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solar energy nexus**

**インドの持続可能なエネルギー転換：農地 - 水 - 太陽エネルギーネクサス
の分析**

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September 2024

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A dissertation submitted in partial fulfilment

of the requirement for the degree of

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in

Graduate School of Environmental Science



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Abstract

India's agricultural sector, employing over 50% of its workforce and contributing significantly to its GDP, faces challenges due to the expansion of the solar energy sector. As solar energy projects convert agricultural croplands, concerns about food security arise. India, being a major global food producer, faces the risk of exacerbating food security issues, especially with around 195 million people in the country already undernourished. Additionally, the growing demand for water to clean solar panels and support the cooling requirements of solar plants adds pressure to India's stressed water resources. Approximately two liters of water are needed to clean one solar module, and a medium-sized solar plant requires a monthly water requirement of 165,000 liters. This additional water demand could further strain India's water supply, impacting both agriculture and domestic needs. This research paper delves into the potential consequences of India's rapid expansion of solar energy on its agricultural sector and water resources. It highlights the need for careful planning and sustainable practices to balance the nation's renewable energy ambitions with food security and water resource management. As India continues its journey toward achieving its ambitious solar energy targets, addressing these challenges becomes paramount to ensuring a sustainable and resilient future for the nation.

The chapter two of the thesis introduces the Solar Panel Index (SPI), an innovative algorithm designed to enhance the identification and monitoring of photovoltaic (PV) solar farms using multispectral satellite data. The SPI leverages six multispectral bands from optical satellite data and cancels out background reflectance intensity, emphasizing the solar panel area to reduce false-positive responses. The study showcases the application of SPI in the Indian context, enabling accurate identification and area coverage estimation of solar plants via satellite data. SPI offers precise location information for solar power plants, aiding in energy generation estimation, performance optimization, and investment decision-making. It plays a crucial role in supporting grid operators and electricity market participants in managing the electricity grid effectively and tracking the expansion of solar energy. The effectiveness of SPI varies based on surface reflectance intensities captured by satellite sensors in different locations. Various threshold values were tested, with a threshold of 0.16 achieving the highest accuracy of 97.8% at the Kamuthi solar farm location. The overall average accuracy across all locations with this threshold was 91.9%.

The research also introduces the concept of the Solar Energy Agriculture Water (SAW) nexus, emphasizing the interdependence of solar energy, agriculture, and water resources. This approach allows for integrated management and optimization of resources across these sectors, addressing sustainability, food security, and climate change challenges. Solar energy's role in the SAW nexus offers sustainable, clean energy solutions while positively impacting agriculture and water resources. Solar energy can power irrigation systems, reduce reliance on non-renewable resources, and enhance water efficiency in agriculture. Similarly, adopting water-efficient irrigation techniques can conserve water resources and reduce energy requirements, contributing to climate change mitigation. Conversely, agriculture can support solar energy expansion by providing land for solar farms or integrating solar panels into farming operations. This synergy creates additional income opportunities for farmers and enhances the resilience of the energy grid, promoting the transition to renewable energy sources. To deepen the understanding of the SAW nexus, a case study at the Pavagadh solar power park was conducted, focusing on its impact on agriculture and water management. Geospatial Land Use Land Cover (LULC) analysis and the Pearson Correlation Coefficient were employed to uncover relationships between land use, solar energy, agriculture, and water resources, revealing strong positive correlations. A field visit to solar power plants in Maharashtra allowed the assessment of the impact of solar panel installations on soil microbial communities. The results indicate significant differences in microbial populations beneath solar panels compared to agricultural farms, emphasizing the need for further research to understand the overall influence on soil health. Water utilization in solar power plants was also investigated, with a focus on cleaning methods. The study revealed variations in water usage, with some power plants relying on groundwater wells and others utilizing self-cleaning robots powered by solar energy. The application of self-cleaning robots presents a sustainable alternative to water-intensive cleaning methods. The study also highlights the concept of agrivoltaics, where solar panels and crops mutually benefit, to enhance food production, conserve water, and generate additional revenue streams. However, the complete conversion of agricultural land into solar farms could threaten food security, impact local water cycles, and exacerbate water shortages in water-stressed regions. Careful planning and management are essential to ensure the expansion of solar energy does not negatively affect agricultural practices and local ecosystems.

In chapter four, the study emphasizes the critical role of Geographic Information Systems (GIS) in the sustainable management of the SAW nexus. We used geospatial datasets to identify the locations of solar farms and to assess land cover changes resulting from their installation. Analyzing the patterns in land cover change revealed that agricultural land was the predominant choice for solar farm installation and expansion. The analysis was supported by statistical data, highlighting the extensive transformation of land. Additionally, we conducted groundwater level analysis using Gravity Recovery and Climate Experiment (GRACE) to assess water resource availability in the respective region and to gauge the potential stress that solar power plants could impose on water resources. Furthermore, we overlaid the solar farm locations with Night Time Light (NTL) data, which serves as a reliable indicator of electrification, spanning from 2014 to 2020, a period marked by continuous growth in the solar industry since its inception. Furthermore, the chapter presents the development of a Land Suitability Map (LSM) for India, based on multiple parameters, including solar potential, distance from the power grid, land surface temperature, and water availability. This LSM serves as a valuable tool for decision-makers, enabling them to make well-informed choices that promote the harmonious coexistence of solar energy production, agriculture, and responsible water resource management within the SAW nexus.

The concluding chapter summarizes the study's findings, highlighting their significance and acknowledging the study's limitations. The policies recommended can ensure sustainable solar energy growth while safeguarding agriculture and water resources. Implementing them can offer valuable lessons for other countries facing similar challenges, mitigating land encroachment and addressing water scarcity concerns.

Keywords: Solar Energy – Agriculture – Water (SAW) Nexus; Solar farms; Solar Panel Index; Land Suitability Map (LSM)

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Tables of contents

Abstract	i
Acknowledgments	iv
Tables of contents	vi
List of Figures	viii
List of Tables	x
Chapter 1. General Introduction.....	1
1.1 Back ground	1
1.2 Research Question	4
1.3 Objective	4
1.4 Significance of the Study	6
1.5 Outline of the thesis.....	8
Chapter 2: Development of Solar Panel Index.....	9
2.1 Introduction to the Solar Panel Index	9
2.2 Methodology for Developing the Solar Panel Index	10
2.3 Application of the Solar Panel Index in the Indian Context	12
2.4 Analysis of Results and Implications	18
2.5 Discussion.....	19
2.6 Conclusion.....	20
Chapter 3: Solar energy development of farmland: synergy of solar power, agriculture, and water.....	21
3.1 Definition and Conceptual Framework of the Solar Energy-Agriculture-Water Nexus	21
3.1.1 The Role of Solar Energy in the Nexus	21
3.1.2 Assessment of the Current Status of the Nexus in India	23
3.1.3 Focus of the study region.....	25
3.2 Data and methods.....	26
3.2.1 Machine learning based map generation	26
3.2.2 Correlation analysis.....	26
3.3 Land use changes	27
3.4 Field visit	32
3.5 Discussion.....	36
3.6 Conclusion.....	38

Chapter 4: Land Suitability Map for sustainable resource management of agriculture land and water in the wake of solar industry	39
4.1 Introduction to sustainability in the context of solar energy, agriculture, and water	39
4.1.1 Importance of solar energy in promoting sustainability.....	39
4.1.2 Application of GIS in sustainable management of solar energy–agriculture–water Nexus ...	40
4.2 Materials and methods.....	42
4.2.1 Study area	42
4.2.2 Data collection and preparation	43
4.2.3 Multi-criteria decision-making model.....	46
4.3 Environmental Implications of Solar Farm Development.....	48
4.3.1 Electrification of villages	48
4.3.2 Land use changes	51
4.3.3 Water resource availability	54
4.3.3.1 Groundwater level change	54
4.3.3.2 Surface water proximity	59
4.4 Generation of Land Suitability Map (LSM).....	60
4.4.1 Selection of parameters for LSM generation.....	60
4.4.2 Integration of AHP with Geo-spatial parameters	62
4.5 Discussion.....	66
4.6 Conclusion.....	68
Chapter 5: Discussion	70
5.1 Disaster risk.....	70
5.2 Solar pumping for irrigation.....	72
5.3 Current scenario of solar farm distribution	74
Chapter 6: Conclusion and Recommendations	76
6.1 Summary of Findings.....	76
6.2 Conclusions drawn from the findings	77
6.3 Limitations and recommendations for further studies.....	77
6.4 Policy recommendations for sustainable resource management	78

List of Figures

Figure 1.1 Cumulative installed capacity of solar energy.....	4
Figure 1.2 Research framework showing the flow of the study with key elements in each chapter.	6
Figure 2.1 Spectrometer used for taking spectral reflectance reading from solar panels.	10
Figure 2.2 Scatter plots of multi spectral bands (a) blue-green and (b) blue-red, highlighting the distribution of solar panel pixels in green area.	11
Figure 2.3 Raster layer generated using Solar Panel Index (SPI), highlighting solar panels locations at (a) Kamuthi Solar Park, (b) Bhalda Solar Park, (c) Kurnool Ultra Mega Solar Park, and (d) Pavagadh Solar Park.....	13
Figure 2.4 Area covered by solar farm facility and the actual area covered by solar panels installation which determines the installed power capacity.....	14
Figure 2.5 SPI derived map highlighting solar farm area in red that gives precise location and coverage of power plant through open-source satellite data.....	16
Figure 2.6 Geographical distribution of solar farms and their corresponding estimated installed capacities.....	18
Figure 3.1 Dynamic relationship between Solar-Agri-Water nexus.....	23
Figure 3.2 LULC of Pavagadh solar park area and its surrounding boundary upto 5km in the years (a) 2007, (b) 2012, (c) 2017, and (d) 2022	28
Figure 3.3 Field visit to (a,b) Avaada solar power plant and (c) Hitachi solar power plant in Maharashtra India.	34
Figure 4.1 The geographic location of the study area map showing the top eight states with highest installed capacity of photovoltaic solar power	43
Figure 4.2 VIIRS derived Night Time Light RGB Map of years 2014, 2017, and 2020, Indicating the change in electricity consumption in the span of six years.....	49
Figure 4.3 State-wise distribution of VIIRS derived average Night Time Light within 100 Km boundary of existing solar farms of years 2014, 2017, and 2020.	50
Figure 4.4 LULC change caused by Solar power plant installation for (a) 2005, (b)1995 and (c)1985 and the states mentioned here are top 8 states with highest solar power installed capacity.	53

