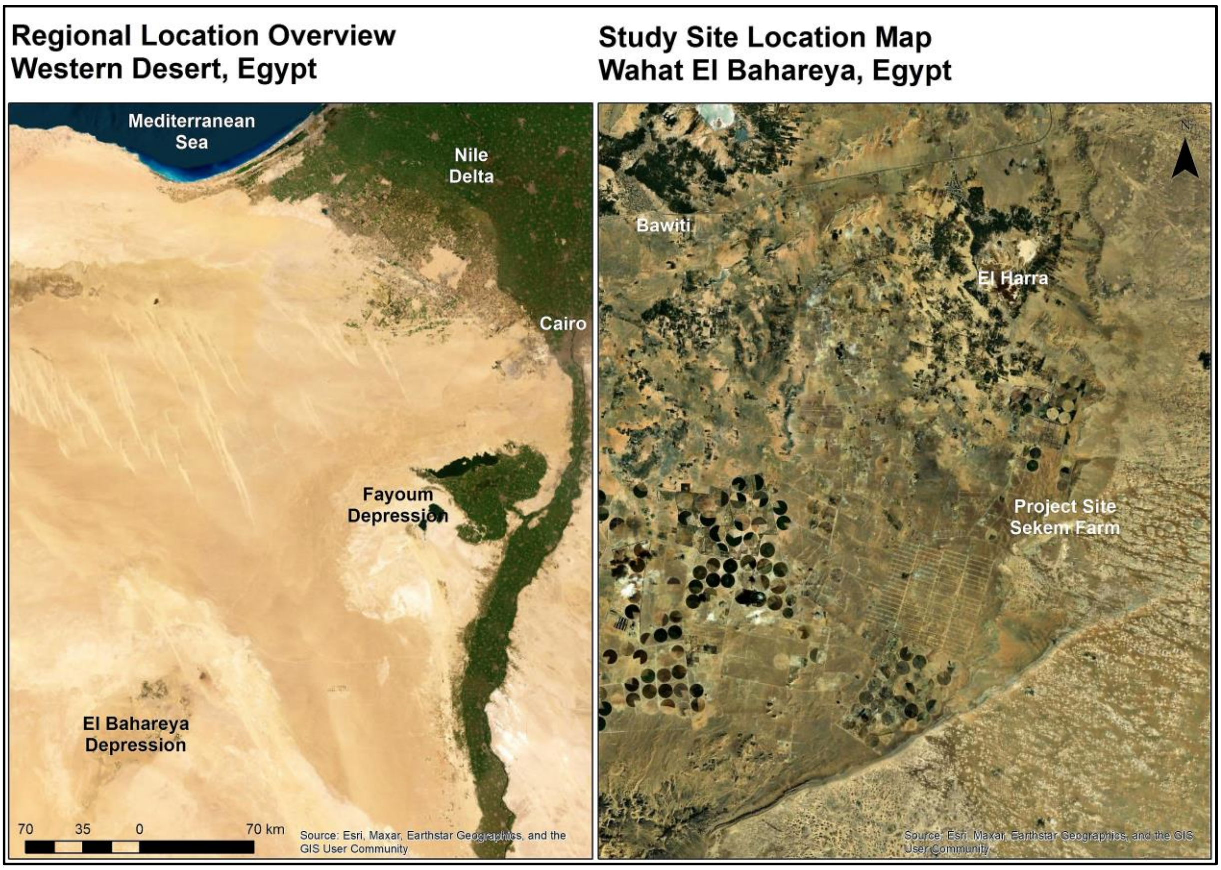

Figure 2: Regional location maps of the study site
Source: Map layout by Johannes David Huber

4.2 Research approach and design

The objective of this study is to investigate adaptation measures for addressing water scarcity in desert farming in Egypt, considering the specific circumstances of increasing surface water constraints. The study is based on a pilot irrigation project located at Wahat El Bahareya in Egypt's Western Desert, aiming to identify sustainable solutions for the extraction of fossil groundwater.

To ensure a comprehensive understanding of the subject matter, relevant literature was consulted providing a theoretical foundation. This literature review informed the development of a semi-structured interview guideline. However, the study does not aim to identify gaps in the existing literature or test specific hypotheses derived from theory in a deductive manner. It rather seeks to contribute to theoretical and conceptual development by adopting a conceptual approach reflecting on theoretical assumptions in light of the collected data (Alvehus, 2020; Bell, Bryman & Harley, 2019). The study design employs an abductive approach as it incorporates deductive and inductive reasoning. Abduction, in this context, goes beyond a mere combination of deduction and induction, as it entails a mutual refinement and development of theory and data in relation to each other (Alvesson & Sköldberg, 2017). This necessitates the researcher to remain open to emergent topics and perspectives that arise from the subjective and individual realities of the interviewees.

To strike a balance between theoretical understanding and openness to new insights during the interviews, the researcher ensured to possess some prior theoretical knowledge and a well-grounded research direction. However, he aimed to avoid being excessively constrained by theory during the interview process (Swedberg, 2012). While complete detachment from pre-existing knowledge and theories is not feasible, the researcher acknowledges that pre-understanding of theory can serve as valuable inspiration for uncovering new patterns (Alvesson & Sköldberg, 2017).

Given the inherent limitations of the interpretation process, the role of the researcher in knowledge creation is ambiguous. Nonetheless, the researcher emphasizes the critical role of creativity and systematic theorization of qualitative material to make sense of the interviewee’s interpretations (Prasad, 2017; Rennstam & Wästerfors, 2018).

4.3 Methods of data collection and analysis

In order to examine the research questions, a qualitative study was conducted in Egypt, which involved expert interviews. The interviews were conducted with experts directly involved in the pilot irrigation project, as well as water resource and water management experts from governmental and international organisations, and academia. The findings of this study are presented through a thematic analysis of the expert interviews, aimed at extracting insights that can be applied to water-stressed countries in arid regions that heavily rely on desert farming.

Research conducted within the interpretive tradition emphasises the importance of careful interpretation and a reflexive approach when dealing with qualitative empirical material to generate knowledge (Alvesson & Sköldberg, 2017). Further, it is important to recognise that qualitative material derived from interview statements may not be objective but is rather influenced by the individual's interpretation of a particular phenomenon.

4.3.1 Conceptualising and facilitating expert interviews

The expert interviews were conducted based on an interview guide consisting of a range of topics that were intended to be explored during the interviews, rather than using specific predetermined questions. In total, six interviews were conducted with experts from various levels during the field research in Egypt. To facilitate a comprehensive exploration of the topic and promote dialogue between the interviewer and interviewee, open-ended semi-structured interviews were considered appropriate (Silverman, 2021). This interview format encourages elaboration and clarification through follow-up questions, enabling a deeper understanding of the experiences related to adaptation under conditions of water scarcity (May, 2011). The inclusion of primarily open-ended questions in the interview guide aimed to provide the interviewees with the freedom to express themselves, thereby facilitating the collection of richer data (Silverman, 2021). The interview guide can be found in Appendix B.

