Palacký University Olomouc

University of Clermont Auvergne

University of Pavia

MASTER THESIS

Resilience thinking within water, energy and food nexus in a drought prone area: A GIS based analysis for solar irrigation suitability

Eniololade Giwa

Supervisors
Professor Maria Sassi - University of Pavia
PD Dr. agr. Stefan Sieber - The Leibniz Centre for Agricultural Landscape Research (ZALF)

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BY

Eniololade Giwa

Supervisors
Professor Maria Sassi - University of Pavia
PD Dr. agr. Stefan Sieber - The Leibniz Centre for Agricultural Landscape Research (ZALF)

DECLARATION

I, Eniololade Giwa hereby declare in lieu of oath, that I wrote this thesis titled "Resilience thinking within water, energy and food nexus in a drought prone area: A GIS based analysis for solar irrigation suitability" and submitted to the GLODEP consortium May, 2022. All information gleaned and literature reviewed from the work of others has been duly acknowledged with an in-text reference and end of text references provided in the document.

Eniololade Giwa

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Zásady pro vypracování

Water, energy, and food are necessary resources for wellbeing and economic development. The physical and economic access to these resources in most Sub-Saharan countries remains very low while the outbreak of COVID-19 is projected to worsen the situation. Resilience thinking is increasingly promoted to address some of the grand challenges of the 21 st century: providing water, energy, and food to all, while staying within the limits of the Earth system that is undergoing (climate) change. Concurrently, a partially overlapping body of literature on the water –energy –food (WEF) nexus has emerged through the realization that water, energy, and food systems are intricately linked —and should therefore be understood and managed in conjunction.

Transforming food systems is among the most powerful ways to make progress towards all 17 SDGS. Meanwhile millions of people have been left behind in the global development spur. Today still, three in ten people, i.e., 2.1 billion, are lacking access to safe drinking water and six in ten lack safely managed sanitation facilities (UN-WWAP, 2019); nearly one billion people remain deprived of electricity (OECD and IEA, 2018); more than 820 million people have insufficient food, and many more consume unhealthy diets that contribute to premature death and morbidity (Fears et al., 2019; Willett et al., 2019). Both the negative environmental impacts and insecurity of water, energy and food supply are expected to worsen in the near future, driven by population growth, increasingly resource-intensive lifestyles and vulnerabilities to disruptive shocks including climate change (Hoekstra and Wiedmann, 2014; Steffen et al., 2018).

The research seeks to identify factors influencing the dissemination and sustainable adaptation of climate-smart, water- and energy-efficient innovations by food system actors in Sub-Saharan Africa.

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doc. RNDr. Martin Kubala, Ph.D. děkan	**doc. RNDr. Pavel Nováček, CSc.** vedoucí katedry

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ABSTRACT

Insecurity of water, energy and food are expected to worsen due to population growth, intensive resource use and vulnerabilities to climate change. Solar energy is attractive because of its potential to deliver equally on water-energy-food security triad and is spreading as a solution to both energy and climate concerns in agriculture. Meanwhile, private actors and public agencies mostly lack information and tools about resource availability and suitability which would enable or disenable sustainable solar irrigation investment. By employing a Geographic Information System (GIS) multi-criteria decision model (MCDM), this study puts pastoralists at the fore and identifies resource suitability of small-scale solar irrigation. It draws on cases of two Arid and Semi-Arid Lands (ASAL) of Turkana and West-pokot, Kenya who are not only drought-prone but resource conflict zone and trans-boundary routes. Groundwater availability and surface water accessibility is the driving factor for analysis; the results showed that groundwater up to 7m, groundwater up to 25m and surface water has a total suitability of 10%, 11%, and 51% respectively. Depending on the technical pump capacity, between 8,102km^2 to 40, 548km^2 would be suitable for solar irrigation and provide pastoralists with the option to either pump from small reservoirs, shallow or very shallow groundwater.

KEY WORDS: *Solar irrigation, Multi-Criteria Decision Model, GIS, Resilience, Drought, Pastoralism*

ABOUT ZALF

The Leibniz Centre for Agricultural Landscape Research (ZALF), an institution of the Leibniz Association.

Mission of ZALF is to deliver solutions for an economically, environmentally and socially sustainable agriculture – together with society. As a contribution to overcoming global challenges such as climate change, food security, biodiversity conservation and resource scarcity, According to its statutes, ZALF serves "the public welfare by communicating scientific insights to the relevant sections of the population, technical communities and business circles". ZALF research stands explicitly for scientific excellence and social relevance.

Structure at a Glance (Research Areas)
ZALF derives its research questions from societal questions which are of high relevance in agricultural landscapes. They are addressed in three interdisciplinary Research Areas (RA), which are closely interlinked via topical and methodological interfaces. There are twenty working groups spread around three research areas which are "Landscape Functioning" , "Land Use and Governance" and "Agricultural Landscape systems"

Working group - "Land Use in Developing Countries"
I joined the Leibniz Centre for Agricultural Landscape Research (ZALF) in Muchenberg, Germany as a Research Intern. I am integrated into the research area 2 "Land use and Governance" and working group "Land Use in Developing Countries". The working group Sustainable Land Use in Developing Countries (SusLAND) focuses on the analysis of land use and landscape systems in emerging and developing countries. Emphasis is placed on questions regarding the avoidance of land use conflicts, the improved adaptation to climate change, food and nutrition security, and the stabilization of the livelihood of family farms. The working group operates in Sub-Saharan Africa, Latin America and South Asia and focuses in particular on resource economics in combination with natural sciences, thus ensuring an interdisciplinary integrated research approach.

Project - WEare4F
My research focused on one of the ongoing research projects within the working group and in collaboration with Water and Energy for food (WE4F) Grand challenge for development. Accompanying and evidence-based research within the water, energy, and food nexus to support the provision and dissemination of economically viable, climate-smart, energy- and water-efficient innovations among SMEs and smallholder farmers in East and West African food systems. It is perfectly aligned with my career ambition which has spurred my deep interest in writing my Master's thesis within this research domain. This experience furnished me with an interconnected blend of theory and practical applications for the right balance of innovation, and a springboard to reach my professional and personal goals.

Project Leader ZALF**:** Dr. Stefan Sieber; Dr. Götz Uckert

Participating institutions (extern)
- Deutsche Gesellschaft für internationale Zusammenarbeit
- Universitäten Elfenbeinküste
- Universitäten in Kenya

Executing agency
- Deutsche Gesellschaft für internationale Zusammenarbeit

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
ASALs	Arid and Semi Arid Lands
DEM	Digital Elevation Model
FAO	Food and Agriculture Organisation of the United Nations
GDP	Gross Domestic Product
GIS	Geospatial Information System
GIZ	Deutsche-Gesellschaft fur international Zesammenarbelt
IDDRSI	IGAD Drought Disaster Resilience Sustainability
IGAD	Intergovernmental Authority on Development
IPC	Integrated Food Security Phase Classification
IRENA	International renewable energy agency
IWMI	International Water Management Institute
MCDM	Multi-Criteria Decision Model
NDMA	National Drought Management Authority
PV	Photovoltaic
SPIS	Solar Powered Irrigation Systems
SRTM	Shuttle Radar Topography Mission
SSA	Sub – Saharan Africa
UTM	Universal Transverse Mercator
WBG	World Bank Group
ZALF	Leibniz-Zentrum fur Agraralandschaftsforschung (ZALF) e.V

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CHAPTER ONE: INTRODUCTION

This chapter provides sections that highlight the background of the study, the ‘unique challenges’ facing ASAL Kenya and adaptation strategies, the problem statement, purpose of the study, the significance of the study and the policy context. Furthermore, it sheds more light on the scope of the study and some limitations encountered during the study accompanied by the organization (outline) of the study.

1.1 BACKGROUND OF THE STUDY

Historically, pastoralism and agro-pastoralism are predominant livestock production systems in the Arid and Semi-Arid Zones. Consequentially, the pastoralist way of life is at risk posed by droughts of increasing frequency and severity. Several factors are making the people living in these zones more vulnerable to climatic shocks such as droughts. Across the eastern Horn of Africa, an estimated 13 million people are faced with acute food insecurity and severe water shortages due to drought. Following three consecutive poor rainy seasons, millions of families’ harvests have failed, and millions of their livestock are emaciated or dead (WFP, 2022). Arid and semi-arid lands are climate change hotspots (IPCC, 2007), where climate change is already having significant and documented impacts, such as longer and more frequent droughts and unreliable rainfall, what has been described as the ‘triple whammy’ of semi-arid regions (Mountfort, 2015). As of January 2022, the most severely affected regions are the southern and south-eastern pastoral areas of Ethiopia, the Arid and Semi-Arid (ASAL) regions of Kenya, and large swathes of south-central Somalia (Edithe, 2022).

1.2 THE ‘UNIQUE CHALLENGES’ FACING ASAL KENYA AND ADAPTATION STRATEGIES

Most of Kenya’s land area is classified as arid or semiarid, much of which is suitable for pastoral activities (Odera et al. 2013). These areas are steppe, dry savannas and tropical scrublands with scattered grazing lands (Abuya et. al, 2019). They have typically high seasonality and annual variability in climatic parameters especially rainfall (Mekonnen & Hoekstra 2014) and temperatures with high rates of evapo-transpiration (Abuya et. al, 2019).

In Kenya, the ASALs occupy 89% of the country and are home to about 14 million people which accounts for one-third of its people (the Republic of Kenya, 2012) and approximately 70% of the national livestock herd (Alois David & Munguti K. K., 2013). Drought is the single most important natural hazard in Kenya which may lead to a decline in food production, affect the migratory patterns of pastoralists, exacerbate resource-based conflict, cause substantial loss of assets, triggering acute food insecurity, shattered livelihoods, hunger, nutrition-related disease and even death among vulnerable households and placing a heavy strain on both the local and national economies (Birch, I. 2018).

Migration is one of the primary ways in which pastoralists and agro-pastoralists have historically adapted to spatial and temporal variation in rainfall and vegetation. The farming communities usually adopt a routine migration pattern to other regions in search of pasture and water for their livestock. Therefore, seasonal mobility is a critical element of their livelihood (Oucho and Gould, 1993; IOM, 2010; Frouws, 2015; World Bank, 2015a). On the other hand, migration and growing populations strain available natural resources, leading to insecurity and conflicts commonly witnessed between and among livestock farmers, and agro-pastoral groups (De Souza et al., 2015, Daily Nation, 2017).

Worldwide, off-grid solar photovoltaic irrigation is currently being developed with the expectation that it will help secure water access to increase food production, reduce fuel-based carbon emissions and energy costs, and increase human resilience to climate change (Lefore, N., Closas, A., & Schmitter, P. 2021). After 30 years of attempts to develop ASAL, some experts now feel that the approach should be centred on understanding traditional risk avoidance strategies of the pastoralists and attempting, through the introduction of broader knowledge and improved technologies to reduce the risks involved in the ASAL region. It can be accomplished by diagnosing the areas where the risk is greatest and by introducing appropriate technologies that could help to reduce the risk. The technologies should be simple, small scale, transferrable, cheap and with chances of demonstrating results to be acceptable by the people. This should eventually evolve into an 'improved' form of pastoralism.

1.3 PROBLEM STATEMENT

Inadequate availability and lack of access to water source makes it difficult to keep livestock for a long time in an area to utilize forage resources sufficiently. Consequently, it causes heavy grazing pressure as a result of large numbers of animals depending on the few water points and also causes intense pressure on soils within the kilometres of a water point. In pastoral areas, household income and food access are increasingly constrained due to atypical livestock migration, increased insecurity from resource-based conflict and terrorism, reduced milk production and consumption, reduced livestock sale values, and high staple food prices, driving Crisis (IPC Phase 3) outcomes. (FEWSNET, 30 Apr 2021).

The October to December 2021 short rains have largely failed, marking the third consecutive below-average season across pastoral and marginal agricultural areas of eastern and northern Kenya(FEWSNET, 2021). Following a significant deterioration from the previous analysis, an estimated 3.1 million people (20% of the population in Kenya’s ASALs region) were classified in IPC Phase 3 (Crisis) or above acute food insecurity in February 2022 (IPC, 2022). Compared to the same period in 2021, there was an increase from 1.4 million to 3.1 million people classified in IPC Phase 3 (Crisis) and IPC Phase 4 (Emergency) (IPC, 2022).

For the current period of analysis, the livestock body condition for all species remained fair to poor with decreased milk production and livestock prices across the counties. The poor livestock body condition was attributed to three consecutive failed seasons, which resulted in a shortage of forage and water as well as long trekking distances from grazing areas to watering points (IPC, 2022). Livestock deaths were reported across several counties, with an estimated over 1.5 million heads of animals that died (IPC, 2022). This loss contributes to the already high vulnerability of pastoralists to environmental hazards and economic shocks.

The adaptive capacity of the agricultural sector to climate change in Kenya is low mainly due to limited economic resources for investment in more resilient production systems, low levels of technological development or adoption of developed technology, heavy reliance on rain-fed agriculture, frequent droughts and floods among others (Wakeford, J. J. 2017). Therefore, to sustainably adapt and mitigate the challenges, there is a need to transition communities that are food-aid-dependent into more resilient food secure and income-earning households using climate-smart agriculture such as the pilot project of solar-driven irrigation system for pasture and fodder production in Kenya.

Irrigation proves effective in mitigating the impact of climate change by providing more system predictable water supplies (GGGI 2017; IRENA 2016; FAO 2011). Yet, the heavy usage of diesel emanates so much CO2 that, in turn, accelerates climate change. Efforts have been made to reduce the investment cost of solar-powered irrigation systems (SPIS); subsidy schemes are implemented and rolled out for both large and small-scale farmers to have access to SPIC and hence making it a viable option. Irrigated pasture and alternative feed systems are underdeveloped in ASALs (Abuya, R., Atela, J., Muhwanga, J., Said, M., Moiko, S., Atieno, F., ... & Bedelian, C. 2019). Pastoralism are viable livelihoods that will remain the bedrock of dryland economies and should appropriately be strengthened with appropriate sites for rehabilitation and/or development of strategic livestock water sources, an adaptation of good practices for fodder production and commercialization, and rehabilitation of natural rangelands.