Figure 4.5 State-wise groundwater level distribution over solar farms.	55
Figure 4.6 Giovanni GLDAS CLSM025 derived annual groundwater level thickness change in centimeters among the six regions of India.	59
Figure 4.7 State-wise distribution of number of Solar farms within the proximity of surface water source	60
Figure 4.8 Rasterized input environmental parameters: (a) Agricultural Crop Land, (b) PV Output Potential, (c) Power Grid, (d) Land Surface Temperature, and (e) Water Availability....	62
Figure 4.9 AHP matrix derived from discussion with experts.....	63
Figure 4.10 Land Suitability Map for solar farm installation in the study area.....	65

List of Tables

Table 2.1 Accuracy assessment of SPI at different threshold values at three different solar farm areas with diverse environmental conditions: Kamuthi, Kurnool, and Bhadla solar park.	19
Table 3.1 Pearson correlation (r) among the classes of nexus.	29
Table 3.2 Canonical Correlation Analysis (CCA) between the nexus and the parameters.	30
Table 3.3 Accuracy assessment: validation error matrix without SPI.	31
Table 3.4 Accuracy assessment: validation error matrix with SPI.	31
Table 3.5 Microbial activity of top soil from agricultural land (A) and under solar power plant site (S).	35
Table 3.6 Parameters content of the soil from agricultural land (A) and under solar power plant site (S).	35
Table 4.1 Different criteria parameters used and their information.....	45
Table 4.2 Value distribution of input parameters.	46
Table 4.3 Percentage distribution LSM categories in India.....	65
Table 5.1 Distribution of currently located solar power plant according to LSM generated from this study.	74

Chapter 1. General Introduction

1.1 Background

To address the complexities of climate change, the Intergovernmental Panel on Climate Change (IPCC) was formed in 1988, under the support of the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) (Bekiashev & Serebriakov, 1981; Reinman, 2012; Secretariat, 2000). The IPCC's role encompasses assessing the scientific aspects of climate change, its impacts, and potential mitigation and adaptation strategies. Their influential reports, including contributions to the Paris Agreement, have played a pivotal role in shaping global climate policy (Hulme, 2016). The Paris Agreement, adopted in 2015 as part of the United Nations Framework Convention on Climate Change (UNFCCC), strives to limit global warming to well below 2 degrees Celsius above pre-industrial levels, with an additional aim of capping temperature increases at 1.5 degrees Celsius (Schurer et al., 2017). This international treaty also seeks to strengthen countries' resilience to climate change impacts and organize resources and technology to support climate action (Easterling & Apps, 2005).

The United Nations and its member states adopted Sustainable Development Goals (SDG) in 2015 (www.unfoundation.org), marking a critical turning point for countries to promote renewable energy production. This led to switching the focus from coal-based generation to photovoltaic solar energy (Noon et al., 2022). India, as one of the world's largest and fastest-growing economies, anticipates continued growth in energy demand in the coming decades (T. Ramachandra & Hegde, 2015). To address this demand while reducing its carbon footprint, India has set ambitious targets for renewable energy, particularly solar power. Initiatives such as the National Solar Mission, launched in 2010, aim to achieve 100 GW of solar power capacity by 2022 (Kumar. J & Majid, 2020). India has also taken a leadership role through endeavors like the International Solar Alliance, which fosters solar energy deployment across 121 countries (Shidore & Busby, 2019). It has embarked on a journey to fulfill its ambitious goals, supported by policies and regulations aimed at promoting the widespread adoption of solar energy. At the forefront of these initiatives are the Renewable Purchase Obligations (RPOs), mandates instituted by state electricity regulatory commissions (Pachauri, 2022). These mandates compel distribution companies to procure a predetermined percentage of their energy from renewable sources, prominently including solar

power. This regulatory framework serves as an important role for incentivizing the integration of solar energy into India's energy landscape.

India is the third largest producer and consumer of electricity in the world (Dale, 2021); however, only 10% of its electricity consumption is covered by photovoltaic solar power, and only 25% of its consumption is covered by all renewable sources combined (www.renewablesindia.in/). National Solar Mission launched in 2010 is expected to be a strong component of the national action plan for the climate change (Pandve, 2009). In the last decade, solar panel installation in the country has been rising drastically from merely 161 MW in 2010 to 40,085 MW in 2021 (Figure 1.1). As of 2021, the installed capacity of the country is around 40GW (Dale, 2021). This is a small portion of what the country has set the target for, that is of 280 GW by the year 2030 (Agarwal, 2021). Previously, India has fulfilled its set target four years prior the schedule (*India Achieved Solar Power Target 4 Years Ahead of Schedule: DST Advisor*, 2019). It is likely that the set target will be crossed in the given timeline. Some ambitious initiatives like ‘One Sun, One World, One Grid’ brings more possibilities in exceeding the goal (A. K. Jain, 2023). The idea of the project is to connect 140 countries around the world with a common grid, especially the countries lying on the equatorial belt, to get the maximum out of solar energy. India already exports electricity to its neighboring countries like Bangladesh, Nepal, and Bhutan (Kumar Shukla & Sharma, 2017). This project may further boost motivation to invest into solar energy as it can boost further economic growth. One major requirement to fulfill this objective of solar projects is the availability of land. A study by NREL, states that the total land use requirement for solar power plant project is about 8.9 acres/MW (Ong et al., 2013). If we must estimate the total land requirement of 280 GW solar power with this input then, it estimates to more than 1 million ha area. As of the end of 2022, an overall capacity of 7.6 GW of rooftop solar has been reported, which increased to 11.08 GW by October 2023 (Koundal, 2023). It is projected to reach 41.778 GW by 2029. From this, it is estimated that India is planning to heavily invest in ground-mounted solar farms to meet its targets. With this juggernaut-like expansion of the solar energy sector, land encroachment is an obvious consequence. Most likely sufferer of this expansion is agricultural crop lands. Agricultural croplands show great potential for PV power potential, as it provides land convenient for power generation from geolocation point of view (Adeh et al., 2019). Already some instances have been

reported where agricultural crop lands have been overturned into solar energy production (Chari, 2020; Karthikeyan, 2019; Malu et al., 2017; Rajasekaran, 2019).

India, an agrarian country, has second largest farm output in the world (Sunder, 2018). As of 2018, the agricultural sector employed more than 50% of the Indian work force, contributing about 17-18% of the country's GDP. India is the world largest producer of pulses and spices, and the second largest producer of rice, wheat, sugarcane, groundnut, vegetables, fruits and cotton (Y. J. N. Kumar et al., 2019). After US and China, it is the largest economy worth around \$2.1 trillion (fao.org/India). Even with such a huge food production, food security is a concern in the country. According to UN India (in.one.un.org), around 195 million people in India are undernourished, making it a quarter of the world's hunger burden (Vyas et al., 2019). Rising solar power is likely to bring more burden onto the food production stemming from agricultural land encroachment (Neupane et al., 2022; Rasul & Sharma, 2016).

The water resources in any region are generally used for agriculture, industrial and domestic purposes (Flörke et al., 2013; Molden et al., 2007). Only 18% of the rainwater is used effectively while 48% enters the river and most of which reaches the ocean (Hegde, 2012). Rest of it is lost to evaporation, transpiration, and runoffs. Water is also used for cleaning solar panels (Moharram et al., 2013). Two liters of water are used to clean one solar module (*Solar Power And Water Consumption*, 2009). For a medium size solar plant of about 10MW, monthly estimated water requirement is 165,000 liters (*Role of Water in Long-Term Performance of Solar PV Plants*, 2019). Rising solar power will also demand for more water, further making more water stress in the region.

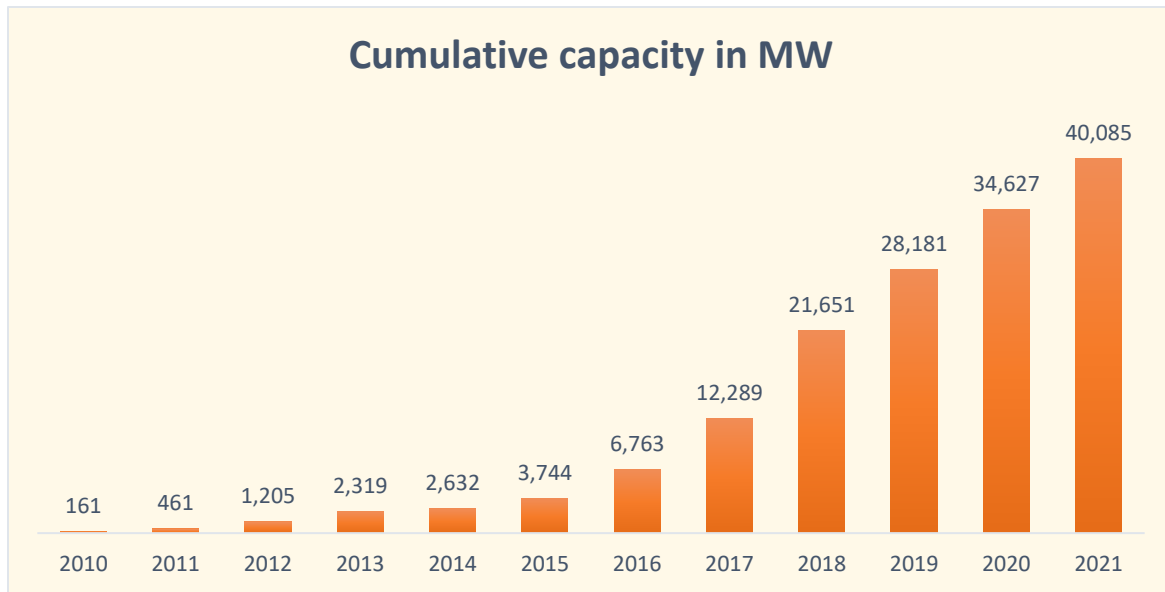


Figure 1.1 Cumulative installed capacity of solar energy.