During the interviews, the interview guide helped to maintain focus on the research questions and topic, while also allowing flexibility to follow the natural flow of the conversation. This flexibility included adjusting the order of open-ended questions to suit the context of the interview and placing more emphasis on areas of particular interest to each interviewee. This approach aimed to establish trust, create a comfortable environment, and promote a more spontaneous discussion (Leech, 2002; May, 2011).

In order to study the adaptive capacity and related challenges in desert farming in Egypt, a purposive sampling technique was employed to identify interview partners that were able to specifically examine and assess the topic of this study comprehensively and critically (Silverman, 2021). The inclusion of different perspectives from the interviewees was considered valuable and constructive, although it was not the primary focus but rather the motivation behind employing purposive sampling.

The interviews were conducted during the field research in Egypt in March and April 2023, with each interview lasting between 45 and 60 minutes. The confidentiality of their personal information was emphasized, and pseudonyms were used throughout the analysis to anonymise and protect participants' identities (Silverman, 2021).

To ensure comprehensive access to the data during the analysis process, all interviews were recorded and transcribed (Silverman, 2021), using Descript software, and manually verified for accuracy. An overview of the interviewed experts, along with the pseudonyms used in the analysis, can be found in Table 2.

Pseudonym	**Profession**	**Expertise**
Dr Tamer	Engineering academic	Solar-powered irrigation systems and photovoltaic
Victor	Project manager at an international organisation	Water resource management
Dr Abdullah	Research associate at an international research institute	Irrigation and hydrology
Rama	Project manager at an international organisation	Agricultural innovation
Dr Mohammed	Economist and senior advisor	Environmental economics and water resource management
Dr Hassan	Water engineering academic	Water resource management and hydrology

Table 2: Overview of interview partners.
Source: own illustration

4.3.2 Analysing the data

The semi-structured qualitative expert interviews are analysed using a thematic analysis approach. This analysis is grounded in a theoretical framework that guides the exploration of the research questions and the data, aiming to address the research questions within the context of the theoretical framework.

Qualitative data analysis is viewed as a non-linear process that involves continuous reflection on the data and topic. As part of the transcription process, which included listening, reading, and verification, substantial time was dedicated to engaging with the material and preparing it for analysis. During the initial coding phase, the data was thoroughly read to ensure that all valuable information was accounted for before proceeding to focused and selective coding (Rennstam & Wästerfors, 2018). Drawing on concepts from the theoretical framework, codes were identified, with particular attention given to those that appeared frequently in the data. The derived themes are *'sustainability of groundwater extraction'*, *'economic-technological water use efficiency'*, and *'socio-behavioural aspects of adaptation'*.

It is important to note that the selection of themes is not solely based on their frequency in the material. Rather, the focus is on the themes that are most interesting and relevant for creating a coherent narrative in line with the research objectives (Rennstam & Wästerfors, 2018). The final dimensions of the analysis were derived based on three overall guidelines: relevance to the research objective, expansion of the focus by providing a new perspective, and contradiction, challenge, or nuance to existing theory. Themes that fell beyond the scope of the research or were not directly linked to the research objectives were excluded from the analysis.

4.3.3 Validity and Limitations

Qualitative research is often criticized for its non-representative sampling and limited generalisability. However, it is important to note that the goal of this study is not to make universal claims but rather to identify and understand complex and context-specific processes (Jack & Kholeif, 2007; Silverman, 2021).

Cobern and Adams (2020) similarly argue that the focus in qualitative research should not be on generalisability, but rather on viewing the results as indicative or transferable. In line with this perspective, this study focuses on a case in desert farming in Egypt, which prevents the global generalisability of the findings. However, they may be transferable to similar contexts in arid countries struggling with water scarcity. Transferability requires a focus on validity by providing sufficient information about the research context (Cobern & Adams, 2020). Hence, this study has prioritised transparency and provided detailed information about the data collection process, methodological choices, and research context to enhance transferability. Generalisations and transferability should remain specific and context-bound (Halkier, 2011).

5 Understanding the challenges of Nubian groundwater extraction in Egypt: An analysis

In this chapter, the interview data of this study will be presented and analysed applying the theoretical framework of social-ecological systems (SES) and put into context by using previous literature presented in the second chapter. The chapter is outlined according to the identified core themes and starts the analysis by initially focusing on the sustainability of groundwater extraction exploring solutions. Subsequently, improving water use efficiency from the economic-technological and socio-behavioural perspective is analysed.

5.1 Sustainable groundwater utilisation in Egypt

5.1.1 Egypt’s unique water scarcity challenge

Egypt faces a challenging situation regarding its water resources, given its heavy reliance on the Nile as the primary source of surface water. However, the decreasing reliability of the Nile's water flow has led to an increasing recognition of the significance of groundwater resources for ensuring water security and supporting agricultural irrigation (FAO, 2020, 2023). In addition, at least 85 percent of Egypt’s groundwater resources are considered non-renewable (Gohar & Ward, 2011). Egypt’s imminent water scarcity and resulting challenges were addressed and reflected multiple times by the experts, describing Egypt’s situation as unique in the regional context due to the virtual absence of precipitation. Dr Abdullah’s quote illustrates this further:

> Irrigation in Egypt, by the way, is a very unique system compared to all other countries in the region. Because Egypt is irrigated agriculture. So, many areas in many countries in the area are rain-fed agriculture like Morocco, for example, like Jordan, Syria … Egypt is mainly dependent on irrigated agriculture. – Dr Abdullah

The situation described by Dr Abdullah resembles the picture that other experts have similarly painted, referring to Egypt’s dependence on irrigated agriculture fed by the Nile River. Dr Mohammed analyses that Egypt’s sole reliance on the increasingly volatile waters from the Nile

River increases the pressure on water security in the country immensely. According to Christoforidou et al. (2023) and FAO (2020), such water-related constraints may be particularly detrimental to agricultural production and food security in Egypt as this sector is the country's biggest water consumer. Dr Hassan addresses the dependence on the agricultural sector as he points to the transboundary nature of Egypt's water surface and underground resources, which "adds another dimension … that must be considered" (Dr Hassan). Dr Mohammed assesses Egypt's shared water resources as well:

> I want to say that there is a deadlock, but there is sort of still no clear understanding … because it's mainly Egypt and to some extent Sudan that are affected. Because Egypt relies on the water coming from the Nile. – Dr Mohammed

This shows how Egypt's possibilities are particularly limited in responding to its increasing water scarcity. The interests of upstream riparian countries constrain Egypt's water security efforts further. Dr Hassan also identifies Egypt's immense population growth, its aspirations to develop economically as well as the impacts of climate change as main drivers of water scarcity, which is in line with the findings in previous research on the causes and impacts of global water scarcity (Christoforidou et al., 2023; Dlamini, Senzanje & Mabhaudhi, 2023; FAO, 2020; World Bank, 2016).

5.1.2 Assessing opportunities for sustainable groundwater use in Egypt

The factors driving Egypt's water scarcity shift the focus towards increasing the agricultural water use efficiency, particularly in areas that rely on non-renewable groundwater for irrigation. In this context, the lens of the theoretical framework applied in this study provides support in assessing the groundwater resources below the study site in Wahat El Bahareya that are part of the larger Nubian Sandstone Aquifer System (NSAS) (El Hossary, 2013; Sharaky et al., 2021). Embedded in a social-ecological system, the NSAS can be classified as a resource system, while the units of water stored in the NSAS are the corresponding resource units. Hence, the aquifer can be considered a common pool resource due to costly exclusion and high subtractability (Ostrom, 2007, 2009).