1.4 PURPOSE OF THE STUDY

The general objective of the study is to analyze and identify solar irrigation hotspots for strategic pastoral drought resilience planning in the ASAL region of Kenya. By employing a GIS-based multi-criteria evaluation, the purpose of this project is to identify the suitability (The quality of being appropriate and desirable for a particular purpose, condition or situation) of small scale solar irrigation particularly suited for pasture/fodder production/rangeland rehabilitation to potentially reduce the vulnerability of ASAL communities dependent on livestock for their livelihoods.

Hence the research seeks to answer the following research question:

1.5 MAIN RESEARCH QUESTION

What is the geophysical suitability of an off-grid solar powered pumping system in drought-vulnerable Turkana and West-Pokot counties of Kenya?

Specific research question

What is the suitability of a small-scale solar irrigation system for pasture production in Turkana and West Pokot using groundwater abstraction at a depth of 7m?

What is the suitability of a small-scale solar irrigation system for pasture production in Turkana and West Pokot using groundwater abstraction at a depth of 25m?

What is the suitability of a small-scale solar-powered irrigation system for pasture production in Turkana and West Pokot using surface water?

1.6 JUSTIFICATION OF THE STUDY

As solar panels become more affordable, solar photovoltaic (PV) pumps have been identified as a high potential water-lifting technology to meet the growing irrigation demand in sub-saharan Africa (SSA) (Schmitter, P., Kibret, K. S., Lefore, N., & Barron, J. 2018). Development partners, researchers and policy makers are proposing PV solar energy-based pumps as a ‘cost-effective’ and ‘clean’ approach to irrigation in developing countries (FAO and GIZ 2015). They hold that solar energy-based pumps offer an inexpensive alternative to electric or fuel-based irrigation pumps (IRENA 2015) enabling farmers to overcome energy-related access and cost constraints in implementing irrigation.

This paper conducts a case study of Turkana and West-Pokot in ASAL Kenya - a dynamic, lower-middle-income ‘frontier’ economy that is of particular interest for several reasons (Wakeford, J. J. 2017). First, the country is acutely vulnerable to climate change and variability, given its geographical location in East Africa and its dependence on largely rain-fed agriculture for nearly one-third of its GDP**.** Secondly, Kenya has been a major front runner within the African continent in the development of renewable energy**.** While the potential benefit of small-scale irrigation appears remarakable, it is constrained by access to the energy sources needed to pump water and the limited opportunities for gravity-fed small-scale irrigation systems (IWMI, 2018). Any action to promote solar-powered irrigation investments requires a consideration of a number of interrelated components. These include suitability mapping (biophysical factors, water availability, infrastructure); environmental sustainability; institutional, policy and regulatory context; finance mechanisms; technology supply chain; and economic sustainability. While any of these components can influence the decision of potential investors to support solar irrigation enterprises, biophysical suitability is by far the most important. If an enterprise is to succeed, it must have access to sufficient resources (e.g., solar energy, access to land and water resources, and physical and market infrastructures, such as roads and marketplaces).

With the increasing interest in irrigation expansion schemes for smallholders in the study area, it is imperative to carry-out suitability mapping, to ensure that such programs target the most needy pastoralist, with respect to their specific location and implement the right technologies. Understanding the suitability of an area for solar irrigation technology also helps investors to estimate potential market size and boundaries. However, little is known about the geospatial potential of solar-based PV pumping for small scale irrigation taking into account not only solar radiation but also the availability of water resources and linkage to markets (Schmitter, P., Kibret, K. S., Lefore, N., & Barron, J. 2018). Enhance the climate resilience of counties in the ASALs and ensure the sustainability of lives.

1.7 POLICY CONTEXT

Unlike neighbouring countries such as Ethiopia, Sudan and Somalia, Kenya is a livestock importer rather than an exporter, and an estimated 22% of the nation's beef is supplied by cattle walked across Kenya's borders (Secretariat, R. E. G. L. A. P. 2012). Although often viewed as physically remote, universally poor, and subject to droughts and conflicts, in reality, pastoralist areas can also be dynamic regional economic hubs, with substantial livestock trade networks to local markets, and, crossing borders, to neighbouring countries (Catley A. 2013).

To influence pathways to resilience, Pastoralists must consider access to rangeland as a top priority, especially for people who rear livestock using mobility. Interventions that facilitate maintenance of migratory movement and that allow access to unused grazing areas remain the most cost-effective ways to mitigate livestock losses during droughts (Leeuw, J. de, Ericksen, P., Gitau, J., Zwaagstra, L. and MacMillan, S. 2011). A policy focus on pastoralism is established for two main points: Firstly, pastoralists are an integral part of those with the least access to infrastructure, services and social benefits. Successful achievement of national and international development targets will depend on the extent to which attention is given to the distinct challenges they face (ASAL policy, 2012). Secondly, governments tend to overlook pastoral areas as they usually underestimate and consider them as areas consuming most of the national wealth with very poor Return on investment (ROI). Although things have turned around now and these areas can no longer be overlooked.

There is a severe consequence of the scarcity of livestock resources as it can trigger more vulnerability to drought and other shocks that could affect the whole population. One of the most inevitable causes is insufficient or availability of quality grazing lands, as a result of continuous rising demographic pressures along with insecure land use acts and/or possession. The increasing recognition that pastoralist systems in the drylands can work with environmental variability, rather than against it, opens up an alternative storyline for global food security under climate change (FAO, 2013). A carefully chosen bundle of appropriate preparedness activities remains the most cost-effective approach to reducing the impacts of shock. ‘Resilience’ has amassed noteworthy traction among the researchers, government, institutes, agencies, and practitioners working across the premise of humanitarian causes and development[1]. The most effective interventions were those that facilitated mobility to provide access to disputed and underutilized grazing lands and water resources. The good news—an increased presence of non-governmental organizations in drought-prone areas substantially improved the speed of information and response, allowing for better and locally embedded management of the drought cycle (Leeuw, J. de, Ericksen, P., Gitau, J., Zwaagstra, L. and MacMillan, S. 2011).

Kenya Vision 2030 states that Kenya will be a country that is firmly interconnected, where no part will any longer be called remote (Anne O.G.W. 2022). This statement is highly significant for the north, where people consistently rank infrastructure as among their top three priorities (NDMA, 2018). Ameliorating infrastructure is germane to opening up the specified region but it must be climate-proofed. This requires that current and future climate risks are factored into the design and implementation of policies, given the cost, significance and anticipated lifespan of infrastructure investments (Anne O.G.W. 2013). The primary policy challenge is how to ensure food and nutrition security sustainably in environments that are prone to drought, where people’s access to and control over critical livelihood resources such as land is insecure, and where climate change will increase unpredictability (Alois Muthini David & Munguti Katui Katia 2013).

1.8 SCOPE AND LIMITATION OF THE STUDY

This suitability mapping puts the pastoralists at the fore by focusing on two ASAL counties (Turkana and West-Pokot) that are not only drought-prone but resource conflict zone and transboundary routes. We do not cover the whole of Kenya but we assume possibilities to advance GIS-based suitability analysis for Solar irrigation intervention in this regard to support planning and long term investments to target areas for up-scaling solar pump-based irrigation, and additional refinements will only make it more reliable and relevant in the future.

We cover proxies for access to livestock market and roads but do not cover a cost and product-based analysis but rely on the assumption of numerous pieces of literature that Solar PV is profitable in the long run. Time limitation to gather on-site data, financial resources to conduct expert interviews for the Analytical Hierarchy Process of assigning weights, and also COVID-19 hampering the project implementation from my organization subjected this research to desktop research. Some hurdles were encountered such as scarcity of data, obsolete data and restrictions to open access data.

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[1] Resilience is seen as a paradigm shift, away from short-term thinking and solutions to address vulnerability to hazards such as drought, toward interventions that, over a longer time, can enhance development and build capacity to deal with dynamic environmental and social challenges and enduring shocks and stresses (Davies, R., & Wroblewski, T. 2014).

It is worthy to note that asides from the rigorous process of finding and accessing GIS data for relevant variables in Kenya, all the maps do not cover a certain area which is the conflicting boundary between Kenya and South Sudan[2]. There are issues surrounding the ownership of the land, hence this has been an area of discourse and not representative in all the input maps that were accessed and downloaded. However, the consistency of exclusion in the raster files offers uniformity and is indicative. Furthermore, the Analytical Hierarchy Process of assigning layer weights could not involve the direct preference of the relevant stakeholders in the study area due to time constraints[3].

The themes embodied in the research are not intended as a wholesome agenda for economic growth in ASALs, but rather reflect prospects for pastoralism and irrigation and within the WEF security framework (Birch, I., 2018).

1.9 ORGANIZATION OF THE STUDY

The study is structured to account for five chapters sequentially. Following this first chapter, a second chapter that focuses on a structured literature review highlights the conceptual, theoretical and empirical framework that underlies this study. The third chapter discusses the methodological and analytical framework, which shall be followed by a fourth chapter that discusses relevant findings and a fifth chapter that focuses on conclusion and recommendation.

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[2] This area is referred to as the Ilemi triangle

[3] However, even though user-defined weights are acceptable with respect to need, this research adopted the most recent AHP weights in the GIS solar irrigation literature.

CHAPTER TWO: LITERATURE REVIEW

This chapter presents an introduction, conceptual framework, theoretical framework, a review of empirical literature and literature gaps.

2.1 INTRODUCTION

This structured literature review is based on both published and unpublished reports, briefs, research articles, scientific journals, conference papers and book chapters. Grey literature and relevant websites of selected UN organizations have complemented this search according to the guidelines of Webster & Watson 2002). The method of a structured literature review was chosen in order to provide a well-founded overview of the current state of knowledge on the research questions and identify possible gaps and contribution to literature.

2.2 CONCEPTUAL FRAMEWORK AND THEORETICAL FRAMEWORK

2.2.1 Kenya context

While reducing the country's economic performance, recurring droughts particularly erode the assets of the pastoral poor, who herd cattle, camels, sheep and goats over dry lands. This repeated erosion of animal assets is undermining the livelihoods of Kenya's pastoral communities, provoking many households into a downward spiral of chronic hunger and severe poverty (Susan MacMillan, 2011). Solar- Powered groundwater pumping systems are the fore-front of pro-poor technologies being promoted for human, livestock and other remote watering applications because they are durable, can be mobile and exhibit long term economic benefits (Van Pelt, R., Weiner, C., & Waskom, R. 2008). Kenya has abundant solar energy sources with an estimated insolation of 5-7 peak sun hours (Ms. Asenath Ndegwa, 2018). The country can utilize this abundance resources as a viable alternative to diesel or electricity for groundwater abstraction and with cost effectiveness.

Drought and conflict are mutually reinforcing. The scarcity of water and pasture experienced during drought periods, and the inter-communal competition over natural resources that results, whether within the pastoral system, between pastoralists and farmers, or between people and wildlife, increases insecurity within Kenya and across its borders (Anne Waiguru, O.G.W. 2013). These stresses are overlaid on other drivers of conflict, such as the subdivision and commercialisation of rangelands, or boundary disputes exacerbated by competitive politics or the discovery of new resources (such as oil in the Kerio Valley). At the same time, insecurity increases vulnerability to drought, by impeding migration, curtailing access to services and resources, destroying assets, and damaging inter-communal relations (Republic of Kenya, 2013). The most vulnerable people in the ASALs have been dependent on relief assistance from the World Food Programme and the Government of Kenya for several decades. The government recognises that emergency food aid is needed to save lives in times of crisis. However, the focus will now be on building community resilience for sustainability, and improving the enabling environment in order to attract investment and promote sustainable growth and development (Republic of Kenya, 2013).

Kenya aims to become a newly industrialized country by 2030, which will require expanding climate change resilience efforts while also increasing its domestic energy production; including through the use of renewable sources (World Bank group, 2020). Adaptation efforts are focused on the country's energy, infrastructure, land use and environment, health, water and irrigation, agriculture, and tourism sectors. (CKP) (Ministry of Environment and Natural Resources 2016). A common observation in the literature is that any programme should be based on a sound understanding of dryland systems (Birch, I. 2018). This matters because of the long history of ill-informed investment, particularly in pastoral areas, that has contributed to their current predicament (Little, 2013; Odhiambo, 2013; Krätli, 2014). The economic potential of pastoralism is routinely under-valued (King-Okumu, 2015; Krätli, 2014). Among the recommendations by Aklilu et al (2013) are: (i) producing fodder for value addition and to reduce drought-related losses, and (ii) improving fodder availability near market centres (Birch, I. 2018).

Member States of the Intergovernmental Authority on Development (IGAD) responded to the drought disaster by mandating IGAD to spearhead the initiative 'Ending Drought Emergencies in the Horn of Africa'. The 15-year IDDRSI strategy coordinates regional activities to improve drought resilience, livelihood opportunities, pro-active conflict prevention and migration governance. Its ultimate objective is to increase the resilience of communities and refugees in the ASAL. Priority areas according to IGAD include disaster risk management, contingency planning, climate change adaptation and mitigation with interventions to enhance drought disaster management in the IGAD Member states, reduced vulnerability to disaster risk in drought-prone communities, strengthening of regional cooperation on community risk reduction and climate adaptation.

2.2.2 Evolution and development of SPIS

The use of solar energy, as a form of renewable energy, fits very well into the Clean Energy Mechanisms. Since 2010 more PV system capacity was installed globally than during the previous four decades (Spooner, 2017). One of the primary drivers for this expansion is decreasing costs (Bloomberg NEF 2019, Kavlak et al., 2018, Hartung and Pluschke, 2018). Solar is now the cheapest form of power in 60 countries (IEA, 2014). Prices have dropped substantially in recent decades, from over USD 60/watt in the 1970's to between USD 0.52 and 0.72/watt in 2016 (IRENA, 2016a). Indeed, lower production costs of PV equipment and government subsidies have popularized this technology; it is now more affordable and attractive to farmers (van Campen et al., 2000; Gopal et al., 2013). The International Renewable Energy Agency (IRENA) predicts a further 59 percent cost reduction for energy generated by solar PV by 2025 (Hartung and Pluschke, 2018).