1.2 Research Question

The primary question addressed in this study is to understand the significant growth in solar power installations in India and its potential impact on agriculture and water management in the country. The study also seeks to identify measures that can help mitigate any negative consequences and promote sustainable resource management in response to the ongoing and increasing adoption of renewable energy strategies.

1.3 Objective

The objectives of the research can be concisely summarized as follows:

- **Identification of solar farm distribution:** The first objective was to identify the distribution of PV solar farms at the national level using the newly developed Solar Panel Index (SPI). This index can be applied to open-source data, facilitating dynamic monitoring of solar farms and estimation of their installed capacities.

- **Quantification of land use change:** The second objective was to quantify the changes in land use resulting from solar farm development, as these projects often require extensive land areas, potentially leading to land encroachments.
- **Assessment of water resource availability:** Additionally, the research study aimed to assess the availability of water resources at solar farm locations in the current scenario. Given the increased water demands associated with solar farm operations, this assessment addressed the potential for water stress in these regions.
- **Evaluation of the solar energy, agriculture, and water nexus:** The study targets a specific solar farm for evaluation that aligns well with the nexus context. Through geospatial analysis and parameter assessment, it sought to understand its strengths and implications within this interconnected context.
- **Development of a Land Suitability Map (LSM):** This objective employed GIS techniques and a multicriteria decision-making model to create a land suitability map. This map serves to guide the selection of optimal locations for solar farm installations from a sustainability perspective. It involved the amalgamation of diverse data sources to generate the desired output.
- **Suggest policies:** Finally, the study put forth policy recommendations related to the implementation of solar industry projects, taking into account the perspectives of the agriculture and water industries. These policy suggestions aim to foster balanced and sustainable development while considering the needs of various stakeholders.

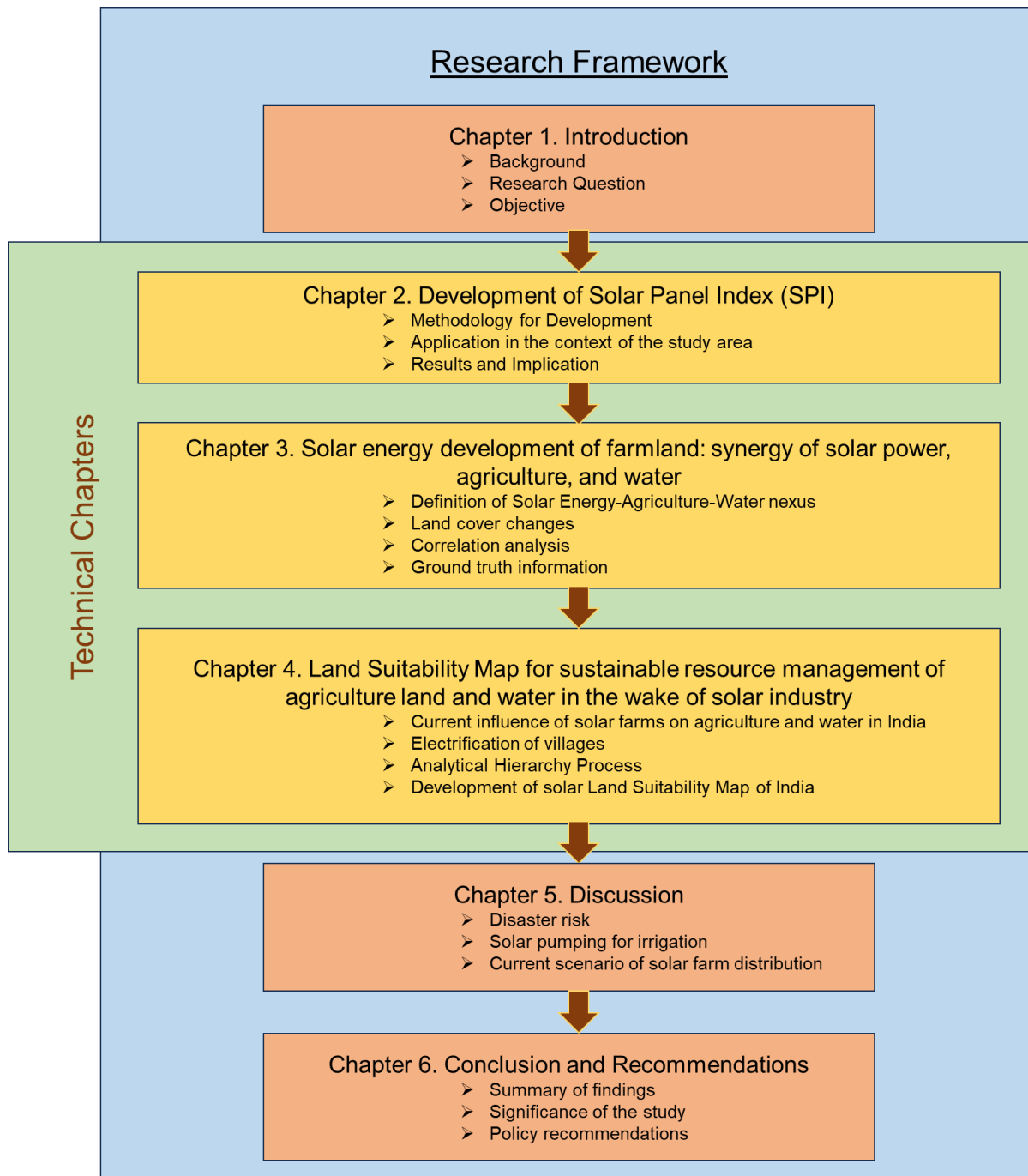


Figure 1.2 Research framework showing the flow of the study with key elements in each chapter.

1.4 Significance of the Study

The significance of this study is interdisciplinary and centers around its in-depth exploration of the intricate relationships between solar energy development, agriculture, and water resources in India.

Firstly, the research acknowledges the pressing environmental concerns arising from the rapid proliferation of solar energy projects, shedding light on the imperative need to comprehend and mitigate their ecological impacts for the sake of sustainable development. Secondly, it underscores the potential threat posed to food security in India due to the encroachment of agricultural lands for solar power plants. This is a particularly critical concern in a country where agriculture plays a pivotal role in the economy and sustenance of millions of livelihoods. Moreover, the study draws attention to the significant water requirements of solar farms and their potential contribution to water stress in regions already grappling with shortages, a vital issue in a nation facing severe water scarcity challenges.

Furthermore, the research's significance is amplified by its employment of methodologies like the Solar Panel Index (SPI) and analytical techniques such as Pearson Correlation Analysis and Analytical Hierarchy Process (AHP). These methods provide a comprehensive and data-driven understanding of the complex interactions within the food-water-energy nexus. The study also goes beyond analysis, offering a set of policy recommendations designed to promote sustainable resource management. If effectively implemented, these policies could serve as guiding principles for policymakers and stakeholders seeking to balance the competing demands of agriculture, solar energy, and water resources.

Additionally, the study advocates for an integrated and holistic approach to resource management, highlighting the importance of considering the interdependencies and trade-offs between different sectors. This approach not only has the potential to lead to more sustainable resource utilization but also carries the promise of economic growth and social development within the growing solar energy industry. In sum, this study's significance lies in its comprehensive examination of the complex and intertwined dynamics among solar energy, agriculture, and water resources in India, as well as its provision of actionable recommendations for policy and planning, making a substantial contribution to the discourse on sustainable development and resource management in the context of renewable energy expansion.

1.5 Outline of the thesis

Chapter 1; Introduction: This chapter is introductory in nature. It gives an outline of the research involve and the research background.

Chapter 2; Development of Solar Panel Index: This chapter is explanation about the newly developed solar panel index for effective monitoring of solar farms.

Chapter 3; Solar energy development of farmland: synergy of solar power, agriculture, and water: This chapter is discussing the interaction between the renewable energy solar power with agricultural practices and water management.

Chapter 4; Land Suitability Map for sustainable resource management of agriculture land and water in the wake of solar industry: This Chapter discusses about the generation of Land Suitability Map (LSM) which can be used locating ideal places for solar farm installation.

Chapter 5; Discussion: This chapter reviews and synthesizes the key findings and implications of the research.

Chapter 6; Conclusion and Recommendations: This chapter is explains the conclusion of the study with its significance and future scope.

Chapter 2: Development of Solar Panel Index

2.1 Introduction to the Solar Panel Index

The Solar Panel Index (SPI) is a novel algorithm introduced in this study that utilizes data from multispectral satellites to improve the identification of PV solar farms. It has been important in locating power plants nationwide, and enhancing the accuracy of Land Use and Land Cover (LULC) map generation. Previous studies have also demonstrated the application of computer vision algorithms on high-resolution imagery and aerial photography (Malof et al., 2015). Some research has emphasized the significance of texture in the mapping of solar power plants (Zhang et al., 2021). Numerous studies leverage Convolutional Neural Networks (CNNs) for detecting solar panels, incorporating advanced models like Faster-RCNN, a ResNet-50 classifier (Golovko et al., 2018), while others employ the EfficientNet-B7 classifier (Parhar et al., 2022) or the YOLO v5 algorithm (Huang et al., 2023). The primary sources of images are aerial datasets and satellite images, obtained through the Google Map Static API (Golovko et al., 2018) (Parhar et al., 2022). Some images exhibit lower resolution due to the incorporation of thermal bands (Vega Díaz et al., 2020). Various limitations exist, such as hardware restrictions limiting the mini-batch size for online training to a single image, potentially impacting the learning trajectory and the overall efficacy of the method (Golovko et al., 2018). If lens distortions in thermal images are not corrected, they could negatively impact the accuracy of solar panel detection (Vega Díaz et al., 2020). Additional challenges arise due to memory constraints and the associated costs of GPU instances (Parhar et al., 2022). In certain instances, the dependency on local descriptors is significant, and inaccuracies therein can result in substantial detection errors (Huang et al., 2023).