The groundwater resources that feed the oasis in Wahat El Bahareya are considered to come from the NSAS (see chapter 4.1). This aquifer system is "huge and very deep" (Dr Tamer) and its "groundwater is of very good quality" (Dr Abdullah), which makes the interest in utilising the water resources in the NSAS comprehensible. Dr Hassan’s remark explains the complexity of the NSAS further:

> The Nubian aquifer contains a huge amount of water, but it's not easily reachable because it goes down and down and down. And even now in Wahat [El Bahareya] … there are two kinds of aquifer, one is shallow, and one is deep. And you are still in the shallow one. To go to the deeper one, you have to invest a lot of money and dig hundreds of meters down. – Dr Hassan

While in his quote he refers to the sizeable NSAS, he also points towards the efforts required to exploit deeper parts of the aquifer that are technologically difficult to access since expensive drilling infrastructure would need to be employed – a challenge that Sharaky et al. (2021) also present in their findings. In the context of the SES framework, the above quotes by Dr Tamer and Dr Hassan imply that this resource system is large in size and its resource units could be highly mobile, constraining management and monitoring of the resource system (Ostrom, 2009).

As with most of Egypt’s groundwater resources, the NSAS is considered non-renewable as well (El Hossary, 2013; Sharaky et al., 2021; UNESCO, 2006). However, the experts have identified a clear lack of data on the available water stock, flow, water quality and renewability of the NSAS. Dr Tamer addresses the uncertainty of the source of the NSAS by pointing towards other possible unexplored sources:

> The source of [the] Nubian aquifer might also be leakage from the Nile. So, it might be renewable from the Nile, from rains or other sources as well. It has not yet been clearly defined where the water comes from and what the main source of the Nubian aquifer is. – Dr Tamer

The limited understanding of the sources and possible recharge processes of the NSAS is confirmed by Dr Abdullah, who explains that even though the NSAS is not renewable, “from time to time there is some precipitation which recharges just a little bit” (Dr Abdullah), Furthermore, Victor is equally uncertain, “whether there’s any recharge”. Dr Mohammed gets to the point of the problem:

> … the figures vary. And they're not definitive. And it's a shared aquifer anyway. That's one thing. The other is that with the growing population … [a]nd with the increased demand for water, for human consumption and economic activities, I think it's not wise to rely on [the NSAS] as a source. – Dr Mohammed

Dr Mohammed addresses in a more direct way what becomes apparent from the other experts. There seems to be a large data and research gap when it comes to the available water quantity as well as the renewability and hydrogeological conditions of the NSAS. The data gap is also acknowledged by previous literature, pointing towards the constraints that the data limitation constitutes for understanding and assessing sustainable water extraction regimes (IPCC, 2022; MacDonald et al., 2012; OECD, 2017a; Siebert et al., 2010). Addressing this data limitation issue is particularly important to assess the renewability and hence, the sustainability of extracting groundwater from the NSAS to avoid the occurrence of the tragedy of the commons (Ostrom, Gardner & Walker, 1994, p.5). Despite the lack of appropriate and comprehensive data as well as the above-mentioned possibility that there might be other recharge sources, several of the experts seem to be rather certain that the majority of the NSAS can be considered non-renewable and, hence, assess potential recharge to be rather insignificant over time (Dr Mohammed, Dr Tamer).

In this context, the sustainable extraction of a resource per definition is only given, as long as the renewability rate is higher than the depletion or exploitation rate. Hence, the SES framework deems it unsustainable to extract water resources from non-renewable resource systems due to certain eventual depletion (Ostrom, 2009, 2015; Ostrom, Gardner & Walker, 1994, p.8). However, the experts suggest a more nuanced approach considering Egypt’s unique situation. After all, the option of not utilising the groundwater would make survival ultimately impossible as Dr Hassan vividly assesses in the following quote:

> The zero option is almost a valid option. But in our case, I don't see that it's something that we can think of. Sometimes, in terms of a developmental plan, you can really see that the zero option, the doing nothing option, might be less harm than to do something. But … a lot of things are pushing us forward. We have to do something because of the needs and demands that are really growing every year. – Dr Hassan

What Dr Hassan refers to as the “things pushing us forward” can be interpreted in the context of immense population growth, economic development as well as climate change that are considered to be the central drivers of water scarcity in Egypt and globally (Christoforidou et al., 2023; Dlamini, Senzanje & Mabhaudhi, 2023; FAO, 2020; World Bank, 2016). As these factors are set to exacerbate water scarcity, the water demands of Egypt are projected to grow further, requiring new water resources to ensure water security against decreasing Nile water flows (FAO, 2020).

These findings shed some light on the complex situation in Egypt and the challenges when it comes to ensuring water and food security. While in strict terms, exploiting the water resources from the NSAS would not be considered sustainable due to its fossil nature, the “zero option” as coined by Dr Hassan, would ultimately make the survival of Egyptian agricultural food production impossible. However, there seem to be limits to further sustainability analysis due to the data limitation identified in this chapter.

5.2 Achieving water use efficiency in desert farming

The analysis from the previous chapter points to the requirement of finding local solutions for extracting non-renewable water resources from the NSAS. Dr Abdullah elaborates on the sustainability of groundwater extraction by suggesting water-efficient irrigation and crops:

> Such water resources, I'm talking about these aquifers, are not sustainable. And they would only be sustainable if they were managed very well. For example, if you have cropping patterns that do not consume a lot of water and you manage the irrigation well … this way you could have some kind of sustainability. The water at the end is being infiltrated to groundwater, charging the aquifer but the more water you consume the more evaporation losses you have. – Dr Abdullah

Dr Abdullah refers to the need to increase water efficiency in agricultural irrigation in order to achieve a certain level of sustainability. Dr Hassan similarly discusses the need to find solutions to “enhance the efficiency and minimise the water usage per feddan” as vital to increase the long-term value of the water resources and ensure the preservation of the NSAS. Likewise, previous research implies that enhancing water productivity through better soil and water management practices and adopting water-efficient irrigation systems is essential to enhance food security and reduce climate change vulnerability (FAO, 2020; OECD, 2017b; Patle et al., 2023). However, the current situation in desert farming in Egypt can rather be characterised by overexploitation and water waste:

> And it is interesting and shocking to see that they are planting crops like rice which use a lot of water there. So, the problem in many places is that water is being wasted … This is a general problem because digging wells everywhere can quickly mean that the water level falls as much as 25 metres which is a huge problem if you design your infrastructure and suddenly the water is 25 metres deeper than expected. – Dr Tamer

In his remark, Dr Tamer points towards the challenges resulting from overexploitation and misuse of water resources. Such behaviour can have detrimental effects on the predictability and productivity of the water resources stored in the NSAS, as farmers and irrigators might find it difficult to assess whether their long-term engagement in utilising the NSAS sustainably is jeopardised by others circumventing sustainable water extraction. The deviating behaviour of a few could have detrimental effects as rule-abiding actors might start overexploiting the resource as well (McGinnis & Ostrom, 2014; Ostrom, 2009).