In the light of challenges encountered by the promotion of electric and diesel-based irrigation since the 1960s and 1970s, the solar-powered irrigation technology has caught the attention over the past decade. In Sub-Saharan Africa (SSA), off-grid solar technology represents a transformative technology in the context of an underdeveloped electricity infrastructure (Szab´o et al., 2013; Wazed et al., 2018). Electric-powered pumps are not always an option since many poor villages in developing countries are beyond the reach of national power grids. Only 5% of rural population in Kenya is connected to the electric grids.

Many actors stand to benefit, from farmers to solar pump suppliers to public agencies. For instance, the use of solar technology in agriculture is increasing - a trend that has the potential to reduce greenhouse gas emissions in a sector under pressure to reduce pollution (IRENA, 2016b). The development of portable and easily operated small capacity pumps is also improving livelihoods in East Africa (e.g., Ethiopia, Kenya), expanding the potential for commercial production, and in some cases, reducing the labour burden associated with traditional surface irrigation (Kunen et al., 2015; Assefa et al., 2021). In addition, smallholder farmers in Ethiopia state a preference for solar, because it lowers labour and time to access water for both domestic uses and food and livestock production (Nigussieet al., 2017). Development partners and international organizations have identified these advantages and the potential win-win scenarios, and as such, have increased their funding to support solar irrigation testing and scaling. Apart from irrigation, solar pumps are also used for providing drinking water for humans and livestock.

2.2.3 Overview of potential and challenges of SPIS

SPIS holds significant potential for short-term recovery for the most vulnerable farmers and, in the longer term, can also help to safeguard domestic food security and strengthen farmers' ability to recover from shocks and adapt to a changing environment. Solar energy is attractive because of its potential to deliver equally on the water-energy-food security triad. Many perceive solar powered irrigation as even transformational by expanding smallholder agriculture production, increasing household water security, and offering solutions for climate smart agriculture development. The technology also reduces greenhouse gas emissions and is, therefore, considered a climate-smart technology within the WEF security nexus which makes solar-irrigation a climate –smart, energy efficient innovation for farmers . The potential for irrigation development to reduce poverty and enable economic growth in sub-Saharan Africa (SSA) (Woodhouse et al. 2017) has been emphasized by policy bodies ranging from the Comprehensive Africa Agriculture Development Programme (CAADP) (NEPAD 2003) to national and sub-national programs.

At the same time, the expansion of solar powered water lifting is often highly contextual with numerous national and sub-national objectives, programs, and projects, varied technologies, and diverse actors across the public and private sectors. Sam Wong analysed if Decentralised, Off-Grid Solar Pump Irrigation Systems in developing countries are Pro-poor, Pro-environment and Pro-women. The PVP literature has reached two general consensus - PVPs help strengthen poor farmers' adaptive capacities by raising their agricultural productivity, improving their household incomes and building social capital. They also help mitigate climate change by replacing diesel with solar energy to reduce CO2 emissions. There is also some evidence to support the positive gendered impact of PVPs on raising women's control of income and diversifying diets, and that improves the overall well-being of their families.

On the surface, solar pumps appear a near-perfect solution to lift millions out of food, energy, and water insecurity and offer a cost-effective alternative to fossil fuel water lifting, as indicated by a continent-wide study of Africa (Xie et al., 2021). However, the lack of an integrated approach to develop solar power-based irrigation is currently a hurdle for appropriate adoption (Ockwellet al., 2018). Furthermore, many caveats remain for solar irrigation development. Groundwater depletion is a major concern, particularly given the current lack of data and regulatory and monitoring systems, as well as weak governance structures. There is also the risk of excluding the majority of resource poor farmers from solar irrigation development and potentially limiting their water access, unless appropriate finance tools, market integration, and targeted initiatives are implemented as solar irrigation expands.

The mainstream approach in the literature tends to compare and contrast PVPs with electric- or diesel-powered irrigation systems over costs, performance and impact. However other paramount arising issues are of concern. Development scholars and practitioners are keen to use the comparison to justify if, and how, the new technology is able to challenge the already operating conventional systems. Yet, the comparative approach is not problem-free. Some researchers have been criticised for taking a binary thinking over 'clean solar versus dirty diesel' or 'efficient solar versus inefficient diesel' (Chandel et al. 2017) and the general consensus in literature is that replacing diesel-based pumps by PVP helps minimise CO2 emissions. The agricultural sector has been considered a big CO2 emitter. 50 to 70% of total emissions are generated from energy activities in the agricultural sector (IRENA 2016). The environmental debate around PVPs has been focused too much on CO2 emissions. Yet, the rising energy-water efficiency, arising from PVPs, has resulted in undesirable environmental trade-offs, such as the depletion of underground water and e-wastes.

Irrigation can affect groundwater cycle, especially groundwater recharge. As EEW (2016) explains, since the operational costs of PVPs are nearly zero, once installed, there is little incentive for farmers to reducing groundwater over-extraction conserve water. Without adequate groundwater recharge, it would lead to unsustainable water consumption, especially in arid and semi-arid regions. The current lack of coordination across diverse stakeholders and objectives within the context of the unsolved issue of groundwater over-abstraction should also not be taken lightly (Closas and Rap, 2017).Yet, the issues of over-extraction are context-specific. Comparing East and West India, GGGI (2017) discovers that a controlled underground water extraction could be beneficial, especially to East India. Being a flood-prone region, PVPs may help lower underground water tables and produce porous alluvial aquifers. They both reduce surface water runoff and risk of flooding.

2.2.4 Solar irrigation and the SDG’s for policy making and inter-sectoral collaboration

The United Nations (UN) has declared 2026 the International Year of Rangelands and Pastoralists, at its Plenary Meeting on 28 February 2022, reflecting the important role healthy rangelands play in creating a sustainable environment, economic growth and resilient livelihoods for communities across the world. Rangelands support the livelihoods and food security of millions of people around the world and have many benefits, not only to herders, but also to other communities through biodiversity conservation, carbon sequestration and delivery of clean water. Pastoralists make the most of a variable environment by using strategic mobility seasonally. Productive rangelands and pastoralism have great potential to deliver on the Sustainable Development Goals (SDGs), and the International Year of Rangelands and Pastoralists represents an opportunity to raise international awareness on these issues of global concern.

In recent years, the complex set of interdependencies among water, energy and food systems – or what is commonly termed the water-energy-food (WEF) nexus – has emerged as a central issue within the overlapping scientific fields of sustainable development and climate change resilience (FAO 2011; Hof 2011; World Economic Forum 2011; Rodriguez, Delgado, DeLaquil & Sohns 2013; Ringler et al. 2013; Stockholm Environment Institute 2014; WWAP 2014; IRENA 2015; Leck et al. 2015).

Governments, development partners and research institutes in MENA and SEA regions have promoted solar irrigation for multiple purposes, aiming to increase energy security, support water access, and increase food production, all with a pro-poor focus to deliver on the SDGs (Rasuland Sharma, 2015; Weitz et al., 2014). Competing sectoral orientations from the energy, water resources and agriculture sectors separately inform the investment in solar irrigation and policies and regulations, impeding the roll out of solar technology on an integrated cross-sectoral level (Closas and Rap, 2017; Marquardt, 2015). Multiple projects scattered across departments and agencies without coordination at the national level result in piecemeal policies, while those policies largely aim at control over the expansion and use of the technology (Marquardt, 2015). In short, there is a mix of sometimes contradictory objectives, including short-term profitability, satisfying equity investors, long-term development goals, and water resource sustainability, among others.

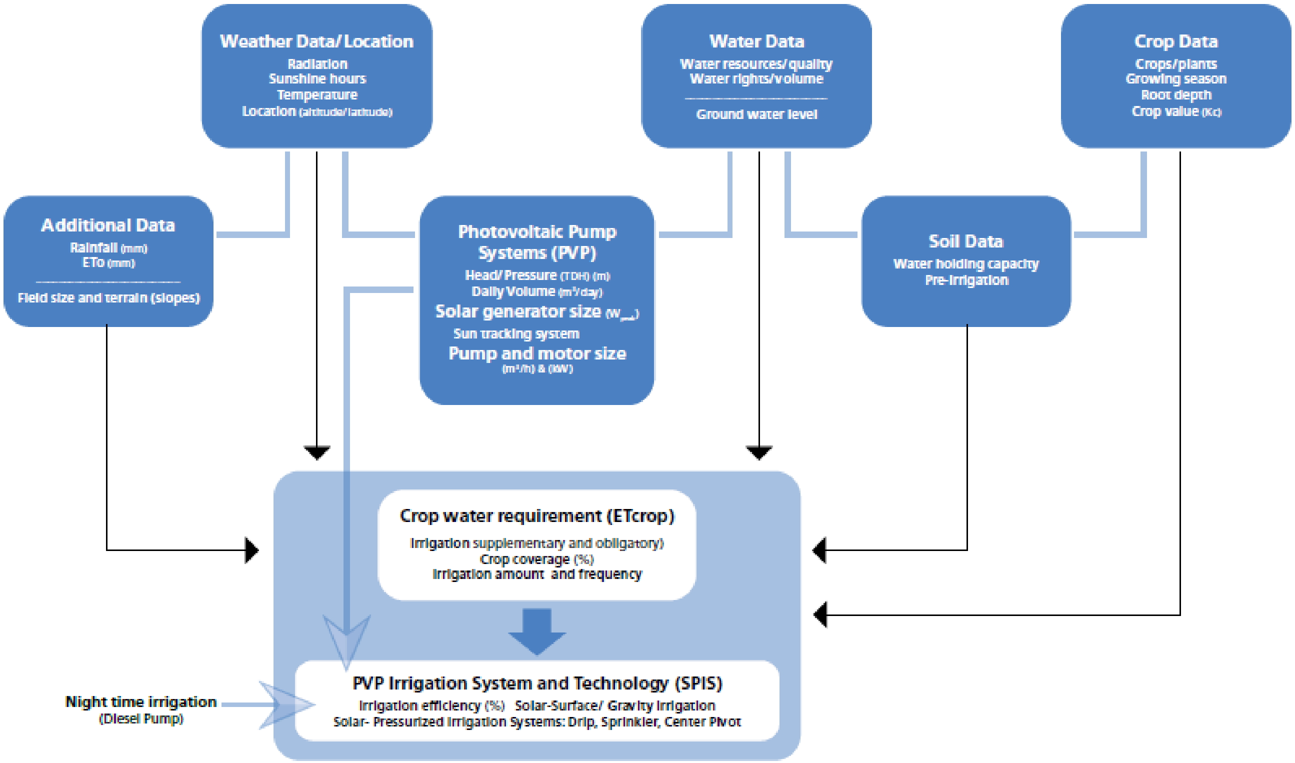
The agricultural sector is a major stakeholder in the efforts to achieve overall water, energy and food security, while also reducing the causes and impacts of climate change (de Amorim et al., 2018). Within the private sector, the energy industry has been leading the push for renewable energy, followed by agriculture and then to a lesser extent water (Leck et al., 2016; Marquardt, 2015). In some areas, private sector initiatives have been much more project-based and therefore short-term oriented, and have overtaken long-term public sector investments in solar irrigation (Agrawal and Jain, 2018; Marquardt, 2015).

2.2.5 Solar Irrigation as a resilience strategy in ASAL drought prone area

In 2011, an extended drought caused a severe famine that impacted more than 13 million people in peripheral arid and semi-arid regions (ASAL) across the Greater Horn of Africa (GHA), prompting renewed calls for a paradigm shift: the focus has shifted from emergency responses to long-term interventions designed to enhance drought resilience in target communities. Surface water and groundwater resources are highly variable throughout SSA and the latest climate scenarios suggest that variability and uncertainty will continue to increase (Gan et al., 2016; Vörösmarty, Ellen, Green, & Revenga, 2005). Hence, with the increasing demand for resilient agricultural solutions in the context of food security and the promotion of irrigation throughout SSA, irrigation technologies are an essential component of climate-smart agriculture.

The current debate over the role of irrigation in social and agricultural development in developing countries has been around the ‘energy-water-livelihood’ nexus, amid issues, such as climate change, food security and renewable energy (Biggs et al. 2015). Resilience thinking is increasingly promoted to address some of the grand challenges of the 21st century: providing water, energy, and food to all, while staying within the limits of the Earth system that is undergoing (climate) change. Irrigation is one of the key pathways for smallholder farmers to build resilience towards climate change (Alemayehu & Bewket, 2017). Concurrently, a partially overlapping body of literature on the water–energy–food (WEF) nexus has emerged through the realization that water, energy, and food systems are intricately linked—and should therefore be understood and managed interdependently.

Figure 1: SPIS Data Requirements For Planning



Source: FAO (2018). Benefits and risks of solar powered irrigation – a global overview

2.3 REVIEW OF EMPIRICAL LITERATURE

2.3.1 GIS for suitability mapping and planning interventions

Meanwhile, private actors and public agencies mostly lack information and tools about water resource availability and suitability factors (Agrawaland Jain, 2018; IRENA, 2016b), which would enable more effective and sustainable solar irrigation investment planning. Geographic information system (GIS)-based mapping has been used effectively to assess suitability and feasibility of each element of the WEF nexus such as renewable energy, water resources or specific crop systems (Akyol, Kaya, & Alkan, 2016 Palmas, Abis, von Haaren, & Lovett, 2012; Szabó, Bódis, Huld, & Moner-Girona, 2011, 2013; Venkatesan, Krishnaveni, Karunakaran, & Ravikumar, 2010; Worqlul, Collick, Rossiter, Langan, & Steenhuis, 2015; Worqlul et al., 2017; Yalcin & Kilic Gul, 2017).

Empirical studies on the GIS suitability analysis in the WEF domain can be grouped into four broad categories which are soil suitability for crop production, suitability for irrigation, suitability for water resource management, suitability for solar resources.