This study introduces a detection algorithm applicable to openly available optical satellite data, which can be utilized for solar capacity generation estimation. The integration of this detection index algorithm with satellite data enables real-time monitoring of solar power expansion in a straightforward manner. This research underscores the utilization of SPI in pinpointing power plant locations and conducting environmental impact analyses on a national scale. The Google Earth Engine platform has significantly streamlined workflow processing. Previous studies have evaluated potential solar power generation in India (Purohit et al., 2013), leveraging the

proficiency of remote sensing and GIS technologies (T. V. Ramachandra et al., 2011). This study continues to harness these powerful tools in the monitoring of solar power.

2.2 Methodology for Developing the Solar Panel Index

SPI is an arithmetic equation that employs six multispectral bands from widely available optical satellite data. These include the Blue, Green, and Red bands, as well as the Near-Infrared, Shortwave Infrared Band 1, and Shortwave Infrared Band 2.

Solar farms are typically installed on flat terrain with panels primarily directed towards the south (in the Northern Hemisphere). The size of these farms is determined by their capacity to produce energy at a given time, which is usually measured in watts. Solar power plants' area with a capacity exceeding 1MW, are termed as solar farms, which are focus of this study (www.solarlandlease.com/size-of-a-solar-farm). They usually cover an area upto 4 ha to 8 ha (*Solar Farm Land Requirements*, 2023). It's important to note that these farms are surrounded by various types of land, including grasslands, shrublands, croplands, and arid land, all of which may influence the surface reflectance detected by satellite sensors.

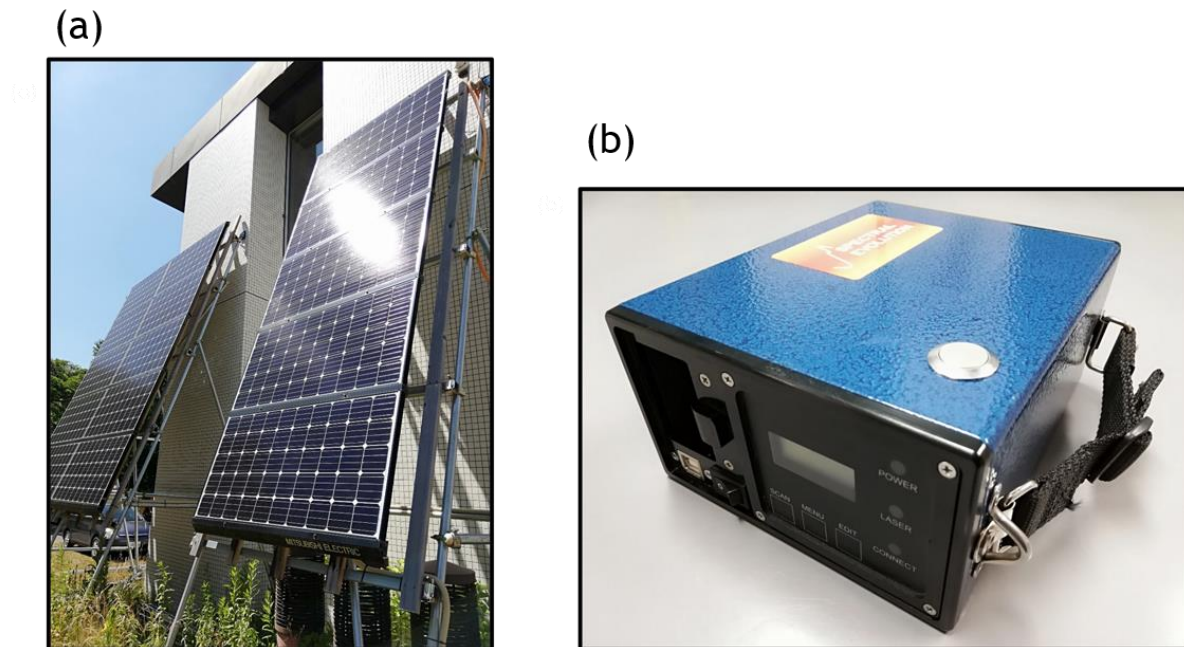


Figure 2.1 Spectrometer used for taking spectral reflectance reading from solar panels.

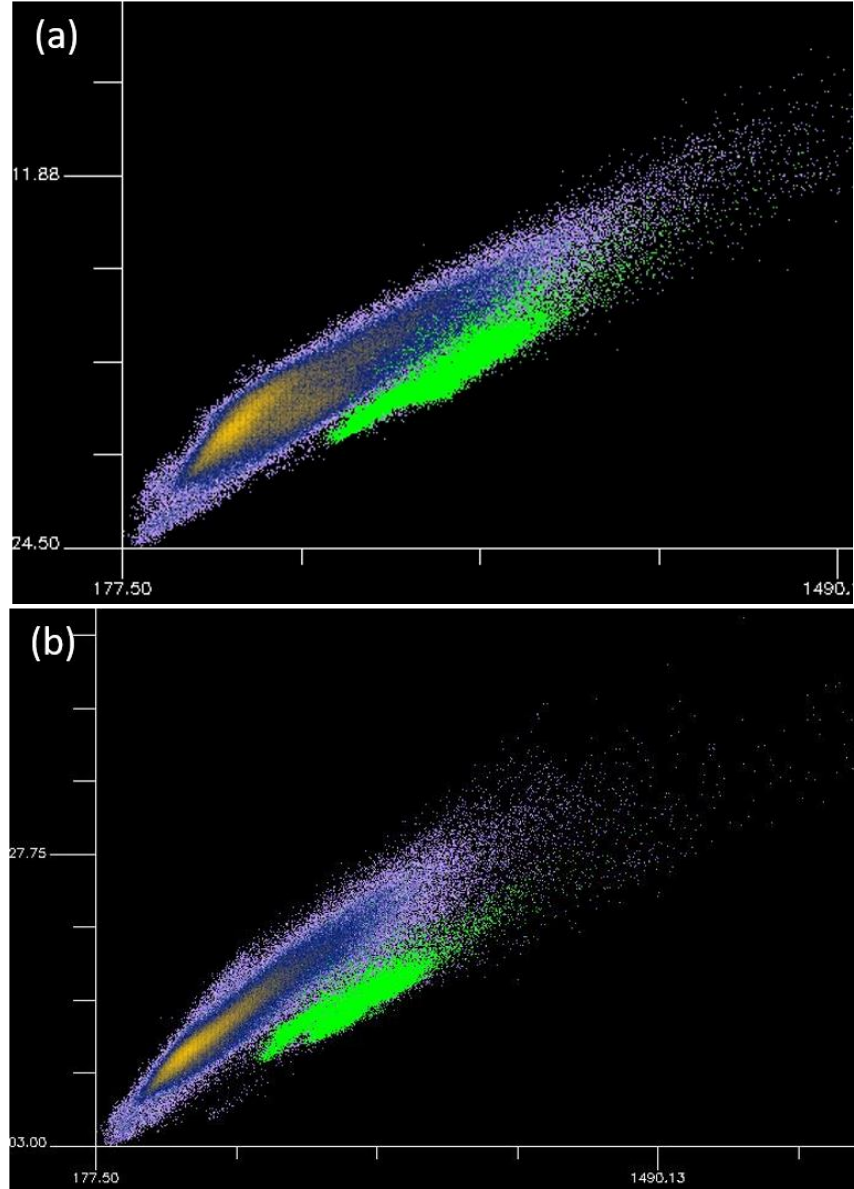


Figure 2.2 Scatter plots of multi spectral bands (a) blue-green and (b) blue-red, highlighting the distribution of solar panel pixels in green area.

The structures of these solar power plants are visible from space, making them ideal for satellite monitoring. Open-source satellite data from the Sentinel-2 and Landsat series, have been frequently used in various studies for monitoring purposes (Moon et al., 2021), and can be used to track solar expansions too. Apart satellite recordings, in-situ spectral profile of solar panels were also recorded using spectrometer as shown in figure 2.1. The SPI algorithm incorporates three bands from the visible spectrum (Red, Green, and Blue) and three bands from the near-infrared

section (Near-Infrared, Shortwave Infrared Band 1, and Shortwave Infrared Band 2). This configuration enables the SPI to cancel out background reflectance intensity, thus accentuating the solar panel area and reducing false-positive responses. To ensure diverse environmental conditions, sample points were drawn from various solar farms across the country. We first recorded and examined the spectral reflectance profiles of photovoltaic (PV) solar panels. The images used for this study were retrieved and analyzed from the Google Earth Engine. These were preprocessed and atmospherically corrected to ensure clarity in the results. Scatter plot of every bands were plotted to better understand the spectral distribution of solar panel pixels (Fig. 2.2 and Annexure A1). The surface reflectance plots were thoroughly studied to understand the reflectance pattern of PV solar modules. Subsequently, we formulated the equation as follows:

$$SPI = \frac{0.3 \times (2\text{Blue} - \text{Red} - \text{Green})}{(2\text{Blue} + \text{Red} + \text{Green})} + \frac{(2\text{SWIR1} - \text{SWIR2} - (0.7 \times \text{NIR}))}{(2\text{SWIR1} + \text{SWIR2} + (0.7 \times \text{NIR}))} \quad (1)$$

We discussed the role of SPI in the improvement of classification accuracy via machine learning, a topic that is discussed further in the 4th chapter.