At this point, the described effects by Dr Tamer can be divided into economic-technological aspects, which will be further analysed in the following chapter, and into socio-behavioural aspects of actors involved in extracting and utilising water from the NSAS, which will be the main subject of chapter 5.2.2.

5.2.1 Economic-technological aspects of improving water use efficiency

Improving water use efficiency can be achieved by modernising and adapting irrigation methods and systems (Abou Ali et al., 2023; Satoh & Aboulroos, 2017). Desert farms in Egypt use different irrigation systems depending on the types of soil and crop, namely centre pivots, drip and sprinkler systems as well as the traditionally used flood irrigation (Gohar & Ward, 2011). According to Dr Hassan and Victor, centre pivot and drip irrigation systems are among the most water-efficient systems and are well suited for the soil and predominantly grown crops in desert farming in Egypt. Dr Tamer analyses further that ”in Wahat [El Bahareya] and desert farming in general, evaporation is a much bigger issue since water is expensive to extract and therefore reducing evaporation losses saves money”. Following his assessment, modernising irrigation systems would reduce evaporation and consequently increase water use efficiency and consequently reduce the ”crop per drop ratio” (Dr Hassan).

One major obstacle to irrigation are the electricity costs for irrigation systems, particularly for water pumps that extract groundwater resources, as they are currently the main expense of operating groundwater-fed irrigation systems and naturally increase with falling well depth as analysed by Dr Mohammed:

> fuel is a problem, and then pumping water using these pumping machines. Which is important and which is getting costly. So, the first step, of course, is to transform those machines into solar-run machines. And at the same time, of course, that will involve costs, but I think the government here can step in and subsidize that. – Dr Mohammed

In his remark, Dr Mohammed identifies the fuel costs as an issue for irrigation since groundwater extraction pumps are primarily operated with diesel. Furthermore, he suggests transforming groundwater-fed irrigation to photovoltaic systems since they come with the advantage of not incurring running costs and are beneficial for reducing CO_2 emissions in the agricultural sector. However, several experts are also worried that solar-powered irrigation systems might lead to further overexploitation due to the elimination of running costs:

> … solar irrigation means that the farmer will withdraw or will pump the water as he wants. Regardless of the water quantity because the water is free. Maybe one of the restrictions to limit the water consumption is the diesel because the diesel is expensive … it'll [take e]ffect especially in areas where deep groundwater becomes more accessible so some farmers start to change to solar irrigation and can then pump deeper groundwater without expensive diesel. – Dr Abdullah

While Rama is similarly concerned that “reducing the cost of irrigation” would “increase water wastage”, Dr Abdullah stresses the possibility that solar-powered irrigation would allow for even deeper groundwater extraction due to the absence of fuel expenses, subsequently resulting in faster groundwater depletion. These findings are in line with the results of Hartung and Pluschke (2018), that voice similar concerns regarding incentives to overexploit water resources which may be the outcome of solar-powered irrigation systems.

Solar-powered irrigation systems are also implemented as part of the night irrigation project that this study uses as the basis for its field visit and data collection. The night irrigation project attempts to increase water efficiency by reducing the evaporation that occurs during irrigation (see chapter 4.1). Dr Hassan elaborated further on the motive, expected results and the solar-powered night irrigation system:

> The motive behind this [project] is to reduce the evaporation … if you irrigate the land during the daytime we have a lot of evaporation from the soil, from the [centre] pivot [irrigation] system and from the leaves of the plant … the night irrigation would really reduce the amount of evaporation … this idea basically wants to combine renewable energy and the levelled reservoir that would allow us to irrigate during the night … you can produce the energy from these solar panels and use it to store the energy in terms of water up on the hill. Then in the night, you can use it for irrigation as pressurised water coming from the hill … and then you can reduce the amount of evaporation because the temperature and conditions in the night are different. – Dr Hassan

In his remark, Dr Hassan explains the water efficiency gains that the project aims to achieve by shifting the irrigation schedule to the night-time, consequently avoiding peak sunshine hours, since this is also the time when high evaporation occurs. Through a levelled reservoir that enables the farm to irrigate during the night, the project reduces evaporation immensely and is "a huge advantage to water efficiency" (Dr Tamer). Dr Hassan continues to explain in what particular way water efficiency will be increased when switching to night irrigation:

> [O]nce the plant gets its water, transpiration won't be that high because the weather is not that hot. So, the plant will not breathe as much and therefore will not transpire. So, the transpiration will be less. Also, the evaporation from the soil surface will be less. – Dr Hassan

In this quote, Dr Hassan refers to water absorption and transpiration of plants, which is central to increasing water use efficiency. During peak hours of sunshine, the high temperature of the soil surface would reduce its ability to absorb the irrigated water and consequently lead to higher evaporation. In contrast, during hours of lower temperatures, the plants and the soil can absorb more of the irrigated water. Hence, crops and soil types are a vital part of achieving water efficiency. Dr Abdullah points towards the sandy conditions of the soil in desert farming that requires certain irrigation systems to avoid water wasting:

> The problem there is with sandy soils that the water holding capacity of such soils is very low. It's not logical to have such flood irrigation or furrow irrigation that consumes much more water since, you know, that the soil will not capture the water. You are just wasting water. And you are just pumping much more water and that's it. That's why such systems are not suitable for sandy soil like in [Wahat El] Bahareya. – Dr Abdullah

The mentioned flood and furrow irrigation methods are traditionally used in agriculture in the Nile Delta in Egypt, consisting of a different type of soil that depicts a higher water holding capacity. Hence, Dr Abdullah's assessment that flood or furrow irrigation would not be suitable for sandy soils with low water holding capacity, proves the importance of considering the type of soil in water-efficient irrigation. This result is in line with the literature that identifies the process of evapotranspiration as a key factor in determining irrigation requirements (Abou Ali et al., 2023; IPCC, 2022).

Dr Hassan continues to explain that the reservoir creates another surface that will naturally experience evaporation. However, he expects that reducing "the evaporation from the land, the evapotranspiration from the plant and the evaporation from the pivot system itself at the sprinklers" (Dr Hassan) outweighs the added surface evaporation from the reservoir. In the long-term, Dr Hassan expects further positive effects of soil health and increased fertility "because you are reducing [the] stress of hot weather and water at the same time and giving the plant better conditions to use the irrigated water" (Dr Hassan).

While Dr Tamer talks about similar expected gains from the project, he also refers to the detrimental effects that the night irrigation project might entail, if not used correctly:

> If you really use the reservoir to only irrigate in the night and not during the peak hours of radiation, then you will save water. But if you irrigate during the night and the day, it will actually need more water because now you can irrigate all day long. – Dr Tamer

His remarks point to the misuse of the reservoir irrigation project as it also makes irrigation around the clock possible. This implies that the benefit of solar-powered irrigation systems that offer reliable and affordable energy while reducing CO2 emissions (Hartung & Pluschke, 2018) are prone to be misused to increase crop yield and may potentially cause further depletion of the groundwater resources, rendering the likelihood of the tragedy of the commons possible (Ostrom, 2009).