2.3.2 GIS based planning using Multicriteria Decision Model

Multi-criteria decision making (MCDM), first developed by Saaty (1977), and a wide range of related methodologies offer a variety of techniques and practices to uncover and integrate decision makers' preferences into “real world” GIS-based planning and management solutions (Ascough et al.,2002). Various applications of MCDM have been used to assess the potential of agricultural water management strategies for smallholder farmers. For example, Worqlul et al. (2017) used MCDM in Ethiopia to identify 7.5% to 12.4% of potential suitable irrigable land that could be irrigated using groundwater resources. The Food and Agriculture Organization of the United Nations (FAO) (FAO, 2012) has developed and used a multi-criteria GIS framework to map the potential for investments in agricultural water management in SSA.

However, a multi-criteria GIS-based platform has just recently been developed to assess the suitability of solar-based PV pumps for smallholder irrigation (i.e., < 1 ha) in Africa). The general paucity of reliable geo-referenced information for solar irrigation in developing countries hampers analysis and planning. Identifying suitable locations for solar-based irrigation is particularly urgent as various investors consider out-scaling the systems. The suitability mapping can be integrated into planning for overall sustainable irrigation development in SSA, and more specifically, to evaluate possible investments in solar pump business models. The gap in suitability maps for solar-based PV pump irrigation suggests the need to develop and test such methodologies in Africa. Therefore, this brought about the first study (Scmitter et al 2017) of its kind which sought to develop a GIS-based methodology utilizing open source software to evaluate the potential of solar-based PV pumps using shallow groundwater and surface water, and test the performance of the model in Ethiopia.

2.4 LITERATURE GAP

Solar-powered irrigation systems are a generic term, which comprise different systems, such as drip and sprinkler irrigations and their impact could be different. . There are diverse models in promoting PVPs in terms of ownership (individual vs collective/communal approach), payment (daily, weekly, monthly or annually) and organisation (individual vs. groups) which have also made the comparison difficult. For example, the research by GGGI (2017) suggests that PVPs in East India tend to adopt the ‘service-based delivery model with a capital subsidy scheme’, whereas the ‘grid-connected buy-back scheme and solar cooperative model’ is more common in West India. Furthermore, there is a very sparse literature on GIS based land suitability for Solar Irrigation, and more specifically the pastoral farmers are not given a special consideration in solar irrigation planning and intervention in ASAL area and along pastoral route which is what this study seeks to address considering the vulnerability of pastoralists and the losses that they incur. This paper therefore contributing to the literature on SPIS suitability mapping and also streamline it to identifying suitable areas for pasture/ fodder production.

CHAPTER THREE: METHODOLOGY

3.1 INTRODUCTION

This chapter uncovers the study area of focus, data collection method, data source and pre-processing. It further provides sections with spatial information of geo-spatial drivers for solar irrigation. The analytical framework with subsections such as overview, mapping suitability (MCDM and the suitability analysis), with a final schematic diagram of the methodological framework from own elaboration.

3.2 STUDY AREA

The study area focuses on two counties in ASAL Kenya which are the great Turkana and West Pokot respectively[1]. It employs the existence of pastoral and agro-pastoral communities living in arid and semi arid zone of north-western Kenya – an area with a long record of food insecurity and dependent on their livestock for their livelihoods. The Great Turkana is situated in north-western region of Kenya (Turkana county government) within the former Rift valley province. It borders Uganda to the west, Lake Turkana to the east, South Sudan to the northwest and Ethopia to the northeast. The county covers approximately 77,500 km^2 in area and is one of the largest counties in Kenya (Johannes et. al 2014) covering more than 13% of Kenya's surface (Turkana county government). West Pokot is one of the 14 counties in the North Rift along Kenya's western boundary with Uganda border. It borders Turkana county to the North and Northeast. The county covers an area of approximately 9, 169.4 km^2 (County Government of West Pokot 2013)

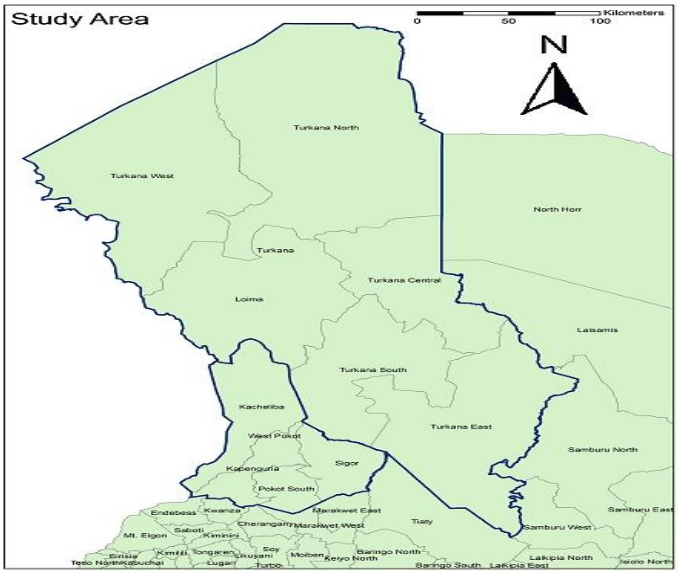


Figure 2: Turkana and Pokot Counties, Kenya[2].

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[1] https://resilience.go.ke/turkana/ [2] https://resilience.go.ke/west-pokot/

3.3 DATA COLLECTION METHOD

The data collection was initiated after identifying the criteria that will influence site selection for SPIS establishment. This study is consolidated on a desktop research; therefore, secondary data collection method was used to obtain relevant data. Input maps selected for the analysis were based on their accessibility (i.e., preferably open source) and relevance for the development of the multi-criteria tool. Five main categories of data were identified to assess the potential of solar PV pumps for surface water and groundwater-based irrigation: (i) Topography (ii) Surface water and groundwater (iii) Land use and land cover (iv) Solar resource (v) Infrastructure

3.4 DATA SOURCE AND PRE-PROCESSING

Data selection focused on geo-physical parameters as well as indicator representing market access. The latter is considered a critical factor providing economic incentives for investment in irrigation development (Schmitter, P., Kibret, K. S., Lefore, N., & Barron, J. 2018). The Arc Gis 10.8.1 was used to pre-process the input data using a common coordinate system Arc 1960 UTM Zone 37N. The vector data layers including road, river, land cover and national park were converted to raster data. As the main objective of the study was to assess the feasibility of solar PV pumps rather than the suitability of irrigable land, the soil suitability input was restricted to the depth of the soil profile by using the depth to bedrock.

3.5 INFORMATION ON GEO-SPATIAL DRIVERS OF SOLAR-BASED IRRIGATION

To identify suitable areas for solar pump-based irrigation, the spatial data that were sourced from a number of international databases include: slope, solar irradiation, elevation, groundwater levels, aquifer productivity, groundwater storage, proximity to rivers, and proximity to town. (see Annex 1).

3.6 ANALYTICAL FRAMEWORK

3.6.1 Overview

The suitability framework developed by IWMI (Schmitter et al. 2018) was deployed for Turkana and West Pokot to assess the potential for scaling solar irrigation pumps. The methodology combines spatial information datasets that are available in the public domain (open source). Areas that are unsuitable for solar irrigation, such as natural parks, forests, and other protected areas are excluded. The suitability maps are pre-processed**,** reclassified and then over-layed using defined weighting factors. The most suitable locations for solar pump-based irrigation in the context of each scenario were identified following the overlay of all the weighted maps assigned with the use of Analytical Hierarchy Process developed by (Saaty 1977) to account for the relative importance of each input map. An important benefit of the suitability mapping methodology is that it allows investors to assign their own weightings, based on their circumstances and priorities.

3.6.2 Technical specifications of solar PV pump

I assessed the suitability of Turkana and West Pokot for solar irrigation using different combinations of solar pump models that differ in dynamic head, and available water resources (surface water and groundwater at different depths) (Gebrezgabher et. al., 2021). Two solar photovoltaic pumps were selected to put into consideration access to land and affordability of the technology,: 0.5 kWh m−2 with a lift capacity of 7 meters (m), and 1 kWh m−2 with a lift capacity of up to 25 m. While there is growing interest in the development of solar PV pump technology for both small- and large-scale farming, this study focused on small scale irrigation options.

3.6.3 Scenario specifications

In total, three scenarios were established to assess the suitability of solar water-lifting devices in the study area. From the three scenarios, two accounted for groundwater, one for only surface water (i.e., rivers and small water bodies). Scenario 1 included groundwater depths up to 25m divided into two classes (0–7 m; 7.1–25 m); Scenario 2 considered very shallow groundwater (0–7 m) levels; Scenario 3 only accounted for the proximity to rivers or small reservoirs. Based on these specifications, suitability was assessed for three different scenarios according to available water sources and water depths in the case of groundwater source.

3.6.4 Mapping suitability (Multi-criteria Model Development, AHP and the suitability analysis)

This study developed a multi-criteria model within the organizations's (ZALF) licensed GIS environment (i.e., ArcGis 10.8) to assess the geo-spatial suitability of solar PV pumps for use with shallow groundwater, very shallow groundwater, as well as from surface water. The solar irrigation suitability analysis framework was developed using a GIS-based Multi-Criteria Decision Model (MCDM). The multi-criteria evaluation was implemented by combining spatial information from a number of geospatial drivers for solar based irrigation. Generally, a multi-criteria model has been applied to determine suitable sites for large-scale photovoltaic farms (Mahtta et al., 2014), smallholder irrigation or even ecotourism (Nino, Mamo, Mengesha, & Kibret, 2017; Worqlul et al., 2015, 2017). It has been used to identify the most suitable sites for agricultural productivity (Emre Ozsahin & Mehmet Ozdes

2021)[1], irrigation agriculture (Aldababseh et. al, 2018)[2] and SPIS installation (Sheila et al., 2020)[3]. The suitability analysis was carried out through three major steps: (i) excluding areas that are not suitable for solar application (ii) reclassifying to suitable classes for each suitability factor and (iii) pair-wise ranking and weighting of reclassified input maps.

I. Constraints formulation (Unsuitable areas for solar PV)

The first step in suitability mapping will be to identify the variables that are likely to constrain solar pump-based irrigation. This constraint layer was developed to differentiate areas that would be suitable for solar based irrigation from those that cannot be suitable under any condition. Protected zones, forests, areas with low groundwater storage or inadequate irradiation. The minimum irradiation requirements of 0.5 kWh m−2 resulted in excluding irradiation below 1,300 kWh m−2 y−1. The slope is an important factor in irrigated agriculture and slopes higher than 8% are not recommended given the erodibility of the soil, although some high-tech solutions (e.g. pressurized drip systems) would allow for irrigated agriculture on slopes greater than 15%. In this study, the slope limit for sustainable gravitational irrigation was set at 8%. All constraints were consistent for all three scenarios with the exception from water source. These criteria were used to exclude non-suitable areas in each map. The constraints were merged to derive three constraint data layers, one for groundwater up to 7m, one for groundwater up to 25 m, and finally for surface water.

Table 1: Criteria for exclusion of unsuitable areas for solar irrigation pump

Constraint Input Map	Exclusion factor
Protected areas	National parks, forest, wetlands, water areas such as lakes and rivers
Land cover	Areas other than grassland, shrubland, bareland
Depth to bedrock	Depth to bedrock < 30cm
Slope	Areas with slope greater than 8%
Solar Irradiation	Areas with a solar irradiation lower than 1,300kWh m^{-2} y^{-1}
Groundwater depth	Groundwater depth of maximum of 7m and 25m
Ground water storage	Low groundwater storage <1,000mm
Acquifer productivity	Less than 0.1 litres per second

Source: Adapted from Schmitter (2018), Gebrezgabherm et. al.,(2021)

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[1] in the paper titled “GIS-Based Land Suitability Analysis for Solar Powered Irrigation System in Non- Irrigated Rice Production Areas of Davao Del Norte”

[2] in the paper titled “Agricultural land suitability assessment for agricultural productivity based on GIS modeling and multi-criteria decision analysis: the case of Tekirdağ province”

[3] *in the paper titled “Multi-criteria evaluation of irrigated agriculture suitability to achieve food security in an arid environment.”

II. Reclassification of criteria factor (Absolute values of Input drivers for the re-scaling)

The absolute values of each of the input drivers were rescaled to a 1-5 scale and used to derive weighted combination maps for the suitable areas. To evaluate potential input drivers, previous literature was reviewed (You et al., 2011; Xie et al., 2017; Nakawuka et al., 2018; Schmitter et al., 2018; Otto et al., 2018;) to define the suitability predictors. They can be categorized under water resource, climate, topographical indicators and socio-economic variables.

Criteria Factor Influencing Site Selection for SPIS

Solar insolation: Solar irradiance is the power received from the sun in the form of electromagnetic radiation per unit area, measured in watts per square meter (W/m2). Solar panels, a component of SPIS, depend primarily on the solar radiation, making year-round sunlight sufficiency critical. Solar panel efficiency is directly proportional to solar intensity, with sunnier sites considered as ideal places for SPIS installation (Kiatreungwattana, et al., 2013).

Groundwater availability: Geographic distribution of irrigation is often linked to physical access to enough water, whether surface or groundwater (Wiggins and Lankford, 2019). Groundwater availability was represented in this study by three indicators: groundwater depth, groundwater storage, and aquifer productivity. While groundwater yield is a major determinant of suitability for groundwater-based irrigation (Foster et al., 2015), the depth of water table is not only a function of the pump used in this study but it also influences cost of extraction (Amjath-Babu et al., 2016). Also, an open water source is equally important as the groundwater source and proximity to available surface water is a primary requirement in planning irrigation projects. Proximity to rivers is an important predictor for irrigable land assessment from direct river abstractions (Assefa et al., 2018).

Slope: This is the steepness of the hill, which can be measured in both units of degrees or percent. In our study we use the latter. Slopes are critical in irrigated agriculture, with those higher than 8 percent deemed not acceptable due to soil erosion susceptibility. Despite recent technological advancements now allowing for slopes greater than 15 percent (Noorollahi, et al. 2016), the slope was limited to 8 percent for the purposes of this study.