2.3 Application of the Solar Panel Index in the Indian Context

India has witnessed the establishment of a multitude of solar plants of varying sizes across the country. The Solar Panel Index (SPI), developed within the scope of this study, offers a robust method for accurately identifying the locations and area coverage of these solar plants via satellite data., as illustrated in Figure 2.3. High SPI values distinctly highlight solar farms at four different locations within India. The Bhadla Solar Park (Figure 2.3b) in Rajasthan state, primarily an arid region, stands as the world's largest solar park with an installed capacity of 2,245 MW (*ALL YOU NEED TO KNOW ABOUT BHADLA SOLAR POWER PLANT*, 2022). Another notable solar park is the Kamuthi Solar Park (Figure 2.3a), situated in the far south of India, in Tamil Nadu state. Other significant solar parks include the Pavagadh Solar Park and the Kurnool Ultra Mega Solar Park, both of which are encircled by agricultural lands.

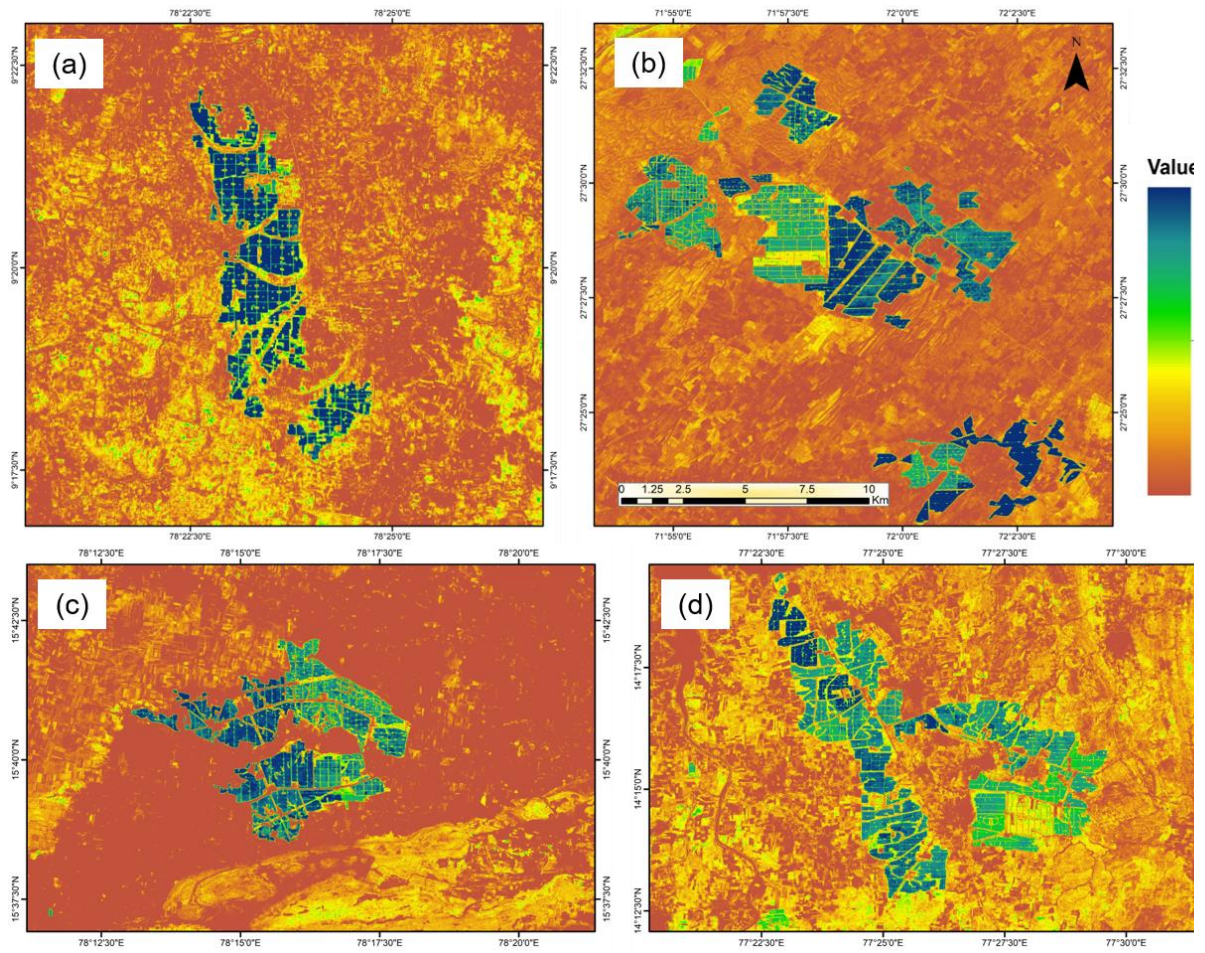


Figure 2.3 Raster layer generated using Solar Panel Index (SPI), highlighting solar panels locations at (a) Kamuthi Solar Park, (b) Bhalda Solar Park, (c) Kurnool Ultra Mega Solar Park, and (d) Pavagadh Solar Park.

Solar farms encompass a substantial land area, with a total land usage requirement of 8.9 acres per MW of installed capacity (Ong et al., 2013). This figure accounts for both the land area occupied by solar panels, constituting the direct land use, as well as other power plant structures. Specifically, the direct land use requirement for solar farms stands at 7.3 acres per MW (Ong et al., 2013). Employing the SPI method provides precise information regarding the direct land use area, which can be highly advantageous for estimating installed power capacity. In Figure 2.4, the highlighted area in blue represents the direct land use area generated by SPI, which is covered by the solar farm. Meanwhile, the shaded region with orange stripes denotes the overall land utilization.

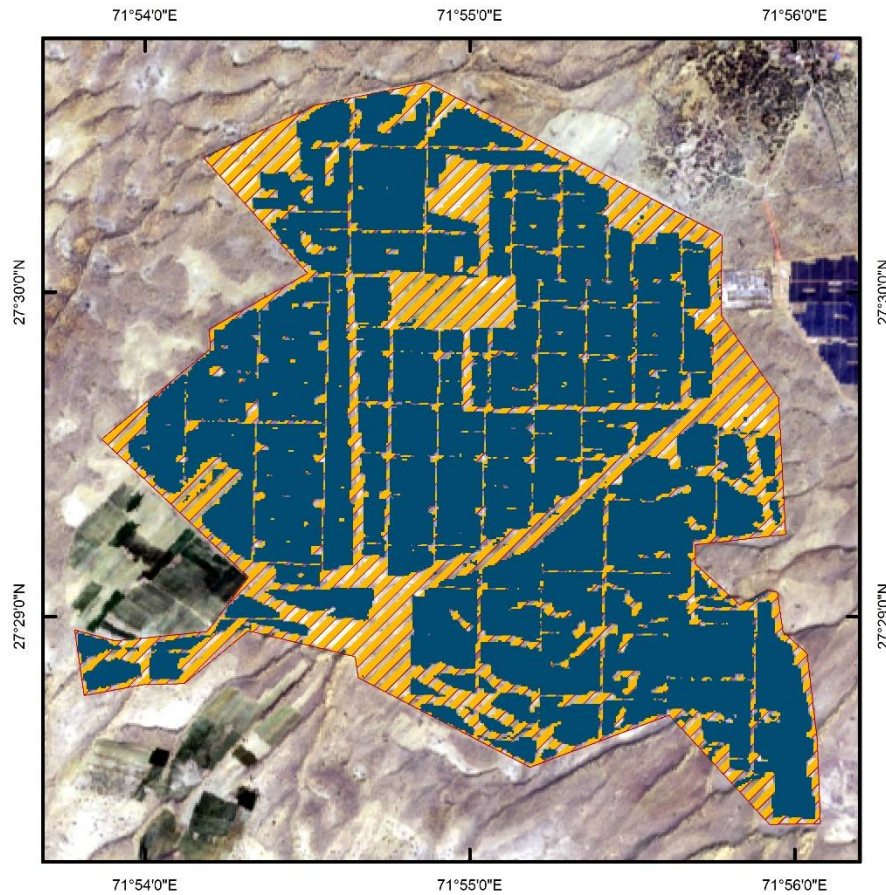


Figure 2.4 Area covered by solar farm facility and the actual area covered by solar panels installation that determines the installed power capacity.

Having precise location information for a solar power plant and its area coverage is of paramount importance for a multitude of reasons. This can be achieved by using SPI method as shown in figure 2.5, it plays a pivotal role in estimating energy production. With accurate data on the farm's location, one can calculate how much irradiance it receives, allowing for precise energy generation forecasts (Park et al., 2021). This information is instrumental in optimizing the performance of the solar power plant, ensuring it operates at maximum efficiency, and consequently, maximizing energy output. Furthermore, this precise location data is valuable for monitoring the growth of solar energy across large geographic areas and tracking the performance of existing solar power plants. By analyzing the efficiency and energy output of multiple facilities, stakeholders can identify trends and areas that may require improvement or expansion. This, in turn, aids in making

informed decisions about where to invest in new solar power plants, selecting the most suitable sites to harness solar energy efficiently, and optimizing investment strategies (Jörges et al., 2023).

Moreover, the utilization of geospatially-localized data becomes increasingly critical in the context of the energy transition. Grid operators and electricity market participants rely on accurate location information to precisely gauge the amount of energy generated by solar facilities (Kruitwagen, 2021). This allows them to manage the electricity grid effectively and balance supply and demand accurately, preventing overloads or underutilization of renewable resources. It also helps in spotting anomalies faster, such as unexpected drops in energy production, which can then be addressed promptly to ensure a steady and reliable power supply. In addition, satellite image processing offers an efficient and scalable method for tracking the expansion of solar energy across vast geographic regions (Edwards et al., 2022). By assessing energy use patterns and predicting future needs based on historical data, stakeholders can identify locations with unserved demand. This data-driven approach helps in strategically placing solar power plants where they are most needed, further accelerating the transition to cleaner, sustainable energy sources.