The findings in this chapter show that technological improvements in irrigation systems to improve water efficiency need to consider irrigated crop and soil types. Furthermore, temperature and solar radiance play a significant role in reducing evapotranspiration, which contributes to increased water use efficiency. When considering these aspects, farmers and irrigators can increase their water productivity and contribute towards more sustainable use of the resource units stored in the NSAS. Thus, responsible and efficient water use would increase the productivity and predictability of the resource system and positively influence the willingness of involved actors to engage in self-organisation activities (Ostrom, 2009).

5.2.2 Socio-behavioural aspects towards sustainable groundwater use

Changing irrigation methods should not only be considered from a technological and hydrological perspective but also requires social transformation and inclusive approaches. The identified variables that proved to be conducive towards actors' self-organisation (see chapter 3.2) need to be analysed and solved to understand the changes necessary to manage an SES sustainably. Before such changes are implemented, raising the awareness of affected local communities is vital to avoid potentially detrimental effects of overexploitation, and understand the long-term benefits of sustainable water use for their livelihoods. Otherwise, transformation processes are likely to be met with resistance and protest (Schofield & Gubbels, 2019).

Importantly, the governance system plays a key role in managing the resource system and the use of resource units by actors (Ostrom, 2009). Egypt's water resource management was touched upon in several of the interviews. While the data at hand does not provide sufficient material for comprehensively understanding water governance in Egypt, several experts describe the governance system to be based on centralised decisions and rules that potentially fall short of considering the local context. For instance, Victor describes the process of implementing water-efficient irrigation methods as top-down:

> They're having programs. But they're very top-down. Like for upper Egypt, they want to develop drip irrigation for the sugar cane production. And then they're talking about huge areas. So, these are all these top-down things. But when you have a program to change 200,000 feddan of sugar cane to drip irrigation, it’s a [huge] project to get farmers organised. There will be resistance. Your farmers will not just accept it like that. – Victor

Similarly, Dr Tamer and Dr Abdullah discuss how a government license must be obtained for every water well, which includes a compulsory hydrological study that is conducted by a governmental research institute. This brief insight into some aspects of water resource management in Egypt provides some guidance in terms of the sustainability assessment within the SES framework. It seems that actors are not able to flexibly self-organise their water extraction sustainably considering their local and cultural context. The literature finds, that the response to water scarcity is influenced by multiple factors such as cultural skills or traditional knowledge (Liwenga, 2008; Pereira, Cordery & Iacovides, 2002). Furthermore, Dr Mohammed explains the lack of integrated policymaking as one of the major challenges in Egypt. Rama and Victor agree by pointing out that even though several ministries are responsible for certain aspects of water resource management, they do not seem to align their management efforts in terms of groundwater resources:

> From an institutional perspective, it's very complicated because we have different ministries who do not work together. So, you have the [Ministry for Water Resources and Irrigation] that works on … irrigation canals … [b]ut the on-farm irrigation is done by the Ministry of Agriculture. – Rama

This rather centralised water management approach depicts a major challenge when it comes to social transformation and the inclusion of farmers and irrigators in water-efficient irrigation projects. In the literature, successfully adapting to water scarcity and climate change involves all people, communities, organisations and nations encompassing not only climatic and technological aspects, but also cultural environments and institutions (IPCC, 2014; Vincent & Cundill, 2022). Furthermore, Mehta (2007) argues that water scarcity must not only be assessed in terms of physical shortages but also as a social construct that arises from wider socio-political aspects. In this context, Dr Abdullah discusses how farmers and investors in Egypt continue to prioritise profitability over sustainability:

> the farmers always think about agriculture profitability, not sustainability. Just to be honest. They don't care what is going to happen for the new generation. They just want to cover the costs, so it’s profitability. Sustainability is strange for farmers. – Dr Abdullah

While Dr Abdullah points out that farmers are primarily interested in covering their costs, Rama explains that they lack awareness of the water scarcity problem and simply do not deem irrigation system upgrades beneficial. Hence, awareness raising among farmers as well as their inclusion in solving water scarcity is necessary to convince actors “that it is in their best interest to transform” (Dr Mohammed). Victor illustrates the problem by exemplifying the following:

> You have to remove sugar cane every year, which is a lot of work. But it's not so complicated if you have a system with PVC pipes or something, you can just add these pipes to it and you can also remove them. The ground preparation takes a bit more labour but then it’s okay. And it’s quite flexible. But it’s not easy to convince the farmers since it’s extra work for them. Why should they do it? They just do flood irrigation and have a good deal. - Victor

Victor’s illustration touches upon a lack of incentives for farmers to upgrade to more water-efficient irrigation methods, such as drip irrigation for sugarcane. Hence, the reason for farmers and irrigators to not transform might be lacking incentives rather than lacking awareness. Dr Abdullah’s remark above also implies that actors involved in extracting water resources from the NSAS might be unable to upgrade due to their financial and economic situation. O`Brien and Wolf (2010) find that not only monetary values play a role in adaptation, but argue that a broader understanding that considers the local meaning of water scarcity as local communities might experience water scarcity differently.

Due to the multitude of aspects when it comes to identifying successful adaptation approaches, water efficiency projects are regularly met with resistance and protest. For instance, the idea of water pricing has been put forward by several experts to create an incentive for farmers and irrigators to use water more sustainably. Several challenges with this idea appeared in the interviews, such as the sheer amount of infrastructure required for implementing a metering system (Dr Mohammed) as well as the political sensitivity of putting a price on water that has been freely available for decades (Dr Abdullah, Victor). Hence, Dr Abdullah explains that water pricing policies are not the preferred strategy as the government is worried that it would be resisted due to the difficult economic circumstances of Egyptian farmers:

> … if you want water pricing, it will be met with resistance. The government is very aware of the circumstance and the low income and how farmers are struggling in Egypt. So, I think the government is smart to not raise this issue, at least for the moment. – Dr Abdullah

In line with Ghazouani et al.'s (2015) findings that the key to successful adaptation measures might not always be income maximisation, but could also be related to cultural habits and traditions. Dr Tamer exemplifies how multi-layered resistance to technological upgrades influences the willingness to transform:

> To our solar panels, in the beginning, we faced some resistance. [T]he issue was that farmers had been using a different irrigation routine for years. Common farmers start their day early in the morning … with the morning prayers … and around midday they rest … With solar irrigation, it does not work like that. The peak sun time is the rest time from maybe 11:00 am to 1:00 pm with maximum radiance. So, you want to tell the farmer that this has to be your work time even though they are used to resting. So, this needs social transformation. – Dr Tamer

This example shows the wide range of aspects that influence such upgrades and changes. Actors in a complex SES might be influenced by trivial aspects such as daily routines in accordance with their traditions, habits or religion. The SES framework applied in this study acknowledges the importance of norms and social capital and discusses the social value of resource systems to local communities. These aspects prove to be conducive to successful self-organisation and sustainable management of an SES (Ostrom, 2009). Hence, the analysis in this chapter is central to understanding the aspects that need to be considered to assess and achieve sustainable groundwater use of the NSAS without the imminent risk of depletion.