Socio-economic predictors: Proximity to town is a proxy for market accessibility (Schmitter et al., 2018) and this is what was used in this study. The adoption of small-scale irrigation is influenced by the high population density and the market for selling agricultural products (Worqlul et al., 2017). Accessibility to markets is an important factor to consider in the suitability analysis for Solar PV and can be represented using various proxies such as proximity to paved roads (Schmitter et al., 2018), the travel time required to access to nearby populated areas or urban center because the adoption of irrigation relies on market access for agricultural inputs and other equipment (Xie et al., 2014)..

Table 2: Reclassification criteria used for the various input maps included in the multi-criteria analysis

Factor	Highly suitable	Suitable	Moderately suitable	Less suitable	Least suitable	Unsuitable
Solar Irradiation (KWh $m^{-2}y^{-1}$)	2,500– 3,000	2,000–2499	1,750 – 1,999	1,500 – 1,749	1,300 – 1,499	<1,300
Slope (%)	0 – 2	2 – 4	4 – 8	NA	NA	>8
Groundwater depth (0-7m) I	0 – 7	NA	NA	NA	NA	>25
Groundwater depth (0-25m) II	0 – 7	7.1 – 25	NA	NA	NA	>25
Aquifer Productivity (l/s)	>0.5	0.1 -0.5	NA	NA	NA	<0.1
Ground water storage (mm)	25, 000	10, 000 – 25, 000	1,000 – 10,000	NA	NA	<1,000
Proximity to river(m)	<50	51 – 100	101 – 200	201 – 300	NA	NA
Proximity to town (m)	200KM	100KM	50KM	25KM	NA	NA

Note: Highly suitable = 5; Suitable = 4; Moderately suitable = 3; Less suitable = 2; Least suitable = 1; Unsuitable = Null

NA = not applicable due to the limitation of the selected solar pump type.

III. Layer weights using AHP process: (Saaty Analytic Hierarchy process in a GIS environment)

Layer weights were determined and assigned using the Saaty Analytic Hierarchy process in a GIS environment. The weights adapted in this study are from Otto et.al 2018.

Table 3: Weighing factors derived for the three scenarios following the AHP

Factor	**Groundwater Scenario 1 (<7)**	**Ground water Scenairo 2 (<25m)**	**Surface water Scenairo 3**
Solar Irradiation	0.278	0.278	0.296
Slope	0.101	0.101	0.131
Ground water depth	0.262	0.262	-
Acquifer Productivity	0.158	0.158	-
Groundwater Storage	0.158	0.158	-
Proximity to water bodies	-	-	0.258
Proximity to river	-	-	0.258
Proximity to town	0.057	0.057	0.057
Consistency ratio	**0.013**	**0.013**	**0.01**

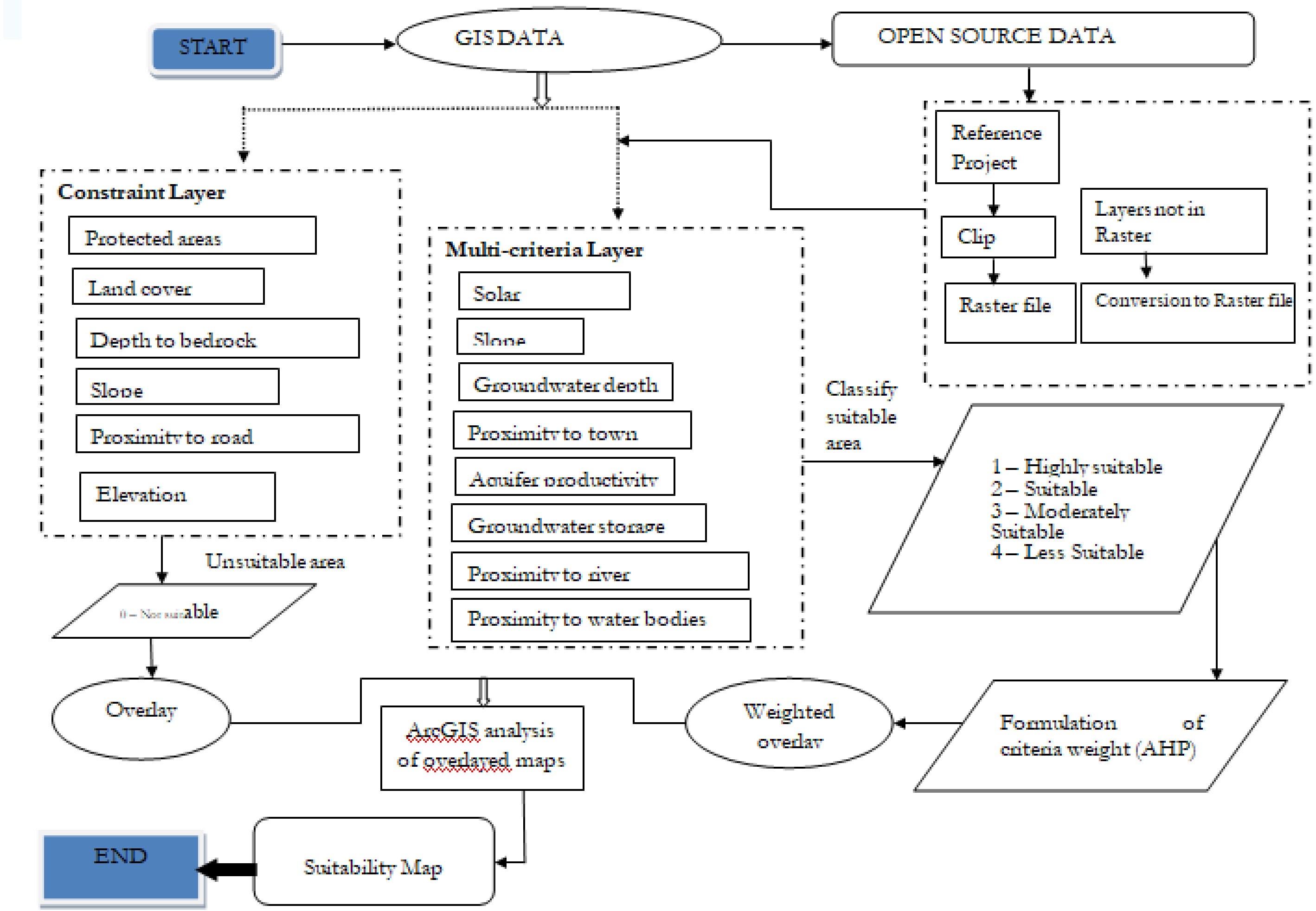

Figure 3: Methodological framework (Source: own elaboration)

CHAPTER FOUR – RESULTS AND DISCUSSION

This chapter presents the results obtained from GIS based analysis of solar photovoltaic irrigation suitability under various water resource source (ground water and surface irrigation) in Turkana and West Pokot counties. The chapter also interprets the results of the analysis and discusses these interpretations alongside the implications of the main findings. The interpretations and discussion precedes the results which are arranged in figures and tables.

4.1 INTRODUCTION

Results obtained in this study are presented and discussed with the following sequence

- Constraints maps discussion
- Table showing the area of land covered by the constraints factor in the study area by Km^2
- Maps showing each constraint factor hindering the installation of Solar PV
- Exclusion zones maps discussion
- Table showing the area of land excluded for scenario I, II, III in Km^2
- Maps showing the exclusion zone for scenario I , II, III
- Reclassified input maps that uncover the suitability classes discussion
- Solar PV irrigation suitability maps discussion by scenarios for two water resource conditions in Turkana and West-Pokot
- Table showing total suitable areas for irrigation by scenarios and suitability classes in Km^2
- Maps showing total suitable area for solar PV irrigation under the three scenarios in Km^2

4.2 CONSTRAINT MAPS

Individual constraint maps that identify areas unsuitable for solar irrigation in Turkana and West-Pokot were generated. A total of eight constraints maps were produced (see Fig. 4.) which include variables such as bedrock, elevation, groundwater depth of maximum 7m, ground water depth of maximum 25m, ground water storage, protected areas, irradiation, water areas and wetlands. Wetlands and water area maps were combined to produce one representative map (G). The wetlands are scattered within both counties to give an exclusion area of 2,797Km^2 while the water area are mostly concentrated in the Turkana eastern border owe-ing to the Turkana lake to give a total of 2,357Km^2 in the study area. From the maps (Fig.4), a very small concentrated portion of protected area was identified which occupied a land area of 1,313 Km^2.

The majority of the groundwater resources are quite deep especially in the Turkana county. Hence the groundwater depth for very shallow water pump of not more than 7m depth and shallow water pump of not more than 25m depth account for a very high amount of constrained area which is 53, 491km and 51,302km respectively.

The least constraint factor by area is solar radiation with an exclusion area of 0.68km^2. This is very intuitive considering that these two counties are located in the ASAL region with well above the minimum solar irradiation of 1, 300 KwHm^{-2}y^{-1} that is required for a maximum water pump head of 25m used in the study. This is in tandem with the solar resource map and data of Kenya prepared by solargis for the world bank which indicates that the range of Kenya's direct normal irradiation computed from long term average within the period 1994 – 2018 is between 3.6kWh/m^2 to 6.4kWh/m^2 per day and 1314kWh/m^2 per year (World bank group, 2020)[1]. According to energypedia, solar irradiation is a key factor in gauging the market potential of SPIS within a region and can be categorized into four classes: levels less than 2.6 kWh/m2 are classified as low solar radiation while solar irradiance between 2.6-3 kWh/m2 is moderate solar radiation; irradiance of between 3-4 kWh/m2 is high solar radiation and irradiance higher than 4 kWh/m2 is very high radiation[2].

For groundwater abstraction, it is worthy to note there was a near-perfect alternation of areas between the groundwater depth constraint and the groundwater storage constraint as the potential suitable areas of less than 7m and 25m groundwater depth (which are not excluded) has a relatively lower and unsuitable groundwater storage of less than 1,000mm which suggest that there is a direct relationship between this variable. Therefore, there is a trade-off between groundwater depth and storage. However, the more important variable for the purpose of the pump specification and suction head is the groundwater depth - this is validated with the weight assigned to the variable groundwater depth which is 0.262 in comparison with the groundwater storage which is 0.158. Also the map of the aquifer productivity was not included because all the areas within study area have values higher than the constraint threshold.

Table 4: Table showing area of land covered by constraint layer in square kilometer

EXCLUSION FACTOR	AREA EXCLUDED (Km^2)
Bedrock	272
Ground water depth (I)	53, 491
Ground water depth (II)	51, 302
Ground water storage	12, 578
Protected area	1, 313
Radiation	0.68
Slope	7, 275
Water areas	2, 357
Wetland	2, 797

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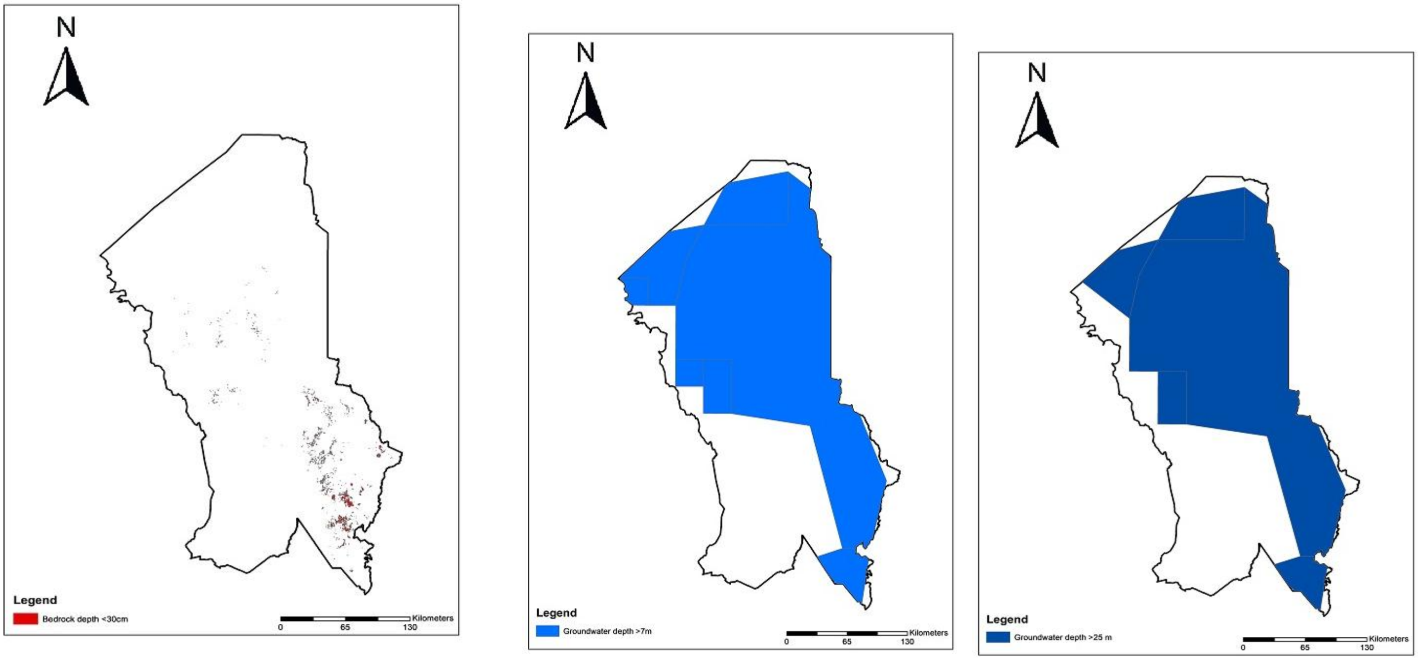
[1] Global Solar Atlas 2.0, Solar resource data: Solargis: https://solargis.com/maps-and-gis-data/download/kenya