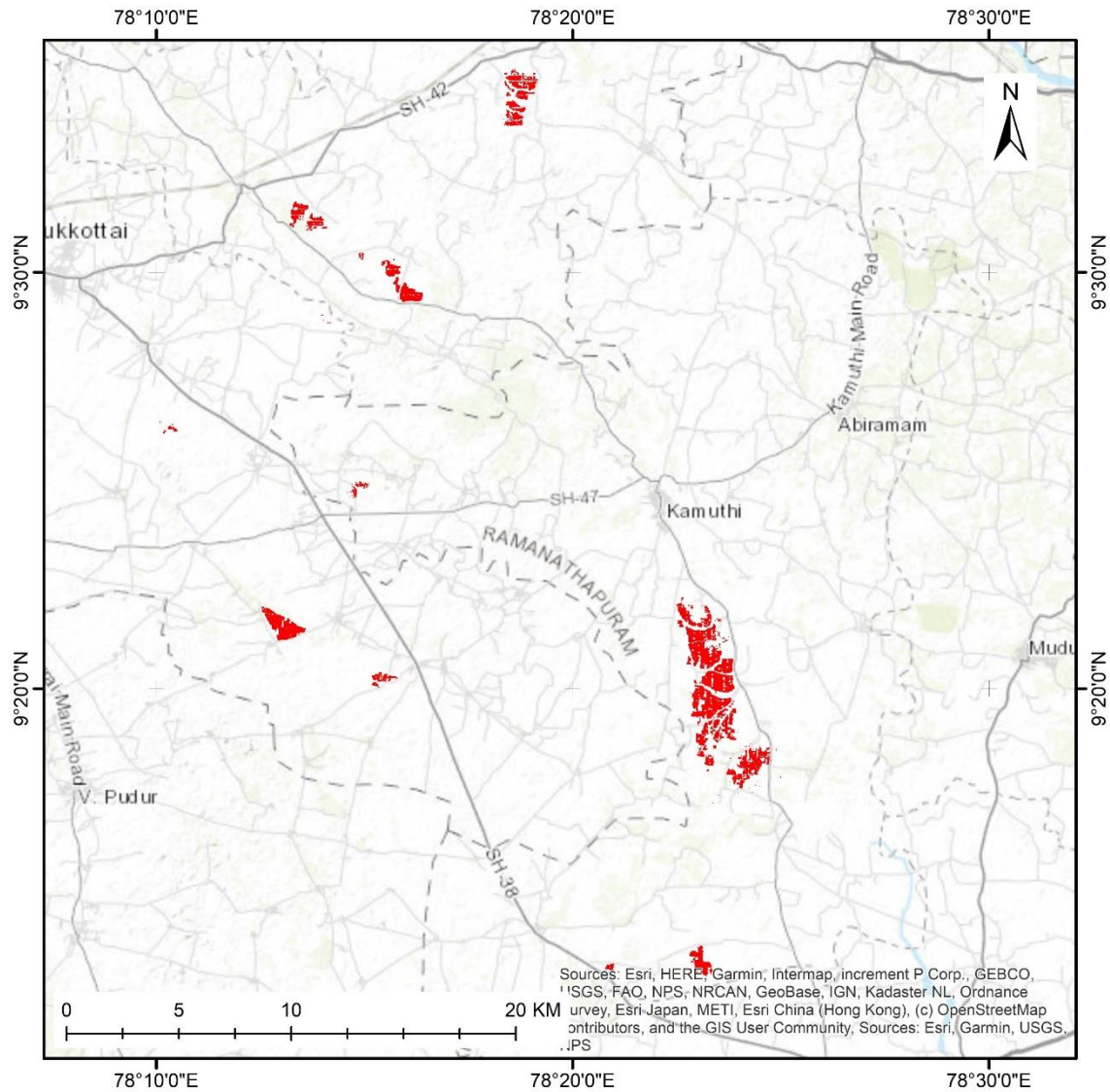


Figure 2.5 SPI derived map highlighting solar farm area in red that gives precise location and coverage of power plant through open-source satellite data.

The map in Figure 2.6 depicts the locations of solar farms in India in 2020, developed using the SPI method. Additionally, the map displays the estimated installed solar power capacity. This method has the capability to be applied to any multispectral satellite imagery, enabling dynamic monitoring of solar farms due to the frequent availability of data. This innovative approach proves highly beneficial in distinguishing solar plants from their surrounding landscapes, even under varying environmental conditions. Through the map it is noticed that solar farms are distributed

throughout the country, with a significant concentration of plants located in the states of Haryana, Maharashtra, Karnataka, and Tamil Nadu. Interestingly, despite the high solar power potential as indicated by India's national power portal, no solar farms were discovered in the northern regions of Jammu, Kashmir, and Ladakh (Annual Report 18-19 Overview, 2019).

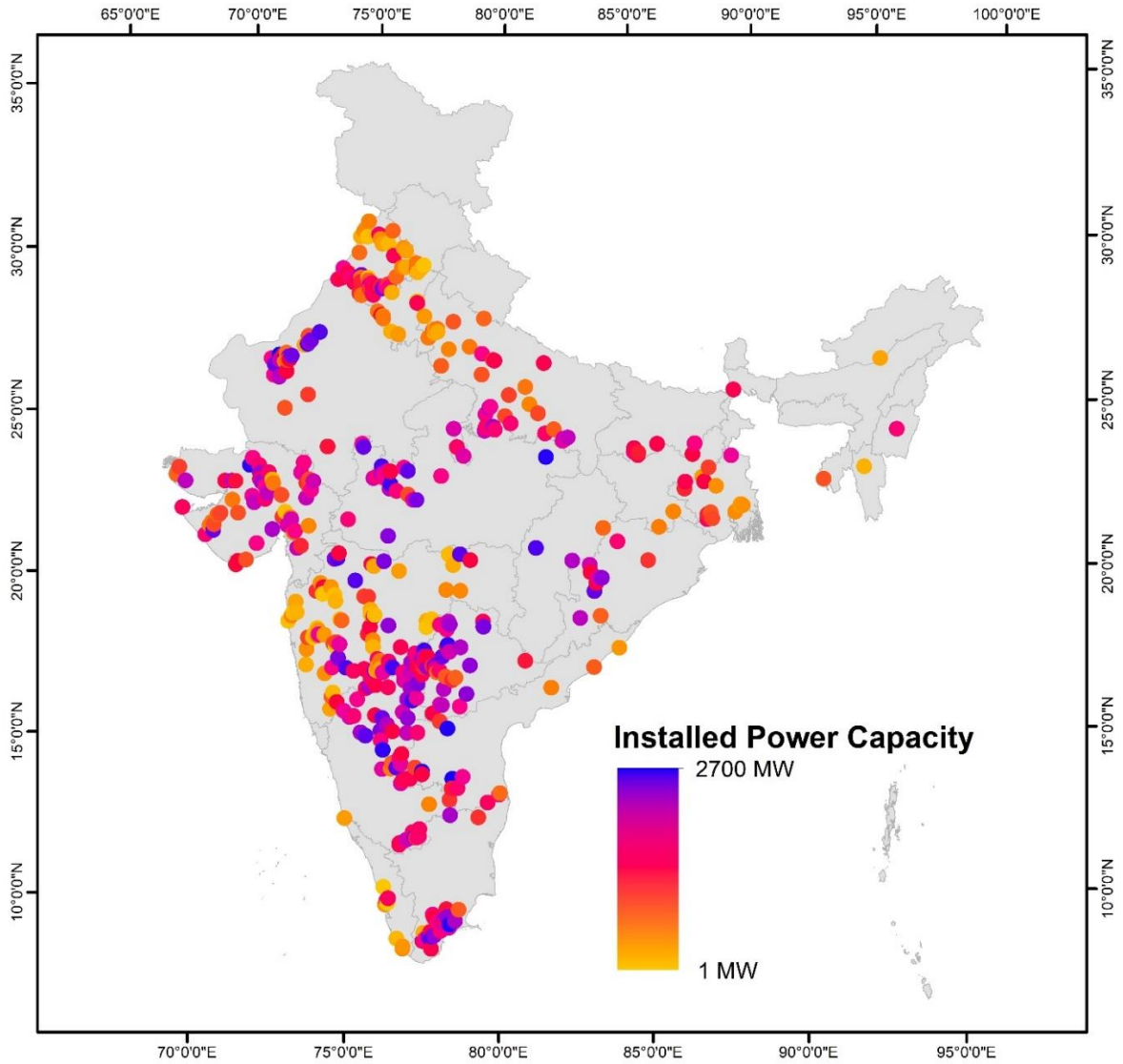


Figure 2.6 Geographical distribution of solar farms and their corresponding estimated installed capacities.

2.4 Analysis of Results and Implications

The effectiveness of SPI in detecting solar farms varies based on the differing surface reflectance intensities captured by satellite sensors in various locations. SPI pixel values range from -1 to 1, and to optimize its performance in distinguishing solar farm areas from other categories, we experimented with different threshold values, including 0.16, 0.2, and 0.24. We conducted

accuracy assessments at three distinct locations, each presenting unique environmental conditions. For these assessments, we randomly selected 1000 sample points, distributing them evenly between solar farms and non-solar farm areas. To validate our findings, we utilized high-resolution images from Google Earth. The comprehensive accuracy results for each location and threshold value can be found in Table 2.4. Remarkably, the highest accuracy of 97.8% was achieved at the Kamuthi solar farm location with a threshold value of 0.16. When considering the average accuracy across all three locations, it became evident that a threshold value of 0.16 outperformed the others, boasting an overall accuracy rate of 91.9%.

Table 2.1 Accuracy assessment of SPI at different threshold values at three different solar farm areas with diverse environmental conditions: Kamuthi, Kurnool, and Bhadla solar park.