6 Results and Discussion

The findings of the analysis highlight the complex challenges associated with the sustainable and efficient extraction and utilisation of fossil water resources in the Nubian Sandstone Aquifer System (NSAS). The aim is to discuss the results in light of how desert farming in Egypt can adapt to the imminent water scarcity under climate variability. The study identifies research and data gaps related to available and accessible water quantity, flow, recharge and other hydrological settings of the NSAS, as highlighted by the experts interviewed. While some research exists on the specifics of the aquifer, indicating that it consists of several regional intertwined aquifer systems (El Hossary, 2013; Frappart, 2020; Masoud & El Osta, 2016; Sharaky et al., 2021; Shokr et al., 2022; UNESCO, 2006), the total available groundwater resources and the technologically accessible resources in the NSAS remain uncertain. Insufficient research on water flow within the aquifer hinders the assessment of resource mobility and the impact of water extraction activities. Addressing these data limitations is crucial for effective assessment and decision-making regarding sustainable extraction practices, preventing depletion, and providing necessary information to local communities and governments.

Moreover, the lack of data limits the discussion on best practices for extracting and utilising fossil groundwater in agriculture. The experts suggest that, despite the lack of comprehensive data and the possibility of other recharge sources, the majority of the NSAS can be considered non-renewable, with insignificant potential for recharge over time. While strict theoretical terms consider the exploitation of non-renewable resources unsustainable due to eventual depletion (Ostrom, Gardner & Walker, 1994, p.8), the experts argue for nuanced solutions considering Egypt's limited and volatile renewable water resources, primarily provided by the Nile River. Increasing water and food demands from immense population growth, industrial and economic development, and the impacts of climate change require the assessment of utilising fossil Nubian groundwater resources to ensure food security and livelihoods.

To enhance water productivity and address water scarcity, the experts suggest focusing on water use efficiency gains in agricultural irrigation. This can be achieved through better soil and water management practices, as well as the use of water-efficient irrigation systems that help reduce evapotranspiration. Factors such as soil and crop types, temperature, and solar radiance play crucial roles in increasing water use efficiency. At the study site in Wahat El Bahareya, the soil's water-holding capacity is considered low due to its sandy texture, which requires irrigation systems to regularly irrigate small amounts of water to prevent water loss through evaporation. Crop selection also influences water use efficiency, with crops like wheat, rice, or cotton being heavy water users. Selecting crops with low water intensity and better yields in desert climate can improve water use efficiency. Furthermore, the choice of irrigation system depends on crop harvesting frequency and field ploughing requirements, with centre pivot systems suitable for highly harvested plants and sprinkler or drip systems preferred for bush or tree crops.

The night irrigation project implemented by Sekem at the study site aims at adjusting the irrigation schedule to the night-time, taking advantage of lower temperatures and the absence of solar radiance, which reduces evapotranspiration. Although there is some evaporation transfer to the open reservoir storing the photovoltaic energy generated during the day, overall water use efficiency is expected to increase. Lower temperatures during the night irrigation provide the soil with more time to absorb the water, benefiting soil health and production output, as the experts suggest. Furthermore, crop rotation is implemented, contributing to soil health and improving water holding capacity. Finally, plant transpiration during night irrigation with lower temperatures is reduced as plants do not breathe as much allowing them to absorb more of the irrigated water. These considerations emphasise the importance of crop and soil types in increasing water use efficiency and adapting to water scarcity in desert farming.

However, technological improvements, such as solar-powered irrigation systems, can create unintended consequences. While solar-powered systems offer reliable and affordable energy, they remove the cost constraints associated with diesel-powered irrigation. This may incentivise farmers to increase irrigation frequency, potentially leading to overexploitation and depletion of the fossil groundwater resources stored in the NSAS.

The analysis recognises that achieving water use efficiency requires considering socio-behavioural aspects alongside economic and technological factors. The example of solar-powered irrigation systems creating unintended incentives highlights the importance of addressing behavioural aspects of water scarcity. According to Ostrom's (2009) framework of social-ecological systems (SES), sustainable utilisation of common pool resources is influenced by behavioural factors, as actors are more likely to avoid overexploitation when others using the same resource refrain from misuse. However, due to the NSAS's massive size, transboundary nature, and data gaps, implementing changes in irrigation practices or investing in water-efficient systems becomes challenging. Farmers and irrigators may lack incentives to adapt due to social values, cultural environments, institutions, limited awareness, and difficult financial situations. Additionally, water scarcity may also be socially constructed and experienced differently in various context-specific settings.

In conclusion, this discussion demonstrates the multi-layered adaptation considerations required to address water scarcity and climate change while attempting to achieve water efficiency in groundwater extraction and utilisation. By applying a framework that considers the NSAS as a social-ecological system, encompassing resource systems, resource units, actors, and governance systems, this study offers insights into the sustainability of the NSAS from multiple perspectives and identifies areas for potential improvement.

7 Conclusion

This study explores the adaptive capacity of desert farming in Egypt in the face of imminent water scarcity, while also addressing the sustainability of extracting fossil groundwater. It particularly focuses on a pilot irrigation project situated in the Bahareya Oasis in Egypt, which relies on the fossil Nubian Sandstone Aquifer System (NSAS) as its water source. To investigate the research questions, a qualitative study was conducted on-site in Egypt, employing semi-structured interviews with experts in the field. The collected data was then analysed through the lens of the social-ecological systems (SES) framework, which offers a comprehensive perspective on addressing water scarcity in the context of desert farming. The findings of the study were presented through a thematic analysis of the expert interviews, yielding valuable insights applicable to water-stressed countries in arid regions that rely on desert farming.

The study identifies clear research and data gaps related to available and accessible water quantity, flow, recharge and other hydrological settings of the NSAS. This data insufficiency hinders the assessment of resource mobility and the impact of water extraction activities and limits the discourse on optimal practices for utilising fossil groundwater in agriculture. Furthermore, in the Egyptian context, this study highlights the need for a nuanced approach to the extraction of fossil groundwater resources, considering the country's constrained and volatile renewable water resources, primarily provided by the Nile River. The escalating water demands resulting from population growth, industrial and economic development and the exacerbating impacts of climate change are identified as key drivers for exploring the utilisation of Nubian groundwater resources.

Consequently, this study reveals that enhancing water use efficiency requires addressing economic-technological aspects, such as the modernisation of irrigation systems and appropriate crop selection, as well as socio-behavioural aspects, such as cultural and traditional reasons for resistance, awareness-raising efforts, and incentivising communities to adopt water-efficient behaviour. Based on these findings, the study effectively addresses the research questions by identifying social and technological challenges associated with water use efficiency and underscores the complex nature of adaptation to imminent water scarcity under climate variability in desert farming.

Although the findings of this research provide valuable insights into the complexities of social and technological adaptation in response to water scarcity, further research is recommended to address the existing data and research gaps concerning the NSAS. Such research endeavours would contribute to the ongoing global discourse on the sustainability of extracting fossil groundwater, aiming to prevent the tragedy of the commons amidst escalating global water scarcity. Additionally, exploring the perspectives of local communities and their experiences of and adaptive capacity to water scarcity would enhance our understanding and effectiveness of regional water governance and policy. Furthermore, investigating the factors that incentivise resource appropriators is crucial for improving water use efficiency and mitigating further depletion of groundwater resources. These research suggestions carry significant implications for North Africa and Western Asia, as these regions face severe water scarcity and are projected to experience even more acute water shortages in the coming decades.

