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Climate Change Adaptation for the Water Sector in Egypt: A focus on Dakhla and Kharga Oasis using Climate Data from 1901-2023

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Securing the Sustainability of Oasis Societies Associated with Water and Land Use in the Western Desert
Science and Technology Research Partnership for Sustainable Development (SATREPS)
Scarce-Water Research Center at Sophia University

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Abstract

Egypt is facing growing challenges due to the multifaceted impacts of climate change on its already scarce water resources. As one of the most arid countries in the world, Egypt's vulnerability is particularly pronounced in desert regions such as the Dakhla and Kharga Oases. These oases are crucial not only for local livelihoods and agricultural expansion but also as indicators of the broader climate dynamics in the Western Desert.

This lecture paper presents a comprehensive analysis of national climate change adaptation efforts in Egypt, with a particular emphasis on water resource management. It also investigates long-term climate trends from 1901 to 2023 using global climate datasets (temperature, precipitation, soil moisture, and evapotranspiration patterns, etc.), focusing specifically on the Dakhla and Kharga Oases. By employing geospatial and statistical tools such as QGIS®, R®, and Excel™, the study quantifies historical climate shifts for the two oases, which could be complimented further on with an assessment of impact on humans and the environment.

The paper also shed some light on Egypt's adaptation framework, which includes 37 nationally defined indicators spanning water resource management, agricultural practices, wastewater treatment, environmental monitoring, and public awareness. A proposed Climate Change Adaptation Index is introduced as a tool to evaluate and guide policy responses.

Initial findings show a temperature increase of up to 3-6°C over the past 120 years in Dakhla and Kharga oases—far exceeding the global average—alongside alarming declines in soil moisture. These trends call for urgent, localized interventions, continuous monitoring, and innovative solutions such as green desalination and integrated water-energy-food systems.

The current study contributes to a better understanding of how adaptation strategies can be shaped by evidence-based climate diagnostics and offers actionable insights for policymakers and practitioners operating in arid environments.

Introduction

Climate change is increasingly recognized as one of the most pressing global challenges of the 21st century, impacting ecosystems, economies, and societies on a global scale. Its effects are particularly severe in arid and semi-arid regions, where water scarcity is already a defining environmental constraint. Egypt, situated in the hyper-arid zone of North Africa and heavily dependent on the Nile River, is exceptionally vulnerable to these changes.

The country's freshwater resources are limited and overstressed (mainly from the Nile river), facing mounting pressures from population growth, urban expansion, agricultural intensification, and industrial activities. Climate change compounds these challenges by introducing greater uncertainty in water availability and distribution, increasing evaporation rates, altering seasonal precipitation, and intensifying extreme weather events such as floods and heatwaves. These dynamics are not only ecological in nature but also carry serious socio-economic and political implications.

Within Egypt, the Western Desert oases of Dakhla and Kharga represent unique environmental and cultural landscapes that have historically relied on groundwater aquifers for human settlement and agricultural development. These oases are also important to Egypt's strategy of desert reclamation and rural development. However, they are also among the regions most exposed to climate-induced stress. Rising temperatures, declining soil moisture, and potential aquifer depletion are already being observed. These trends threaten not only agricultural productivity and food security but also the sustainability of ongoing settlement and development projects.

In this lecture paper we investigate the impacts of climate change on these two oases using historical climate datasets from 1901 to 2023. It integrates geospatial analysis, quantitative climate diagnostics, and national policy review to assess Egypt’s current climate change adaptation strategy in the water sector. Special attention is given to the Monitoring and Evaluation (M&E) framework developed by the UNDP, UNESCO, and Egyptian authorities, which includes a set of 37 indicators designed to measure vulnerability, preparedness, and response capacity.

Through the lens of Dakhla and Kharga, the study sheds light on the broader narrative of climate resilience in Egypt’s desert regions, offering insights into how localized data-driven analysis can inform national strategies. It ultimately argues for the necessity of context-specific adaptation measures that are grounded in historical evidence, community needs, and sustainable resource use.