	Threshold values			Accuracy in %
	0.16	0.2	0.24	
Kamuthi	97.8	97.2	94.8	
Kurnool	84.9	97.2	96.6	
Bhadla	93	73.5	50.7	
	91.9	89.3	80.7	

2.5 Discussion

The SPI-derived geospatial dataset locating solar farms and estimating their capacities holds immense utility across various domains. Government bodies and energy planners can use this resource to assess the current solar farm distribution and capacities, facilitating the formulation of energy policies, renewable energy target setting, and future energy planning (Resch et al., 2014). Grid operators benefit from a clearer understanding of solar farm locations and capacities, aiding the seamless integration of solar energy into the electrical grid for a stable power supply. Investors and financial institutions can utilize the dataset to identify viable investment opportunities in the solar energy sector, enabling informed decisions on funding new projects. Environmental agencies and researchers can employ the dataset to evaluate solar farm environmental impacts and implement mitigation measures in sensitive areas. Urban and regional planners can incorporate this data into land use planning, ensuring compatibility with other land uses and minimizing

conflicts. During emergencies, authorities can rely on the dataset to swiftly assess solar farm locations and capacities, prioritizing recovery efforts. Researchers, educators, and facility managers use the dataset for academic studies, operational optimization, and performance comparisons. Environmental organizations utilize it to advocate for renewable energy investment, while market analysts track solar energy market growth and trends, gaining insights into its competitiveness and expansion potential.

2.6 Conclusion

SPI algorithm has proven to be a highly effective tool for the detection of solar panels, demonstrating an overall accuracy of 91.9% when employed with a threshold value of 0.16. It can be applied to multispectral data from various sources, making it adaptable to different contexts and datasets. Additionally, the utilization of the Earth Engine platform has proven to be particularly effective for the implementation of the SPI algorithm, allowing for the generation of comprehensive datasets covering the entirety of India. This combination of SPI's accuracy and applicability, along with the efficient use of Earth Engine, holds great promise for advancing research and applications in the field of solar panel detection and monitoring, contributing to the sustainable development of solar energy resources in India and beyond.

Chapter 3: Solar energy development of farmland: synergy of solar power, agriculture, and water

3.1 Definition and Conceptual Framework of the Solar Energy-Agriculture-Water Nexus

The concept of the Solar Energy Agriculture Water (SAW) nexus highlights the connections between energy, agriculture, and water resources. To gain a deeper understanding of these relationships, we can leverage the conceptual framework of the Water-Energy-Food (WEF) nexus, which offers a valuable tool for analysis (Purwanto et al., 2021). The WEF nexus approach recognizes the interdependence of food, energy, and water systems and aims to optimize their utilization and management. Typically, this framework focuses on understanding the drivers, structures, institutions, intermediary processes, various scales involved, goals pursued, and the overall utility of WEF relationships (Itayi et al., 2021). When we apply this framework to the Solar Energy Agriculture Water (SAW) connection, we can gain valuable insights into the interrelationships among these systems and develop integrated solutions to enhance their utilization and management. For instance, solar energy can replace traditional fuels to power irrigation systems, reducing reliance on non-renewable resources and simultaneously improving water efficiency in agriculture. Similarly, adopting water-efficient irrigation techniques can help conserve water resources for other purposes while reducing the energy required for water pumping (Correa-Porcel et al., 2021). Furthermore, integrating energy into agriculture not only aids in reducing greenhouse gas emissions but also contributes to mitigating climate change. The principles of the nexus can reveal the intricate connections within the Solar Energy Agriculture Water relationship and guide us towards managing our resources in a sustainable and interconnected manner.

3.1.1 The Role of Solar Energy in the Nexus

The main motive behind solar energy is to bring sustainable, affordable, and clean energy (SDG#7). Unexpectedly it is having a severe consequence on eradication of zero hunger (SGD#2) and providing clean water and sanitation (SDG#6). ‘Solar Energy-Agriculture-Water’ (SAW) nexus is at the core of the sustainable the development of modern society. The nexus should be considered

over individual sectors in development strategies of the countries (El-Gafy, 2017). The SAW nexus (Figure 3.1) refers to the interconnected relationship between these three sectors, and how they can work together to address challenges related to sustainability, food security, and climate change. Solar energy can be harnessed in agriculture in many ways, such as using solar panels to power irrigation systems or to generate electricity for farm operations (Mérida García et al., 2018). This can reduce the reliance on fossil fuels, increase energy efficiency, and reduce greenhouse gas emissions. Water is a crucial resource in agriculture, and solar energy can help to address water scarcity by powering desalination plants, pumping groundwater, or providing energy for irrigation systems (S. Kumar et al., 2022). Additionally, solar energy can be used to power sensors and other technologies that can help farmers manage their water resources more effectively (Hernandez et al., 2019).

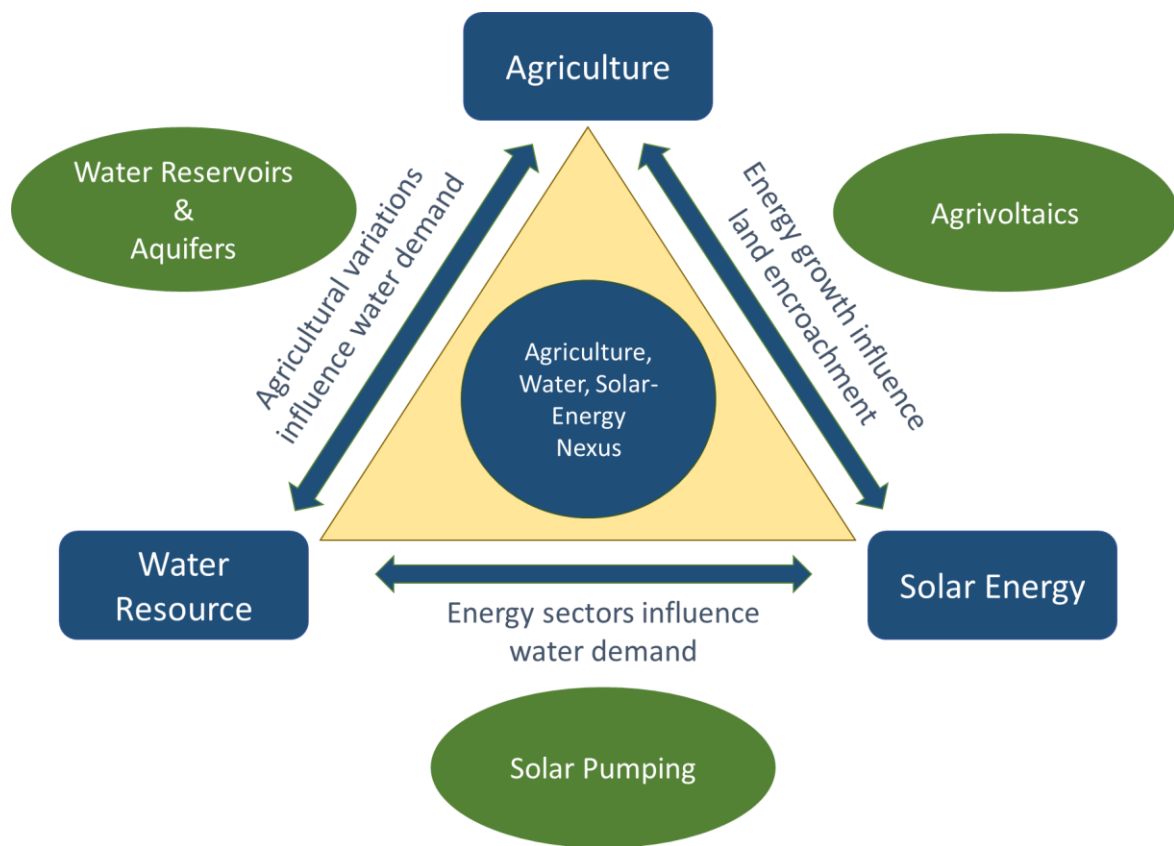


Figure 3.1 Dynamic relationship between Solar-Agri-Water nexus

In turn, agriculture can play a role in supporting the expansion of solar energy by providing land for solar farms or by integrating solar panels into their operations (Pascaris et al., 2021). This can provide additional income streams for farmers, increase the resilience of the energy grid, and support the transition to renewable energy. Overall, the SAW nexus represents an opportunity to create more sustainable and resilient food and energy systems that benefit both people and the planet.

3.1.2 Assessment of the Current Status of the Nexus in India

The current status of the SAW nexus in India is characterized by a growing recognition of the interdependence of these three critical sectors. India faces significant challenges related to water

availability, food security, and energy efficiency, making it imperative to find innovative solutions (Kholod et al., 2021). One significant development is the adoption of solar-powered irrigation systems in various parts of the country (Rakitskaya, 2021). These systems provide farmers with reliable access to water for crop cultivation, particularly in areas with limited grid connectivity. This not only aids in addressing water scarcity issues but also promotes sustainable agricultural practices (Beaton et al., 2019).

The Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) scheme is a prominent initiative aimed at leveraging solar energy to meet agricultural needs (S. K. Jain et al., 2023). The scheme focuses on installing solar power plants to incentivize farmers to use both off-grid solar pumps and "solarize" grid-connected pumps. By doing so, it seeks to enhance agricultural productivity, reduce energy costs for farmers, and contribute to the nation's renewable energy goals. Additionally, the Solar Pump Irrigators Cooperative Enterprise (SPICE) in Gujarat is a notable example of how farmers are actively engaging with solar technology (S. Verma et al., 2014). Through this cooperative, farmers have not only improved their irrigation practices but have also found a source of additional income. By selling surplus power generated by their solar pumps back to the grid, farmers in SPICE have collectively earned a lot in few years (S. Verma et al., 2014). This initiative demonstrates the potential for solar energy to empower farmers economically while contributing to sustainable water and energy practices. India is making significant strides in integrating solar energy into agriculture to address the water-energy-food nexus challenges. Initiatives like PM-KUSUM and success stories like SPICE in Gujarat are positive indicators of the country's commitment to harnessing solar power for agricultural sustainability and improving the livelihoods of its farmers.