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Appendix A

Report on research visit to Wahat El Bahareya project site | 28th – 29th March 2023 | El Harra, Western Desert, Egypt

The field trip took place with a team of researchers and experts involved in agricultural irrigation and centre-pivot irrigation systems. The site visits as well as several conversations with the researchers and experts are the basis for this report. The land measures used in this report are Egyptian feddan. 1 feddan translates to approximately 4200km² or 0.42 hectares.

The farm in Wahat El Bahareya is part of SEKEM Land Holdings and is located in the Western Desert in Egypt. It has a size of approximately 1835 feddan (770 hectares) and consists of two parts, which mainly differ in the type of irrigation systems used. Wahat 1 has a size of 575 feddan and is used for the cultivation of permanent crops such as olive trees, jojoba or palm trees. This allows for the utilisation of drip irrigation requiring a complex network of irrigation pipelines. Despite the high water efficiency of this method, intensive labour and maintenance are required. The pipes last approximately three years before having to be replaced.

Wahat 2 has a size of 1260 feddan and consists of non-permanent crops such as chamomile. Due to the frequent harvesting and ploughing, centre-pivot irrigation systems are better suitable and applied here. Upon completion, Wahat 2 will consist of 24 centre pivot installations, each having a length of 265 metres, resulting in a diameter of 530 metres per field. Each field will have a size of 52.5 feddan. The different fields are still under construction and new pivots are added continuously. Figure 1 displays the layout of the farm. The centre pivot irrigation systems (illustrated by the green circles in the layout) need approximately 12-15 hours to irrigate one field depending on the speed of the pivot and the amount of water needed for the certain crop. Centre pivots are relatively standardised systems that have been developed in Egypt over the last 10-15 years and show higher water efficiency in comparison to the traditional flood irrigation used primarily in the Nile Delta and along the Nile River.

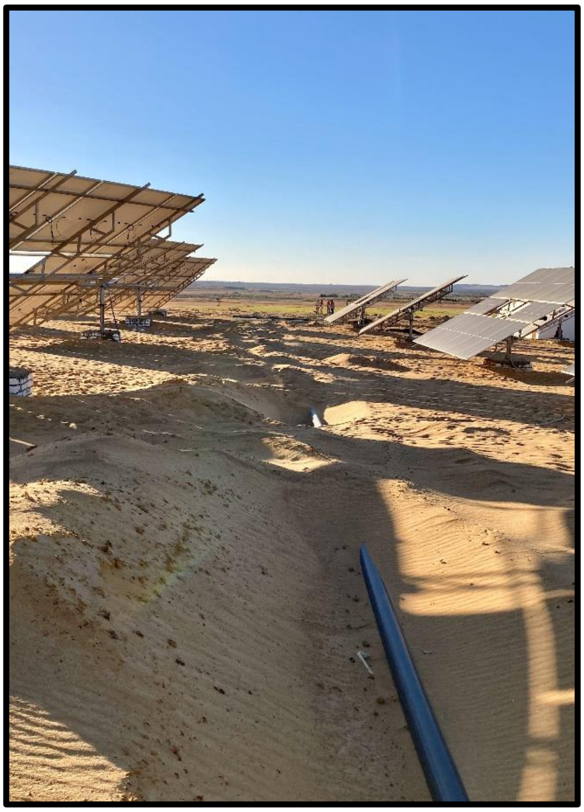
The night irrigation project is currently being implemented at pivot 20, as highlighted in figure 1. The proposed idea for this pilot project is to use photovoltaic panels (yellow squares in figure 1) to generate the required electricity for pumping groundwater into a reservoir situated about 50 meters above the centre pivot, creating a water pressure of approximately five bar. According to irrigation experts, ten meters in altitude create approximately one bar of water pressure, which is a thumb rule used for estimation purposes. Though some water pressure is lost due to the non-vertical nature of the pipes, it is still adequate to ensure proper sprinkler functioning, as centre pivots need between 0.7 to 1 bar. The reservoir is designed to store PV-generated energy during the day, which can only be generated during sunlight hours, to be used for night irrigation. It is relatively easy to integrate the reservoir with the existing centre pivot systems, enabling the farm to switch to night irrigation. The reservoir's size will ensure enough water to irrigate three centre pivots for three days, even when sunlight doesn't provide sufficient energy for the required pumping capacity. The pilot project is expected to increase water use efficiency by up to 30 percent. It is important to note that groundwater in Wahat El Bahareya is non-renewable, which emphasizes the importance of even small efficiency gains. To that end, the reservoir is planned to be an open reservoir, which will create an additional water surface area and experience evaporation during the day. The amount of water lost through evaporation depends on the size of the water’s surface area and the season of the year. Therefore, the reservoir is designed to be as deep as possible to reduce water surface area, but limestone at a depth of about 6-7 meters prohibits further excavation. Despite the additional water loss through evaporation, experts are not overly concerned since the expected water use efficiency gains from night irrigation are much higher.

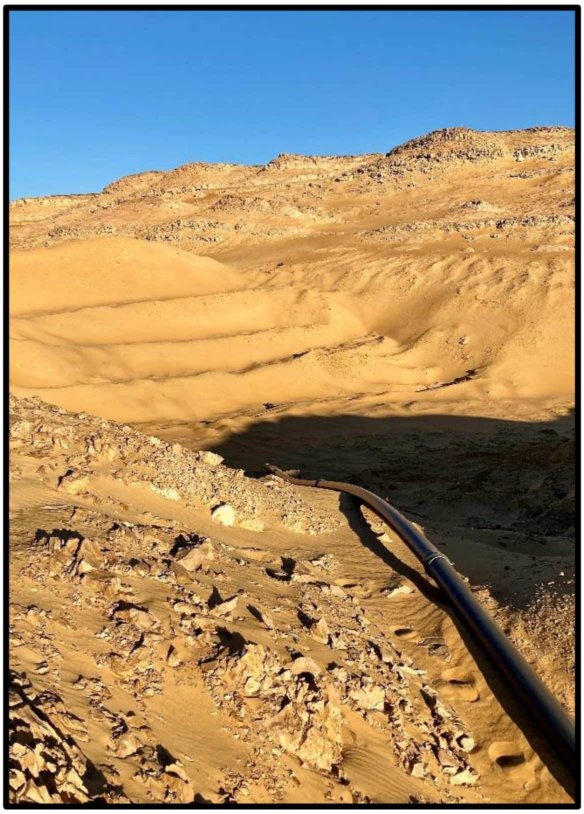
On this farm, SEKEM uses modern irrigation systems such as drip irrigation, centre pivot irrigation and sprinkler irrigation. The experts and researchers that visited the farm discussed precision farming techniques such as remote sensing or soil moisture sensors that decide when and how much the soil needs to be irrigated, this could be a solution for further water use efficiency gains. Furthermore, the farm implements crop rotation and biodynamic farming to improve the soil’s ability to retain water and reduce water losses and soil stress. In addition, non-conventional water sources such as treated wastewater are piloted and promoted.