[2] https://energypedia.info/wiki/SPIS_Toolbox_-_Solar_Irradiation

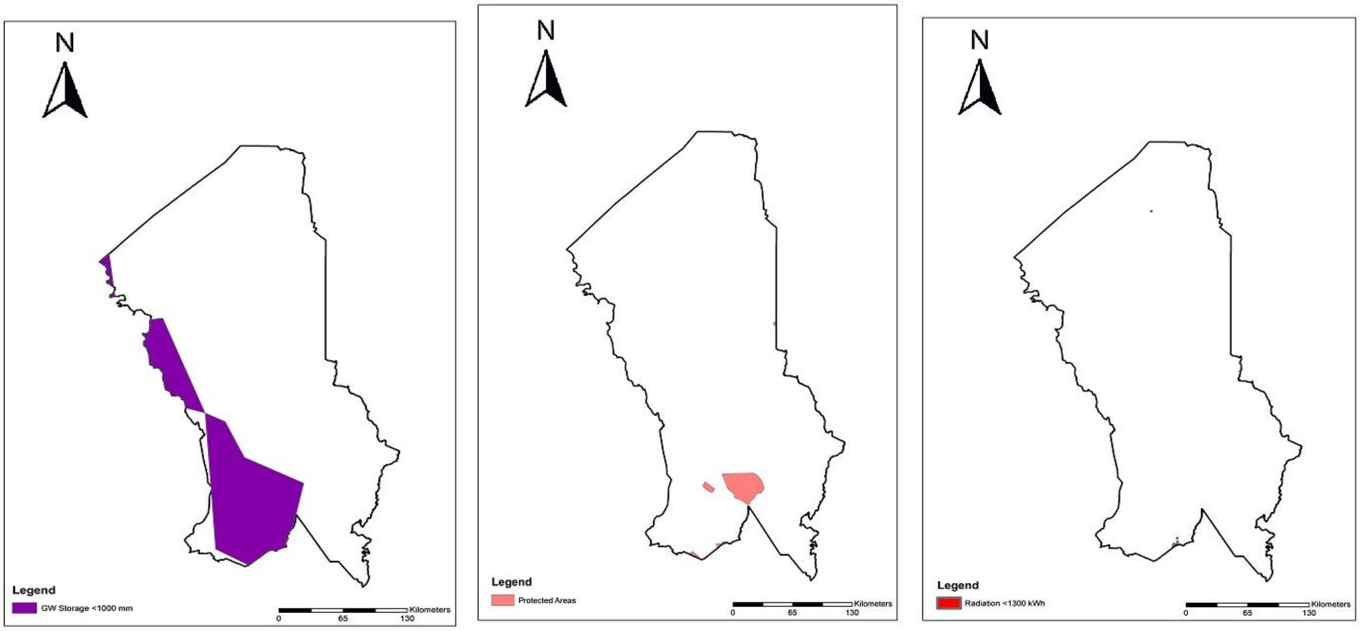
Figure 4: Maps showing each constraint factor hindering the installation of Solar PV

NB: The maps have two colored and white areas are used to depict the potential suitable areas for solar PV irrigation whereas the portion with other colors are used to depict unsuitable areas according to the constraint

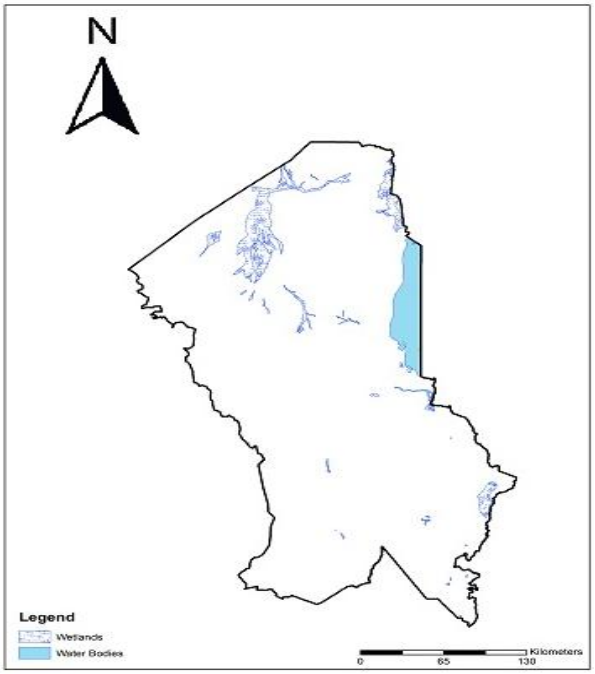
A. Bedrock Map **B. Ground-water depth 1** **C. Ground-Water depth II**



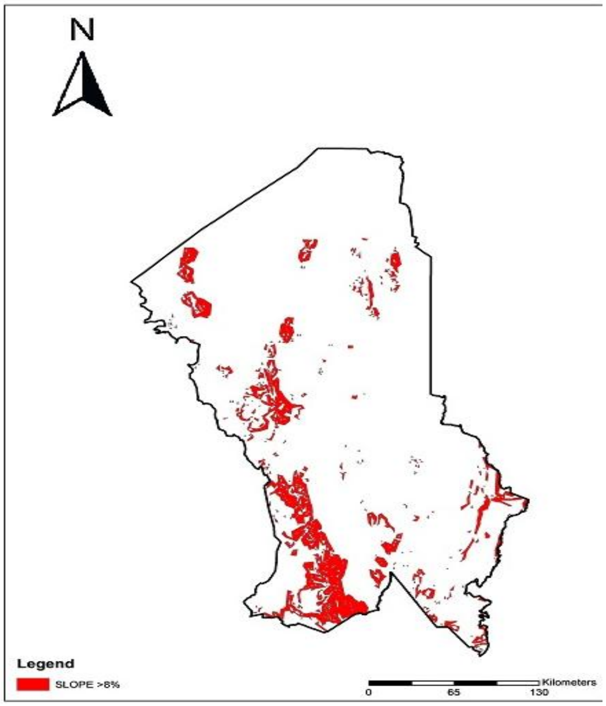
D. Groundwater Storage **E. Protected Areas** **F. Radiation**



G. Wetlands and Water areas



H. Slope



4.3 EXCLUSION ZONES MAP

The individual constraint maps (A-H) in fig.4 above were clipped and overlaid to generate exclusion zone maps for each water source scenario in Fig. 5 below. For each exclusion zone only constraint maps relevant to each scenario are included. Exclusion zone map for scenario I (70,454km^2) included all the constraint maps except map G and C in fig. 4 which are ground water depth II, wetlands and water areas. Exclusion zone map for scenario II (69,587km^2) included all the constraint maps except map F and C in fig.4 which are ground water depth I, wetlands and water areas. Final exclusion zone map for scenario III (35, 855km^2) included all the constraint maps except map F and G in fig.4 which are ground water depth I, and groundwater depth II.

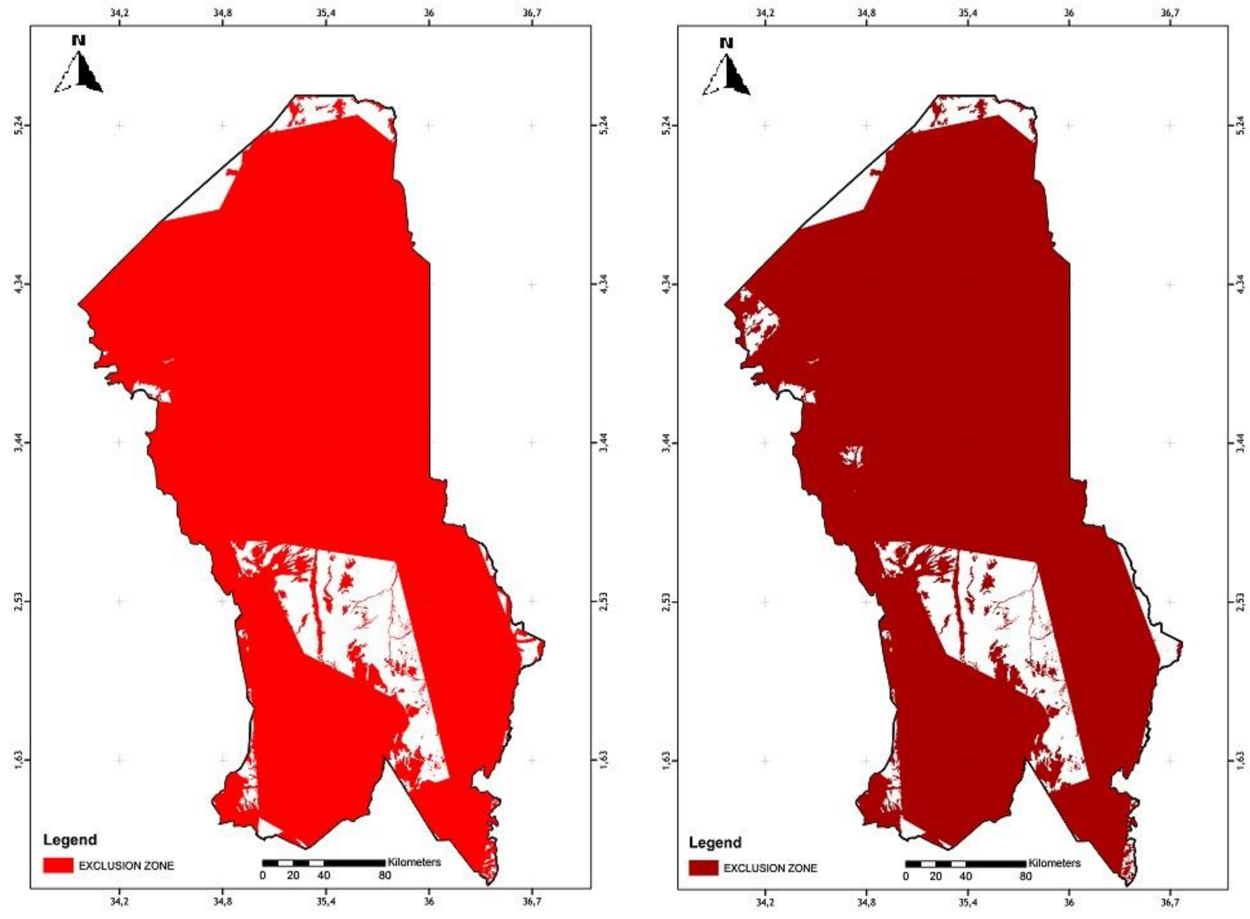
Ground water (scenario I and II) exclusion zones showed a relatively high area of exclusion compared to surface water exclusion zone. We can categorically say that even though areas with suitable groundwater storage is high, there is a large constraint area which do not meet the required suitability of shallow (25m) and very shallow (7m). Hence, groundwater depth explains this difference between ground water scenarios and surface water scenario as all other constraint factors except water resources remains constant in deriving the exclusion zone map for each scenario.

Table 5: Table showing total exclusion zone by scenario

SCENARIO I (Groundwater depth up to 7m)	70, 454
SCENARIO II (Groundwater depth up to 25m)	69, 587
SCENARIO III (Surface water)	35, 855

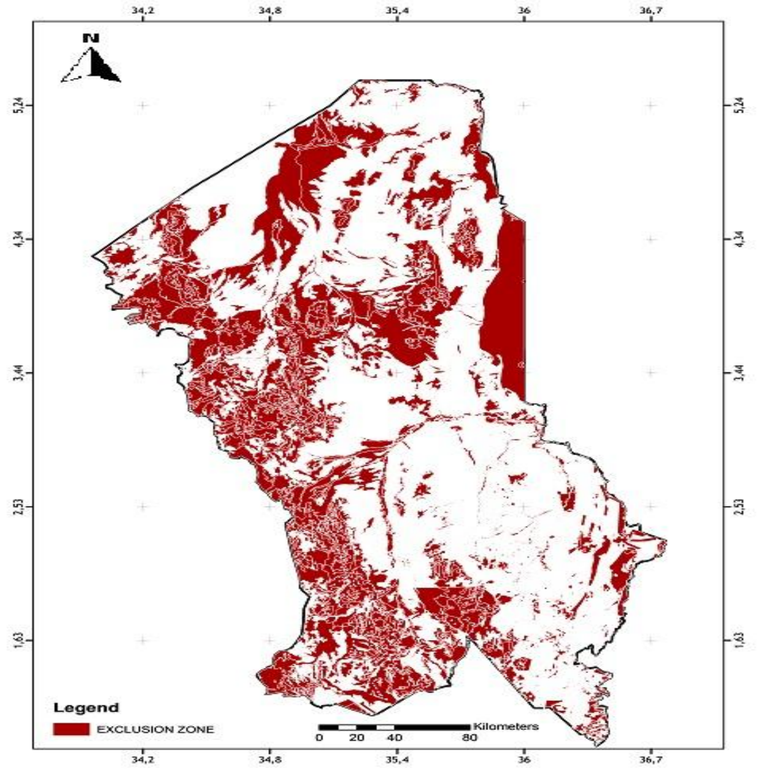
Figure 5: Maps showing the exclusion zone for scenario I , II, III

NB: Scenario I and II are maximum ground water depth of 7m and 25m respectively. Scenario III is the surface water.



Exclusion zone map for scenario I **Exclusion zone map for scenario II**

Exclusion zone map for scenario III



4.4 SOLAR PV SUITABILITY MAPS BY SCENARIOS FOR TWO WATER RESOURCE CONDITIONS IN TURKANA AND WEST-POKOT

This section discusses the results of solar PV suitability mapping for different water resource conditions. Figure 5 shows the final suitability map of the total solar irrigable areas for pasture/rangeland production in Turkana and West pokot which is the main question that this research sought to answer with respect to the varying scenarios. The total area for the analysis is 79, 688Km^2 and the final output was represented in three suitability classes (See table. 6).