Egypt and the Oases: A Geographic and Strategic Overview

Egypt’s geography is dominated by vast deserts, with over 96% of its land area classified as arid or hyper-arid. The Nile River, accounting for more than 90% of the country’s renewable freshwater resources, supports most of Egypt’s population, agriculture, and economic activities along its narrow valley and delta. However, beyond the Nile basin, Egypt hosts several key oases scattered across the Western Desert, of which Dakhla and Kharga are among the most prominent. (Figure 1)

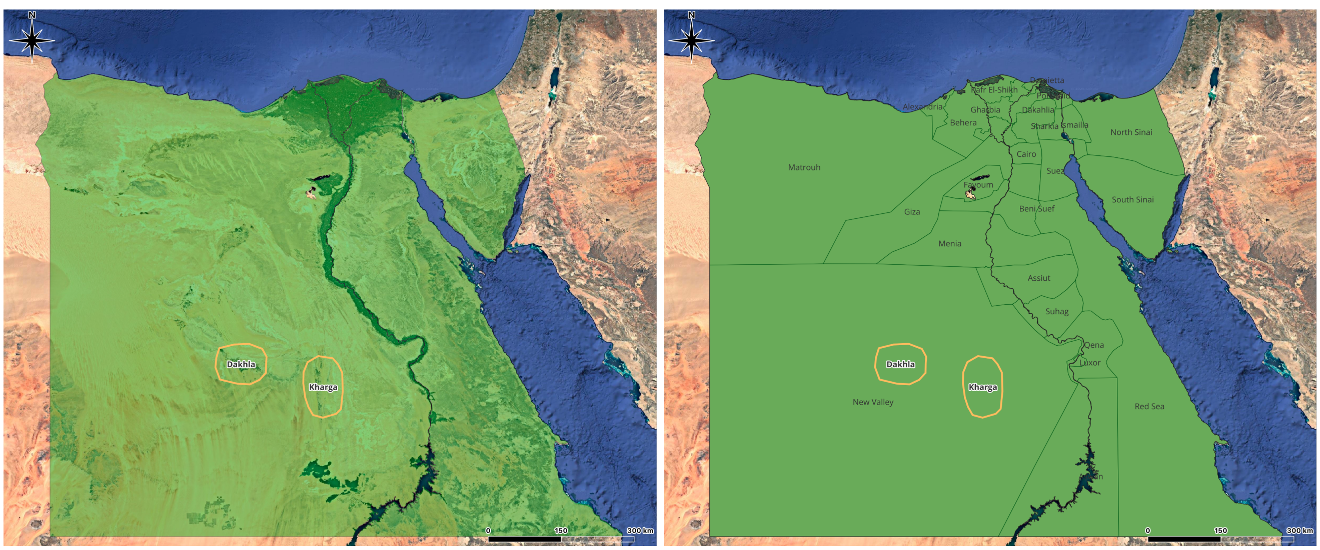

Figure 1. Left: Map of Egypt showing the aridity of the country, and the locations of the Dakhla and Kharga oases. Right: Map of Egypt with its 27 Governorates (Administrative divisions)

Source: Google Earth base map. Egyptian Central Agency for Public Mobilization and Statistics (CAPMAS) polygon for Egypt, and for administrative divisions, projected using QGIS. Oases polygons are produced by the author.

The Dakhla and Kharga Oases, located in the New Valley Governorate, lie approximately 200–300 km west of the Nile Valley (Figure 1). These oases are not merely isolated desert depressions; they are part of an ancient network of human settlement and trade, historically linked through caravan routes that connected North Africa with the Sahel and Sub-Saharan Africa. Their habitation dates back thousands of years, and archaeological findings attest to their longstanding role as agricultural and cultural hubs.

Climatically, both oases are characterized by extremely low rainfall (often less than 1 mm annually), high diurnal temperature ranges, and strong solar radiation. Their ecosystems are entirely dependent on groundwater, mainly from the Nubian Sandstone Aquifer System—one of the world’s largest fossil aquifer systems, shared with Sudan, Chad, and Libya. This non-renewable groundwater is the primary source of water for irrigation, domestic use, and recent desert reclamation projects.

In recent decades, the Egyptian government has launched several large-scale development initiatives aimed at expanding agriculture and human settlement in these regions. These include the “New Valley Project” and subsequent programs intended to alleviate population pressure in the Nile Valley, create employment, and increase national food production. Dakhla and Kharga have become central to this vision, with expanding road networks, agricultural schemes, and land distribution policies targeting young farmers and investors.

However, the environmental cost of these interventions is significant. Pumping groundwater without adequate recharge, clearing natural vegetation, and exposing soil to erosion and salinization may accelerate ecological degradation. Moreover, climate change introduces additional stressors—such as increased evapotranspiration and reduced soil moisture—that compound the fragility of these desert ecosystems.

Given their strategic role in Egypt’s territorial and agricultural expansion, the Dakhla and Kharga Oases are essential sites for understanding how climate change intersects with human development. Their geographic isolation, dependence on finite water resources, and exposure to climate extremes make them natural laboratories for examining the limits and potentials of adaptation in arid environments.