According to the experts, centre-pivot irrigation systems have several advantages:

- **Uniform water distribution:** Centre pivot systems deliver water uniformly across the entire field at a controlled rate, ensuring that all crops receive the same amount of water.
- **Increased efficiency:** These systems are highly efficient in water delivery, reducing losses from evaporation or runoff.
- **Reduced labour costs:** Centre pivot irrigation is fully automated and requires minimal labour to operate.
- **Precision farming:** Modern centre pivot systems integrate with GPS mapping and soil moisture sensors, allowing for optimal water coverage and usage.
- **Efficient use of land:** Centre pivot irrigation increases the amount of land that can be irrigated at a given time, as compared to other irrigation systems.

The following pictures give an impression of the local situation and the night irrigation project in Wahat El Bahareya:





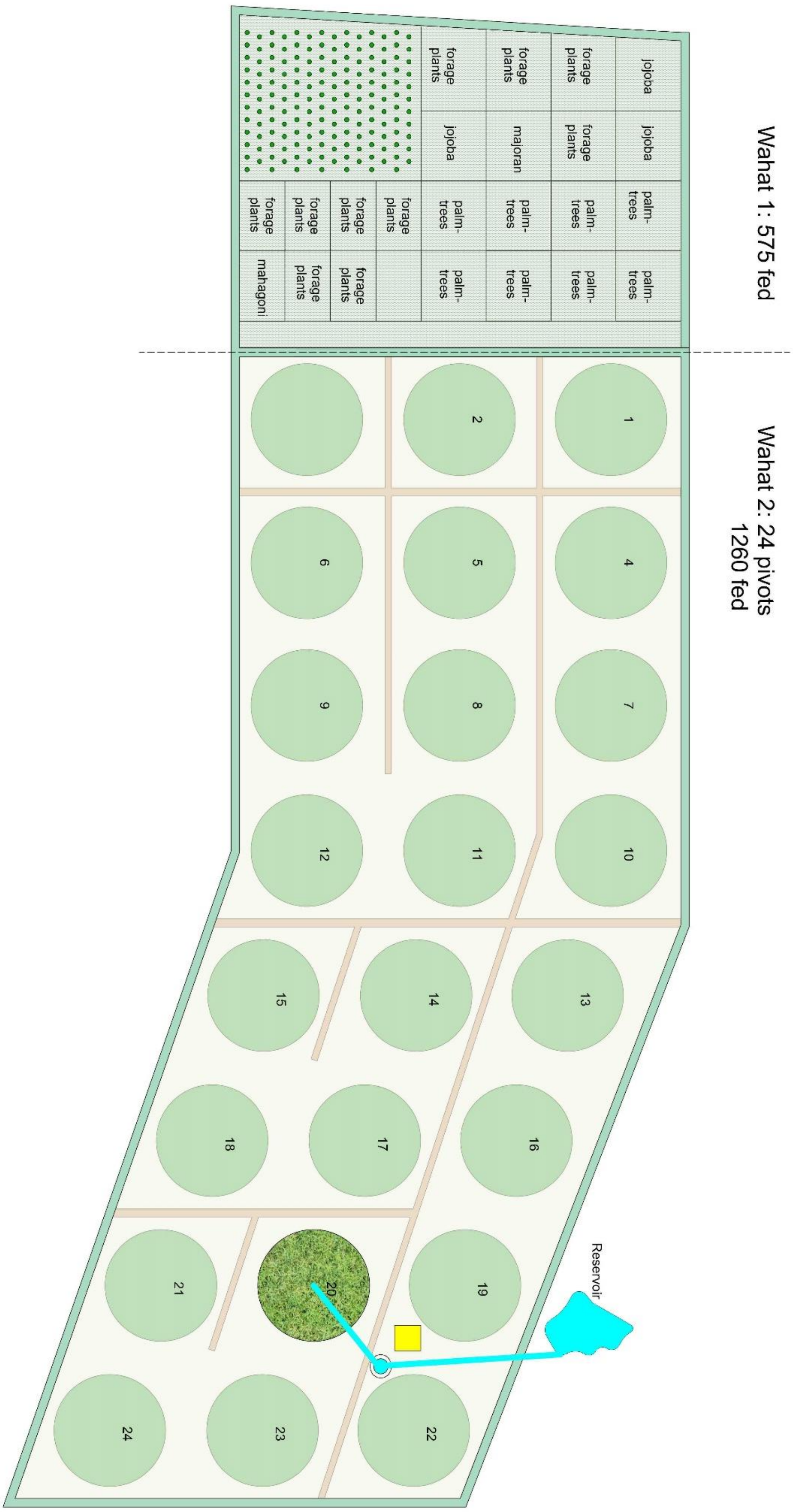


Figure 1: Layout of Sekem's farm in Wahat El Bahareya, Western Desert, Egypt
Source: own illustration based on information gained at site visit

Appendix B

Guiding questions for semi-structured expert interviews

This interview guide was loosely used for conducting semi-structured expert interviews. The different topics were discussed depending on the interviewees' expertise and professional background as not all experts were equally able to provide in-depth answers to all questions. Generally, the guiding questions of this interview guide can be divided into three different groups: technical questions, consequential questions as well as questions related to water resource management and policy.

1. Technical project questions

Questions that target the night irrigation project in Wahat El Bahareya directly to enhance the understanding of the technical details of the project as well as challenges and limitations.

- How does the night irrigation work? What are the technicalities of the pivot? What is the irrigation capacity per feddan?
- How is the reservoir built? How exactly will be ensured that night irrigation works? What is the capacity and size of the reservoir?
- What are challenges with the photovoltaic electricity generation? What is the kilowatt capacity installed and what capacity is needed?
- How is evaporation brought to a minimum through the night irrigation project? How applicable is the solution to other farms?
- What other solutions or methods are done on the farm to increase water efficiency? What else needs to be considered when it comes to increasing water efficiency?
- Choice of location: What is the benefit of farming in Wahat El Bahareya and generally desert farming?

2. Consequential questions

Questions that directly result from the technical questions to enhance understanding of the direct impacts and consequences of the night irrigation project.

- The issue of sustainability of the extraction of groundwater from the Nubian aquifer is central as it opens the discussion of whether it is at all a question of sustainability. What value can be achieved per water drop and is improvement possible?

- What needs to be discussed/considered when attempting to assess the sustainability of fossil groundwater extraction from the Nubian Sandstone Aquifer System?

- Source of the groundwater at Wahat El Bahareya: How much water is available in the Nubian aquifer and what quantity is realistically, technologically and economically accessible? Is the water completely fossil?

- Project as an adaptation measure to climate change: How can irrigation in Egypt be adapted to climate change? What might be possible challenges?

3. Policy questions

Questions related to water resource management and policy as well as the water governance system in Egypt’s agriculture.

- How is water resource management of shared groundwater and surface water resource done? Are there strategies regarding the sustainable management of the Nubian aquifer? How is the cooperation with the neighbouring countries that share the aquifer with Egypt?

- What are the challenges in the governance system? What is the government struggling with and how are civil society and farmers included in finding comprehensive solutions to the challenges faced on-farm level?

- As groundwater is a common pool resource, how is water management done on a national, regional and local level? Are there mechanisms against water waste or illegal water extraction? For instance, is information and data collected about every well existing in Egypt to understand the true extraction of groundwater?