While the lowest suitable area 53km^2 was found in the low suitability class when groundwater of 7m was considered, scenario III has by far the highest suitable area of 29, 591Km^2 which is moderate suitability class when surface water is considered. In instances where very shallow and shallow groundwater up to 7m and 25 m are considered, most of the suitable areas fall within the 'suitable' category and the least suitable areas fall within the low suitable category. (See table. 6). However, when considering only surface water source, total suitability is significantly (up to 5 times) higher with the most suitable areas in the "moderately suitable" category. The use of very shallow solar pumps with a suction head of 7m would be suitable for 8, 102km^2 (Scenario I, Table. 5), solar pumps with a suction head of 25m would be suitable for 8, 897km^2 and surface water yields a total of 40,548Km^2 total suitable area. This implies that there are more potential for solar irrigation for surface water than ground water, which could be because the study area is situated in ASAL regions with low water table, along side high evaporation and undoubtedly deep groundwater depth which is the second most important attribute following solar radiation according to the AHP process. Recall that according to the AHP process of assigning weights to the maps prior to analysis, the highest relevance was given to solar radiation followed by water resources such as ground water depth, ground water storage and productivity respectively in the case of ground water abstraction. We do not record any suitability in the ilemi angle, this would probably be because the solar irradiation map does not cover this area and it has the highest weight in the suitability analysis.

Aside from solar irradiation, the main input for Scenarios I and II was the spatial groundwater data established for Africa by the British Geological Survey (MacDonald et al., 2012). The coarse resolution of 5 km strongly influenced the look of the output of the final suitability map, as the result was initially highly pixelated. However, this was remedied by coverting the input maps from raster to polygon and back to raster file.

Furthermore, MacDonald et al. (2012) reported that in many African countries, well-established boreholes would be able to supply between 0.1 and 0.3 $l\ s^{-1}$, which is suitable for hand pumps. Whereas the average discharge of the solar PV pump type I and II would depending on the water level, largely fall within this range, the abstraction might be higher than the sustainable aquifer productivity. For Kenya, aquifer productivity mainly ranges between 0.1 and 20 $l\ s^{-1}$ (fig. 6), this could lead to over-abstraction when solar PV pumps such as type I and II are being promoted. Although the aquifer productivity was included in the multi-criteria analysis, the smaller weighting factor compared to the groundwater depth might result in an under-estimation of the feasibility of solar pump type I and II in some locations. However, comparing the discrepancy between the suitable groundwater map and the areas suitable for solar PV in Scenario III shows that the main factors for solar unsuitability were most likely land cover, land use, ground water storage and ground water depth. As seen in Fig (6), majority of the ground water depth is between 50m – 100m. Also there is only a slight increase between very shallow area of 0 – 25m and very shallow area of 0-7m. This suggests the reason why there are closeness in the results of suitability of scenario I and II.

Table 6: Suitable area for solar PV irrigation under the three scenarios (square kilometre)

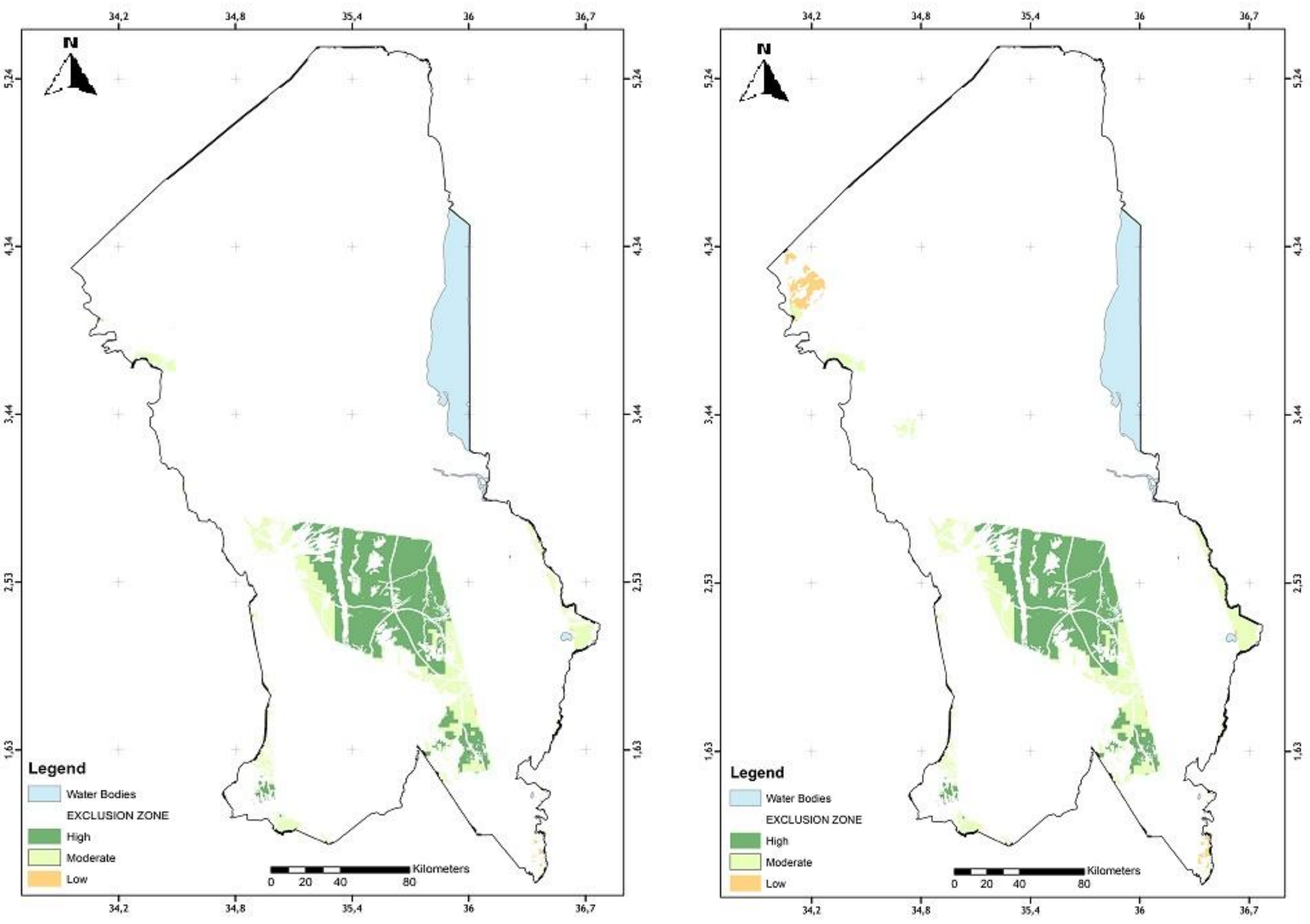
SUITABILITY	**SCENARIO I** **Groundwater depth up to 7m**	**SCENARIO II** **Groundwater depth up to 25m**	**SCENARIO III** **Surface water**
Highly suitable	4, 957	4, 963	500
Moderately suitable	3, 092	3, 445	29, 581
Low suitable	53	489	10, 467
TOTAL	**8, 102**	**8, 897**	**40, 548**

Figure 6: Maps showing the suitable areas for scenario I, II and III

NB: The suitability map was shows three classes

🟩 High suitability
🟨 Moderate suitability
🟧 Low suitability

🟦 Water body
☐ Unsuitable



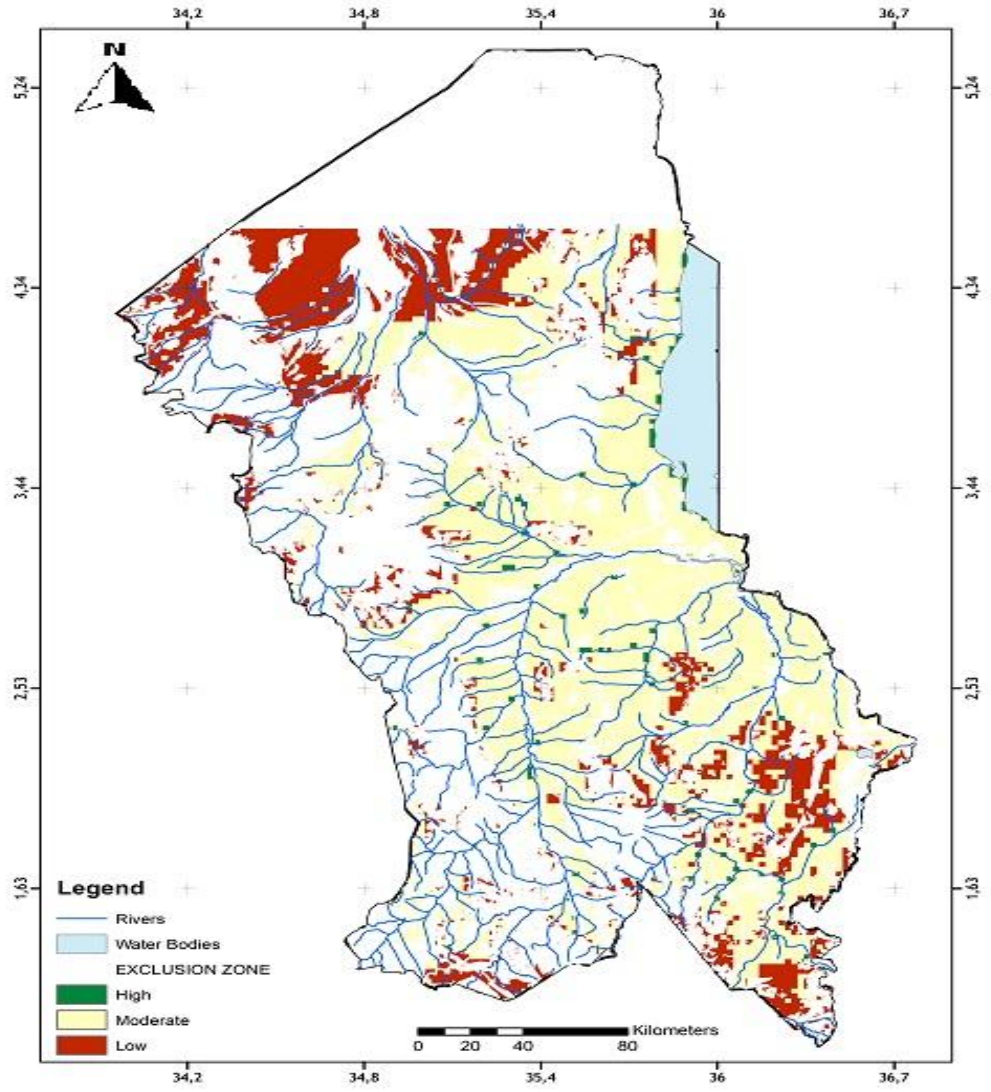
A. Groundwater Suitability Map Scenario I

B. Ground water Suitability Map Scenario II

🟩 High suitability 🟨 Moderate suitability 🟥 Low suitability

🟦 Water body ▬ Rivers ☐ Unsuitable

C. Surface water Suitability Map Scenario III



CHAPTER FIVE – CONCLUSION AND RECOMMENDATION

The results from this study show the resource feasibility of using solar-based pumps to extract water from both groundwater and surface water for Turkana and West-Pokot. The analysis shows the suitability of solar pump technologies with a capacity to withdraw water not deeper than 25 m. The results reflects the influence of the weights, while the weighting results (Table. 3) show an acceptable consistency between all three scenarios, the suitable areas identified are highly dependent on the prioritization of biophysical factors. The multi-criteria model approach is frequently used - however, the development of the model highly depends on the main purpose of the suitability analysis (Akyol et al., 2016; Palmas et al., 2012; Venkatesan et al., 2010; Worqlul et al., 2015; Yalcin & Kilic Gul, 2017). For example, if the main aim was to assess market potential for solar PV pumps including maintenance services and spare parts, higher weighting would be given to the distance to roads and proximity to towns, resulting in potentially different suitability maps. Therefore, stakeholders using the suitability maps derived in this study should acknowledge the prioritization of biophysical over market-related factors. However, the framework does provide a good basis for further analysis which should be strongly embedded within the socio-economic context relevant in those specific locations.

Depending on the water source and the technical constraints of the solar pump (i.e.,size of suction heads), the suitability ranges from 8,102km^2 (Scenario 1) to 40, 548km^2 (Scenario 3). Even though we are interested in the suitable areas, it is important to also take note of the possible unsuitable areas that can hinder the installation. Overall, the locations found to be suitable for solar PV pumps after excluding constraints areas are mainly in areas with proximity to surface water. These areas consist of locations that are currently irrigated by various irrigation technologies and new areas that could be potentially developed for solar energy-based irrigation. Differentiating between these two types and overlapping these conditions is currently not possible because data on the areas presently irrigated using solar power are not readily available or reliable.

GIS suitability mapping for solar irrigation is an under exploited theme in research and an inter-sectoral domain that require the attention of relevant stakeholder. So many interventions could already fail even before implementation if certain resource feasibility analysis are not conducted. Problems such as droughts that causes a multiplier effect on livelihoods, income, food security, water security require interventions that have a domino effect on other sector. The intervention is a relevant WEF nexus technological innovation that will not only provide solution in terms of adaptive capacity but also prevent problems in terms of mitigating climate change, reducing vulnerability and building resilience.

This research is particularly of interest because it shift focus to an area that deserves some attention especially in a country where arid and semi-arid lands are predominant and pastoralism is a major source of livelihood. Livestock farmers are also vulnerable to climate change and at risk of water insecurity, food insecurity and reduced income but receive lesser attention than crop farmers. Suitable areas can serve as water points for human and livestock consumption on the way to some underexploited rangeland resources while migration routes can be created along suitable areas. Also fodder crops can be produced on irrigated land, whereby income are diversified and the remains are used to feed livestock. Farmers can reseed degraded lands or adopt a zero grazing in overexploited areas plus cut and carry system. The spatial data used in this assessment allows for a first rapid estimation of solar-powered irrigation potential. Other important characteristics such as the quality of the water, the access to and quality of seeds, the amount of water required by livestock and also the water needs to grow the pasture, should be integrated during further analysis. Improving the resolution and accuracy of shallow groundwater availability would in turn increase veracity of the current estimates for potential solar PV-based pumping.