Climate Change and Human Efforts

Climate change presents a complex and multifaceted challenge to water-scarce nations like Egypt. The country is witnessing a growing convergence of climate-related stressors that directly affect the quantity, quality, and timing of water availability. These impacts, in turn, generate cascading effects on agriculture, human health, food security, energy production, and overall socioeconomic stability. Understanding these interconnected dynamics is essential for designing meaningful adaptation strategies.

Pathways of Climate Change Effects in Egypt

Egypt’s climate is characterized by hot, dry summers and mild winters, with minimal rainfall concentrated along the Mediterranean coast. However, climate data and long-term observations indicate significant alterations in this pattern:

- Rising Temperatures: Egypt has experienced a steady increase in mean annual temperatures, with projections indicating further rises of 2–4°C by the end of the century.
- Changing Precipitation Patterns: Rainfall has become more erratic, undermining planning and water management.
- Sea Level Rise: Coastal areas face increased saline intrusion into groundwater systems.
- Extreme Weather Events: Heatwaves, sandstorms, and intense wind events are becoming more frequent.

The impact of those manifestations (and others), on Water Resources, on Water Availability, on the Environment and on the Socio Economics of Egypt is illustrated in Figure 2, and explained briefly in the following paragraphs:

Impacts on Water Resources

- Nile Flow Variability: Climate fluctuations upstream affect Egypt's water security.
- Flash Floods and Flooding: Sudden rainfall overwhelms dry terrain and damages infrastructure.
- Groundwater Depletion and Salinity: Over-extraction and declining recharge threaten aquifer sustainability.
- Soil Moisture Decline: Declining moisture impacts agriculture and increases desertification.

Socioeconomic and Environmental Consequences

- Agricultural Vulnerability: Reduced yields and food insecurity.
- Urban and Industrial Demand: Rising water demand coupled with declining quality.
- Public Health Risks: Heat-related illnesses and waterborne diseases.
- Displacement and Migration: Climate-induced migration from rural areas.

- Cultural and Ecological Heritage: Loss of biodiversity and degradation of heritage landscapes.

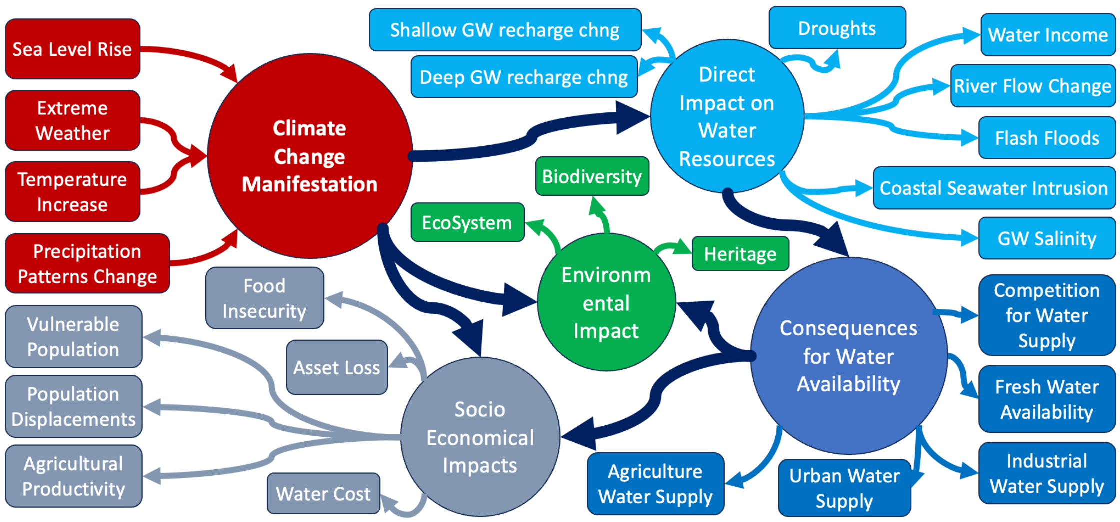

Figure 2. Climate Change Manifestations and its impact.
Source: The author.

National Adaptation Measures

Recognizing the existential threat that climate change poses to water security, food production, and human development, Egypt has taken important steps to mainstream climate adaptation into its national planning frameworks. The country's adaptation agenda is framed within broader development strategies such as **Egypt Vision 2030**, the **National Climate Change Strategy 2050**, and its **Nationally Determined Contributions (NDCs)** under the Paris Agreement. Water is positioned as a priority sector due to its centrality to agriculture, human health, industrial development, and environmental sustainability.

A cornerstone of Egypt's adaptation effort is the establishment of a **Monitoring and Evaluation (M&E) Framework** to systematically track vulnerability and resilience. This framework is designed not only to assess the current status of water systems but also to provide data-driven support for decision-making, project design, and resource allocation. It includes a total of **37 indicators** grouped into **six thematic categories**:

- Water Resources Management (9 indicators)
  Focused on water supply, per capita availability, and water resource planning, including desalination and groundwater use.
- Agricultural Water Management (11 indicators)
  Monitoring modern irrigation technologies, crop water consumption, areas under water-efficient cultivation, and farmer training.
- Wastewater Management (7 indicators)
  Addressing the quality, treatment, and reuse of industrial and domestic wastewater and performance of drainage systems.
- Environmental Monitoring (5 indicators)
  Targeting water quality in sensitive ecosystems, including lakes, and identifying regions at risk from sea-level rise.
- Water Infrastructure (3 indicators)
  Focusing on the functionality of canals, wells, and network losses in drinking water distribution systems.
- Public Awareness and Capacity Building (2 indicators)
  Measuring training of professionals and awareness campaigns addressing climate resilience in water use.

Methodology for Oasis Climate Assessment

To assess the effects of climate change on the Dakhla and Kharga Oases, this study relies on a scientifically rigorous and data-driven approach that integrates historical climate data, geospatial visualization, and statistical analysis. The methodology is designed to produce robust and replicable insights into climate dynamics over more than a century (1901–2023), focusing on variables that directly impact water availability, soil conditions, and ecosystem stability.

Data Sources

The primary source of historical climate data used in this study is the **TerraClimate database**, a high-resolution, global gridded dataset that provides monthly climate and climatic water balance data for global land surfaces. TerraClimate combines time-varying data from sources such as **CRU Ts4.0** and **JRA-55 reanalysis datasets** with high-resolution climatological normals from **WorldClim versions 1.4 and 2.0**. These datasets are further refined through **climatically aided interpolation** to produce monthly records for precipitation, temperature (minimum and maximum), solar radiation, vapor pressure, and wind speed.

Additionally, derived water balance variables such as **evapotranspiration**, **climatic water deficit**, **runoff**, **soil moisture**, and **snow water equivalent** are computed using a plant-extractable soil water capacity model. All data are provided in NetCDF (.nc) format, making them compatible with a wide range of scientific computing environments.

Variables Assessed

The analysis focused on climate indicators most relevant to arid land management and groundwater-dependent ecosystems, including:

- Average, maximum, and minimum **temperature**
- Precipitation and number of rainy days
- Potential evapotranspiration
- **Soil moisture** levels
- **Wind speed** and direction
- Cloud cover and vapor pressure
- Ground frost frequency

These variables were selected because of their strong influence on water availability, crop viability, groundwater recharge, and thermal stress.

Analytical Tools and Process

To manage and interpret the complex multi-dimensional datasets, the study employed a three-stage analytical framework as shown in Figure 3:

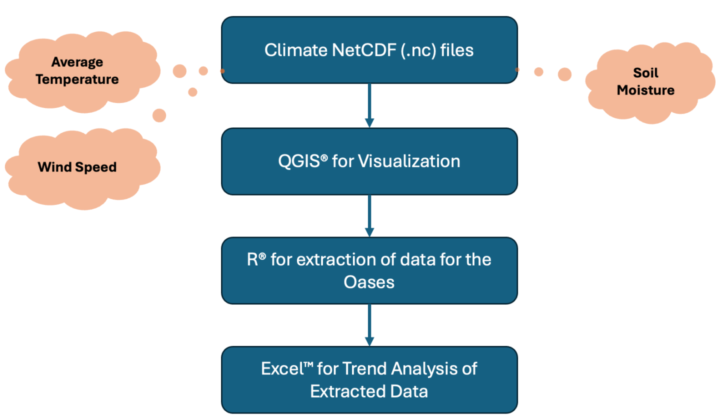

Figure 3. Outline of the Analytical Process used to assess Climate Change in the Dakhla and Kharga Oases. Source: The Author

- Geospatial Visualization (QGIS®)
  High-resolution raster layers were visualized using QGIS®, a leading open-source Geographic Information System (GIS). Spatial layers for temperature, precipitation, and soil moisture were mapped over time to detect geographic trends and anomalies.