In places where water and land are more limited, expansion of irrigated areas increases competition over water resources, therefore rationing and proper water management is required to avoid over extraction of water and over exploitation of land. Furthermore, attention needs to be given to the temporal and seasonal fluctuations of the water resource, as this may be limiting during periods of frequent drought, even when irrigation equipment is available. To make solar PV a feasible alternative, there must be access to credit options to purchase technologies, input and output markets, asides information about the suitability, The finance sector has lagged behind other sectors in solar irrigation development, resulting in unequal access to financial resources and limited adoption of solar irrigation technology for smallholder farmers, particularly in marginalized communities (e.g., small farmers, women and youth) (Amankwah-Amoah, 2015; Murray et al., 2016). Also this innovation for pastoral farmers is not so pro-women as majority of pastoral farmers are men.

Irrigation is one area that has mostly been left or perceived to be an agricultural related intervention and also mostly directed to staple crop production. From farm to fork, agriculture contributes greatly to the increase of Co2 emission to the environment from production to processing to transportation and even to waste disposal. With the clamour for renewable energy source, solar irrigation can attract the concerted efforts and interest of stakeholders in water, energy and food sector.

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ANNEX 1

Table showing spatial data used in the assessment

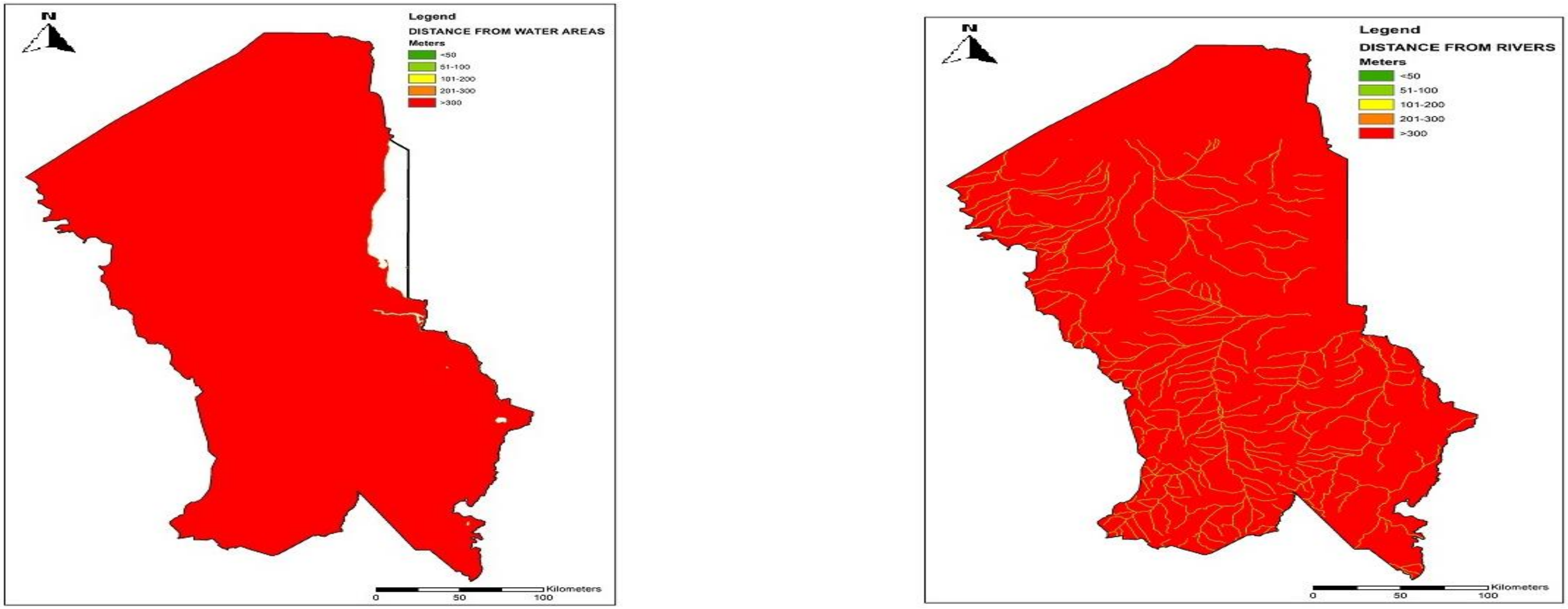
Data	Source	Year
Solar radiation	Global Solar Atlas: https://globalsolaratlas.info/download/kenya	2019
Land use and land cover	World Resource Institute: https://www.wri.org/data/kenya-gis-data	2016
Depth to bedrock	International Soil Reference and Information Centre (Hengl et al. 2015) http://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/bfb01655-db81-4571-b6eb-3caae86c037a	2017
Slope	Derived in this study from SRTM 30m DEM	2017
Aquifer productivity, ground water depth and storage	British geological survey: https://www2.bgs.ac.uk/groundwater/international/africangroundwater/mapsDownload.html	2012
Protected areas, proximity to town, river and road	World Resource Institute: https://www.wri.org/data/kenya-gis-data	2016

ANNEX 2

Supplementary Figure: Maps showing the suitability classification of input maps

NB: Note that here the red colors denoting “least suitable” do not mean these areas are “unsuitable” for solar PV but are the areas just have the lowest suitability in terms of the input map in question.

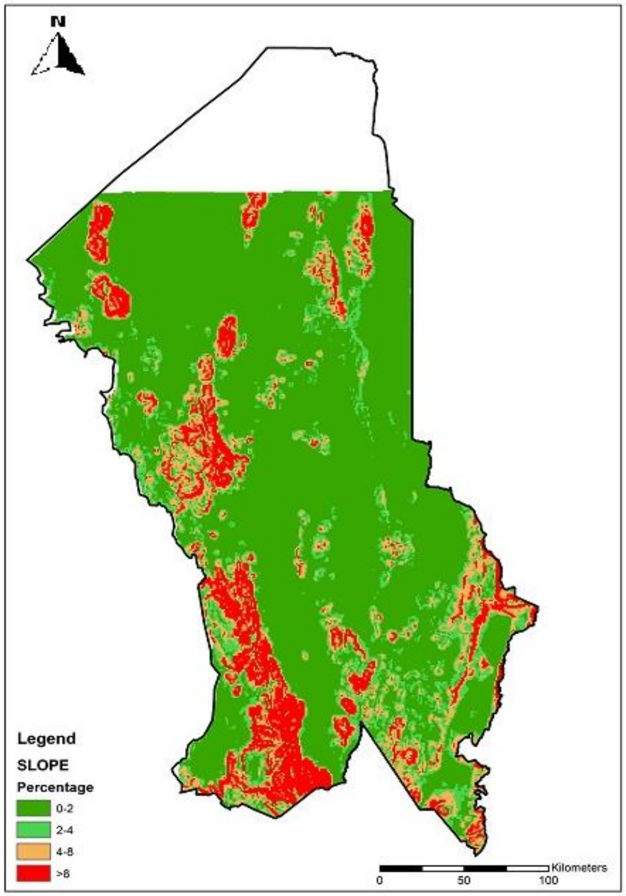
🟩 Highly suitable
🟩 Suitable
🟨 Moderately suitable
🟧 Less suitable
🟥 Least suitable



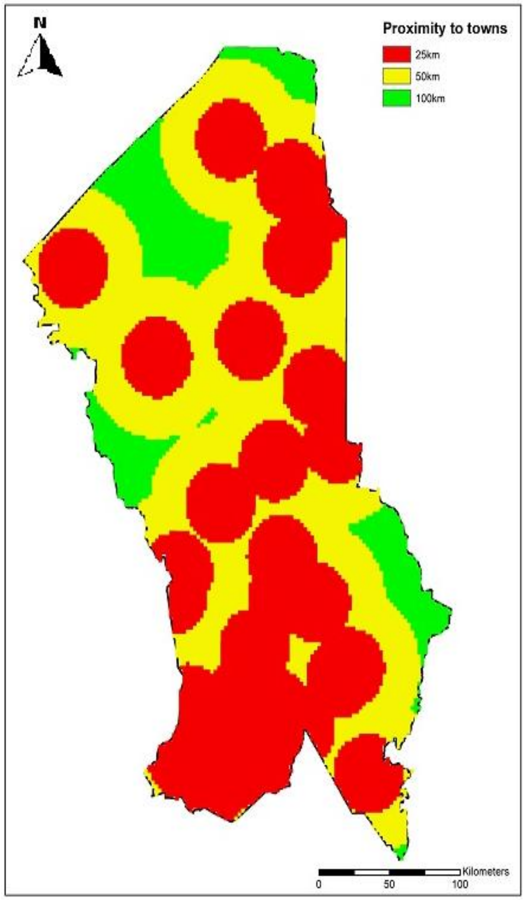
A. Distance from water areas

B. Distance from rivers map

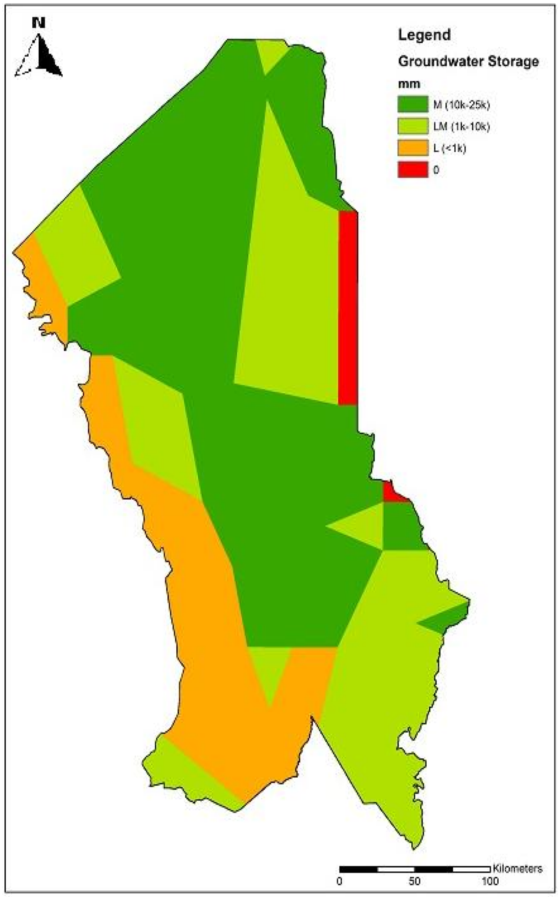
C. Slope Map



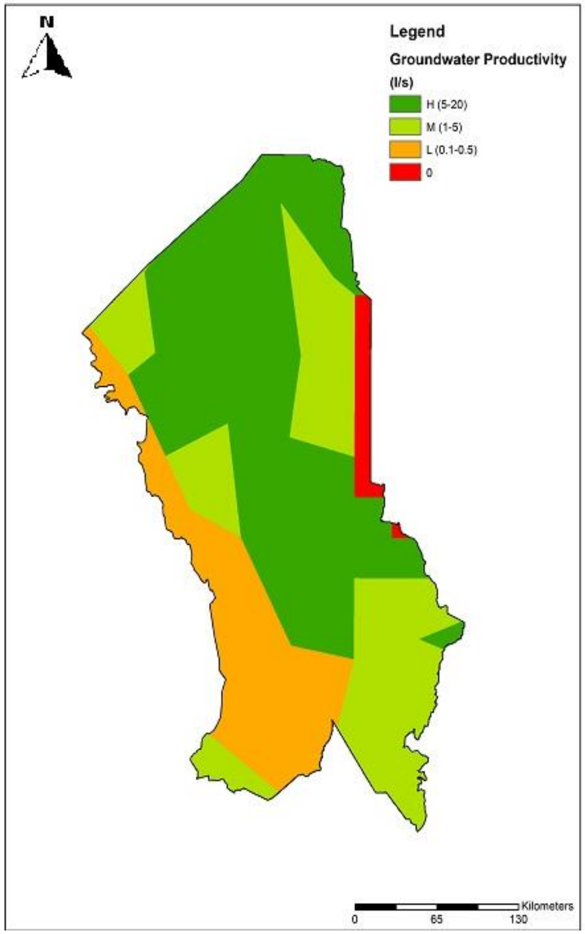
D. Proximity to town



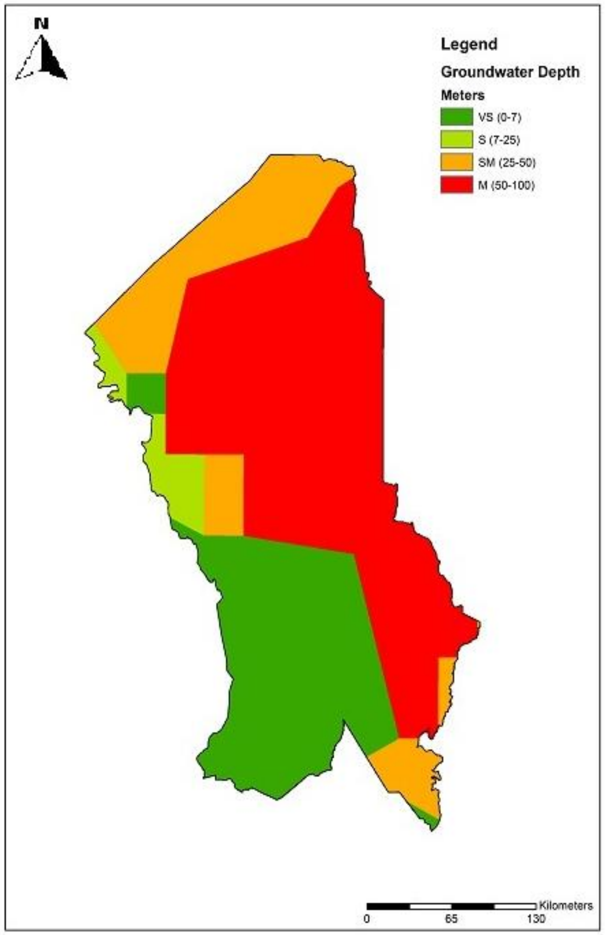
E. Ground water Storage



F. Ground water Productivity



G. Groundwater depth



H. Solar Radiation