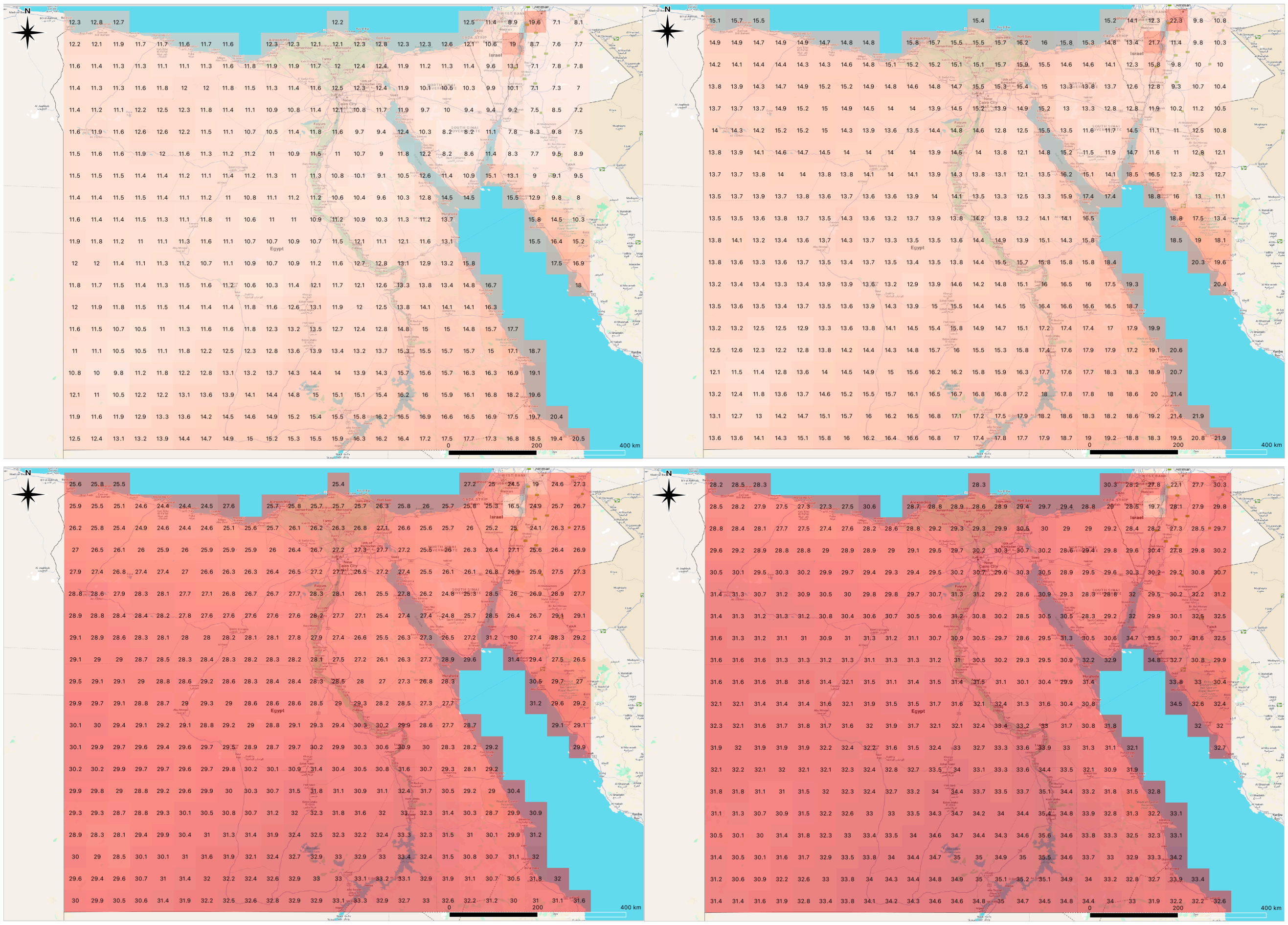

Figure 4. QGIS® projection for Average Temperature. Upper left: Average Temperature on January 15th 1901. Upper right: Average Temperature on January 15th 2023. Lower left: Average Temperature on July 15th 1901. Lower right: Average Temperature on July 15th 2023.

- Data Extraction and Processing (R® and RStudio™)
  Using the R® programming language and RStudio™ interface, time-series data were extracted for Egypt, with a particular focus on the Dakhla and Kharga Oases. Climate values were sampled at pixel points corresponding to the coordinates of the oases (Figure 5). The data were cleaned, restructured, and compiled into climate profiles for each variable.

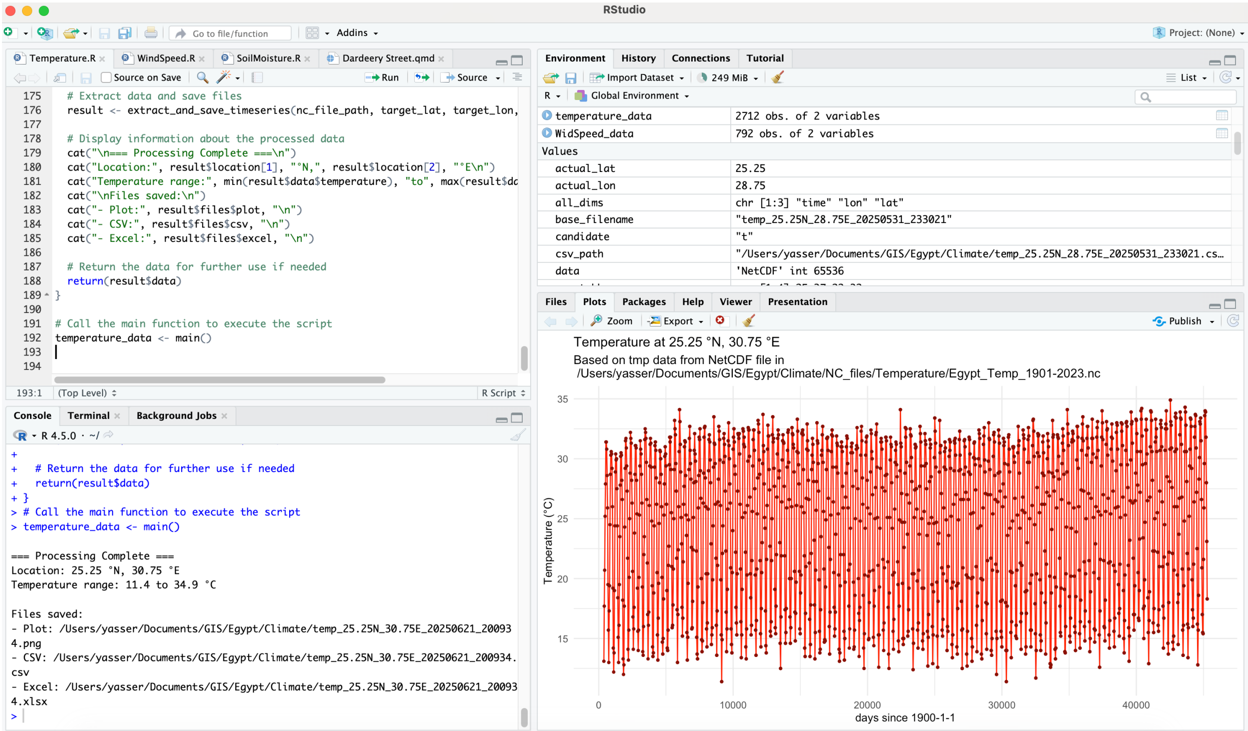

Figure 5. Data extraction and analysis using R® script for specific coordinates
Source: The Author.

- Trend Analysis and Plotting (Excel® and R®)
  Time-series plots were generated to compare climate conditions across selected years (e.g., 1901 vs. 2023), and between months with climatic significance (Figure 6). Visual comparisons were supported by basic statistical trend lines to demonstrate directional changes.

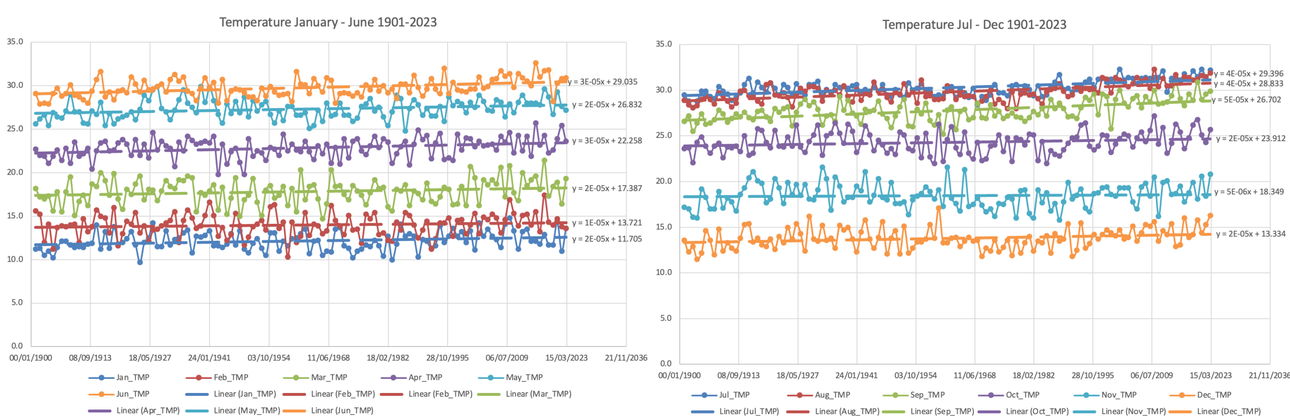

Figure 6. Analysis of Average Temperature during the 12 months of the year for the period of 1901 - 2023, based on the extracted data for Dakhla Oasis. Upper left graph: Monthly trend for January – June. Upper right graph: Monthly trend for July – December.
Source: The Author

Spatial and Temporal Resolution

The TerraClimate data used in this study offer a spatial resolution of approximately **4 km² per grid cell**, which provides meaningful granularity for local assessments in isolated desert areas. Temporal resolution is **monthly**, covering a period of over 120 years. This scale enables the detection of decadal shifts and inter-annual variability—both critical for long-term adaptation planning.

Findings for Dakhla and Kharga Oases

The application of long-term climate data to the Dakhla and Kharga Oases reveals significant environmental transformations that have occurred over the past century. We can observe -for example- that the slope of the linear function for all the trend lines is positive, which confirms the visual observation that throughout the 120 years, an increase in temperature is observed. These changes are not only statistically significant but also materially impactful in terms of water resource management, land use planning, and community resilience. The data confirm that the Western Desert oases are experiencing climate stress at a magnitude higher than the global average.

Temperature Trends: A Marked Warming

One of the most prominent findings is the **persistent increase in surface temperatures** in both oases. Comparative analysis between 1901 and 2023 shows a rise in average temperatures ranging from **3°C to 6°C**, depending on the season and location. For instance, January temperatures have increased significantly, indicating warmer winters, while July data reflect more intense and prolonged summer heat.

This level of warming far exceeds the global average, which is estimated at approximately **1.1°C** since the pre-industrial period. In arid and semi-arid zones like Egypt's Western Desert, localized warming often progresses more rapidly due to surface albedo effects, reduced vegetation cover, and intensified desertification processes.

Such increases in temperature have cascading effects, including:

- Elevated **evapotranspiration rates**, leading to greater irrigation demand
- Increased thermal stress on crops and livestock
- Higher energy demand for cooling in residential and agricultural systems

Soil Moisture Depletion: A Critical Indicator

The analysis of soil moisture trends from 1957 to 2023 shows a **steady and concerning decline**. Soil moisture is a critical determinant of agricultural viability in desert regions. Reduced moisture levels indicate a decrease in the soil's ability to retain water and support vegetation, especially in reclaimed or marginal lands.

Declining soil moisture affects:

- Crop rooting depth and germination rates
- Nutrient cycling and soil microbiome health
- Increased vulnerability to wind erosion and surface crusting

The combination of high temperatures and low moisture is particularly dangerous in areas undergoing land reclamation, as it can reverse years of agricultural investment if not managed adaptively.

Wind Speed: Subtle but Notable Trends

The data covering wind speed between 1957 and 2023 show **no dramatic increase or decrease**, but a slight **declining trend in average wind intensity**—consistent with the global "stilling" phenomenon, where surface wind speeds have gradually reduced due to changes in land surface roughness and atmospheric circulation.

Although less immediately impactful than temperature or soil moisture, wind trends have implications for:

- **Dust transport and sand dune activity**, especially near archaeological and heritage sites
- Passive cooling systems and wind energy feasibility
- Evaporation rates from open water surfaces and reservoirs

Spatial Visualization and Temporal Comparison

The visual comparison of raster layers from 1901 and 2023—using QGIS and R—reinforces the analytical trends. Maps of January and July temperatures clearly show warming across both oases (Figure 4). These visualizations are essential for communicating risk to policymakers and stakeholders unfamiliar with raw data formats.

Overall, the data suggest that Dakhla and Kharga have become **hotter, drier, and more exposed** to long-term climate volatility. These findings confirm the urgent need for proactive adaptation, particularly in the domains of **water resource planning, agricultural system design,** and **groundwater sustainability monitoring.**

Conclusions and Takeaways

This study underscores the urgent and intensifying challenges that climate change poses for Egypt's water security, particularly in fragile and ecologically sensitive environments such as the Dakhla and Kharga Oases. By analyzing over 120 years of climate data—covering temperature, precipitation, evapotranspiration, and soil moisture—it becomes evident that these oases are experiencing disproportionately high levels of environmental stress compared to both the national and global averages.

Climate Change Is Not a Future Threat—It Is a Present Reality

The data confirm that climate change is no longer a distant or theoretical issue for Egypt. Increases in surface temperature ranging from 3°C to 6°C over the past century in the Dakhla and Kharga regions demonstrate that the warming is both real and accelerating. These figures exceed global averages and are already affecting ecological systems, water demand, and agricultural productivity.

This reality calls for a dual approach:

- **Mitigation**, to reduce Egypt's contribution to global greenhouse gas emissions, particularly through transitions in the energy and transport sectors, and more important
- **Adaptation**, to build local resilience, especially in water-dependent sectors such as agriculture, urban development, and ecosystem management.

The Western Desert Oases: Sentinels of Environmental Change

Dakhla and Kharga are not only geographically isolated; they are also strategically significant. They contribute to Egypt's vision for land reclamation, rural development, and food security beyond the confines of the Nile Valley. As such, these oases act as "climate sentinels"—revealing the limits and consequences of expanding human activity in hyper-arid zones.

The findings—particularly the steep rise in temperatures, decrease in soil moisture, and vulnerability of groundwater—suggest that development in these areas must proceed with caution. Continued land reclamation and agricultural expansion without comprehensive impact assessments could lead to ecological overshoot, resource depletion, and eventual socioeconomic strain.

Policy Is Moving in the Right Direction—but Gaps Remain

Egypt has shown notable progress in building institutional frameworks for climate adaptation. The Monitoring and Evaluation (M&E) system represents important steps in making climate resilience measurable, trackable, and actionable. Additionally, initiatives embedded in Egypt Vision 2030 and the National Climate Change Strategy 2050 aim to institutionalize adaptation across sectors.

However, several gaps persist:

- **Data Gaps**: There is a lack of high-resolution, localized, and real-time climate data across rural and desert regions.
- **Implementation Gaps**: Many adaptation policies remain underfunded or fragmented across institutions.
- **Capacity Gaps**: Local communities, especially in rural oases, require enhanced training and tools to manage climate-related risks independently.

Bridging these gaps requires investment not only in infrastructure but also in knowledge systems, community empowerment, and integrated governance.

Recommendations: Strategic Priorities Moving Forward

Based on the findings of this study, the following recommendations are proposed:

- Expand Groundwater Monitoring

Install real-time monitoring systems for aquifer levels and salinity across Dakhla and Kharga. Data should be open-access and used to model depletion rates and sustainable extraction thresholds.

- Develop Localized Water Budgets
  Each oasis should have a localized, GIS-based water budget diagram that quantifies all inflows, outflows, and losses—integrating data from climate projections, human use, and ecological needs.
- Evaluate the Climate Footprint of Reclamation Projects
  Reassess large-scale agricultural and settlement schemes in arid zones with climate impact assessments that evaluate long-term sustainability under different warming scenarios.
- Enhance Climate Education and Public Awareness
  Expand awareness campaigns and training programs in oasis communities on climate-smart agriculture, water conservation, and climate risk preparedness.
- Promote Innovative Solutions
  Explore cutting-edge adaptation technologies such as:
  - Atmospheric water harvesting from air humidity
  - **Green desalination** powered by solar energy
  - **Nexus-based solutions** integrating water, energy, and food systems in circular models
- Design for Flexibility and Uncertainty
  Climate adaptation planning must embrace **flexible, scenario-based design** that allows for mid-course corrections based on new data and evolving climate conditions.

Toward a Resilient Oasis Development Model

Ultimately, Egypt's experience with the Dakhla and Kharga Oases can serve as a test case for arid-region adaptation models across the MENA region and beyond. By combining traditional knowledge, modern science, and policy innovation, Egypt can build a roadmap for resilient, inclusive, and ecologically sound development in one of the world's most water-stressed regions.

Acknowledgment

The main driver behind the development of the current study was an invitation from Prof. Erina Iwasaki, and Prof. Naoko Fukami from Sophia University in Tokyo – Japan to hold a half a day seminar on the water issues of the Egyptian Oases during the first week of June 2025.

Hence, the author would like to thank Sophia University and in particular professors Iwasaki and Fukami for the motivation and the invitation to present this work at Sophia University on the 5th of June 2025.

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