In addition to the ongoing developments in the Solar Energy-Agriculture-Water nexus in India, it's important to consider how the presence of dominant energy industries can influence the dynamics of the broader Energy-Population-Urbanization nexus within society. Previous studies, have shed light on how these industries shape the interplay between energy, population growth, and urbanization. Moreover, some studies have employed the 'Life Cycle Assessment' (LCA) approach, a quantitative tool designed to evaluate the environmental advantages of various energy alternatives. This approach, allows for a comprehensive assessment of the environmental impact associated with different energy sources and technologies (Yuan et al., 2018). As India continues

to explore the potential of solar energy in agriculture and other sectors, it is crucial to integrate these findings into holistic policy and planning efforts that address the interconnected challenges and opportunities in the nation's energy and sustainability landscape.

3.1.3 Focus of the study region

In this research case study, our focus centered on a specific geographical location, Pavagadh solar park, to conduct an in-depth analysis of its impact on surrounding agricultural and water management practices. To unravel the intricate relationships within the SAW nexus, we employed a combination of GIS tools and techniques, complemented by various analytical methods. Our objective was to uncover the subtle connections and dependencies between these sectors, revealing how the presence of a solar farm influences the agricultural and water resource dynamics in the region. By harnessing the power of geospatial analysis and advanced analytics, our study aimed to provide valuable insights into the sustainable coexistence of solar energy production, agriculture, and water resource management in this specific context.

The Karnataka Renewable Energy Development Ltd (KREDL) and the Solar Energy Corporation of India (SECI) founded the Karnataka Solar Power Development Corporation Ltd (KSPDCL) in March 2015 with the intent to inaugurate solar power initiatives in Karnataka (Poovana, 2017). The project spans an expansive area of 5,260 ha, encompassing the five villages of Balasamudra, Tirumani, Kyataganacharlu, Vallur, and Rayacharlu (GoK Order Dated 29-10-2015 According in-Principle Approval to Establish 2000MW Pavagada Solar Park, 2015). The selection of Pavagada as the project's site was dictated by availability of high solar radiation. Pavagada taluk is located at an elevated plateau in a semi-arid region surrounded by rocky hills, which the state Government had declared as drought-stricken several times in past 60 years (Poovana, 2017). Solar power plant companies have adopted a practice of leasing land from agricultural landowners instead of buying it outright. This approach enables farmers to maintain ownership of their land while benefiting from a steady stream of rental income.

The Pavagadh solar power plant project, however, has raised certain concerns, particularly pertaining to its potential impact on local water scarcity and soil quality (Lakshmi prasada, 2021). This model of leasing instead of purchasing land can be seen as a symbiotic relationship, where

both the solar companies and the landowners stand to gain. The companies gain access to the necessary land for their operations, while landowners can enjoy a steady income source without relinquishing their ownership rights. However, it is essential that these operations do not exacerbate local environmental challenges. In the case of the Pavagadh solar power plant, this balance is crucial to ensuring the project's sustainability, as its potential effects on water scarcity and soil quality could significantly impact the local environment and agricultural practices. Therefore, it's crucial that such potential impacts are thoroughly investigated and mitigated to ensure sustainable development.

3.2 Data and methods

3.2.1 Machine learning based map generation

The utilization of machine learning models has become increasingly prevalent in the creation of Land Use Land Cover (LULC) maps, with numerous studies demonstrating the effectiveness of this approach in producing high-quality and exceptionally accurate land cover maps (Talukdar et al., 2020). Among the various methods employed, the Random Forest (RF) machine learning algorithm has consistently produced the highest accuracies (Cánovas-García et al., 2017; Schonlau & Zou, 2020). Accordingly, we adopted the RF algorithm in our study. The RF algorithm is a supervised machine learning technique that leverages ensemble learning to combine predictions from multiple decision trees, ultimately yielding a strong result (Breiman, 2001). Studies have also demonstrated the application of correlation analysis techniques with LULC classes to determine the strength of correlation among the classes (Arrighi & Castelli, 2023).

3.2.2 Correlation analysis

Correlation analysis serves the purpose of assessing the strength and direction of the relationship between two variables. It enables the identification of the extent of association between these variables, as well as whether the relationship is positive or negative in nature. For measuring the linear relationship between two continuous variables, Pearson correlation analysis is employed. This analysis quantifies the strength and direction of the relationship on a scale ranging from -1 (indicating a perfect negative correlation) to +1 (indicating a perfect positive correlation), and 0

indicates no correlation. It was used to determine the relationship between land use and land cover (LULC) and land surface temperature (LST) in Abuja Municipal, FCT, Nigeria (Awuh et al., 2019). This method was helpful in determining the relationships within the SAW nexus. On the other hand, Canonical correlation analysis (CCA) is employed to measure the relationship between two sets of variables. CCA is a statistical technique used to identify and measure the relationships between two sets of variables. It identifies the linear combinations of variables in each set that are most strongly correlated with one another, and quantifies the strength of these correlations in terms of a canonical correlation coefficient. It is a valuable tool for determining the degree of association between these sets and uncovering the underlying factors contributing to this relationship. Previously, it was used to assess the correlation between land-use conflict potential and LULC in Chengdu, China (J. Chen et al., 2023).

3.3 Land use changes

Annual LULC maps were generated using the ‘Random Forest’ machine learning algorithm and applied to Landsat images using Earth Engine prowess. Cloud-free annual Landsat images were retrieved from the year 2007 to 2022. The Pavagadh solar power park commenced its building from the year 2017. This way, the considered time period covers the analysis years before and after the onset of the power plant. The accuracy assessment of the model will be explained in the later section of this chapter. The geographical scope for LULC map generation covered the solar farm area and the adjacent buffer regions extending up to 5 kilometers, all of which primarily constituted agricultural crop land. The LULC map was categorized into five distinct classes: PV Solar panels, Crop land, Trees, Water bodies, and fallow land. Figure 3.1 illustrates the LULC map, which encompasses the power plant and its surroundings within a 5-kilometer boundary, featuring water bodies (reservoirs) and cultivated agricultural land of four years.

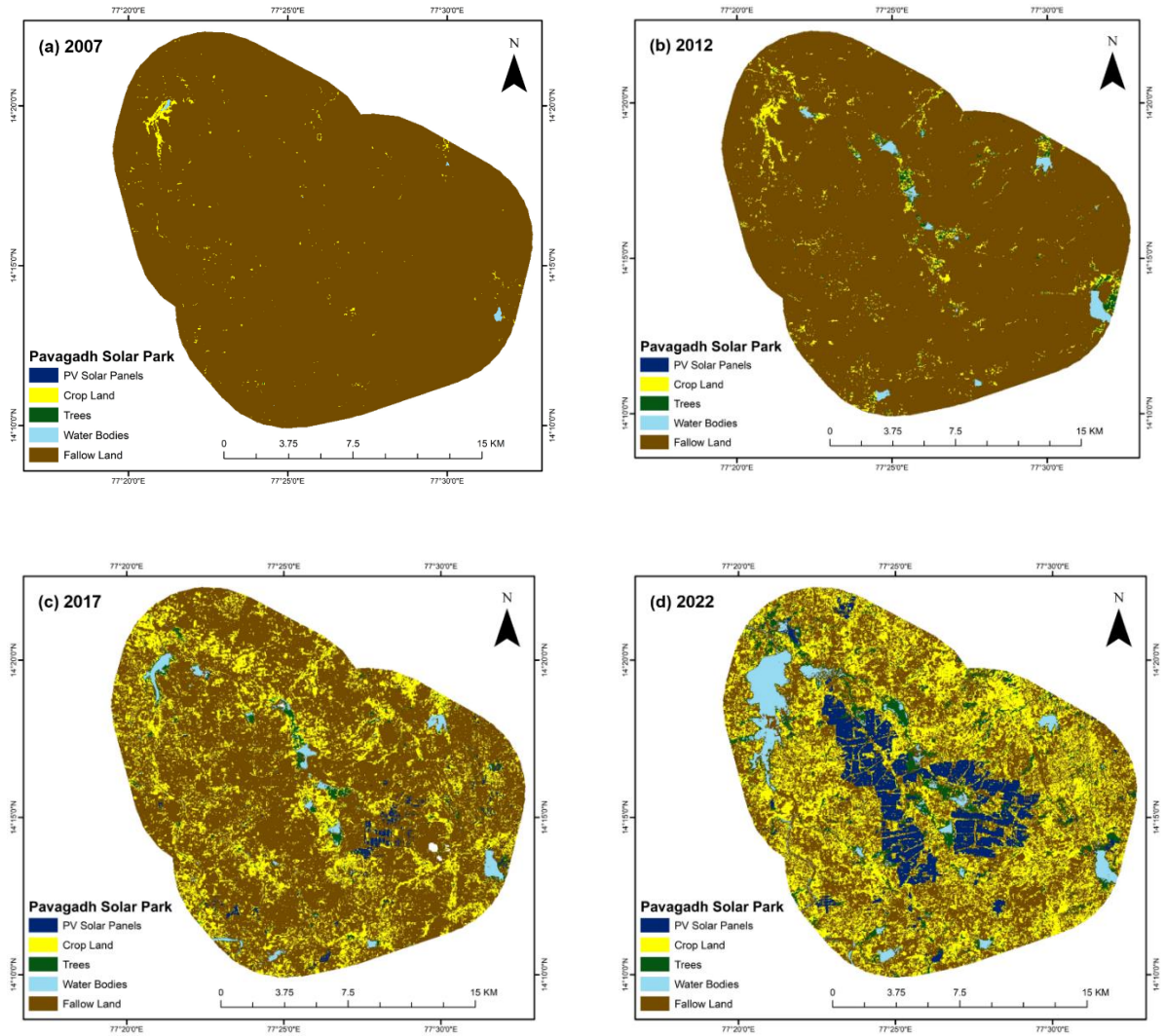


Figure 3.2 LULC of Pavagadh solar park area and its surrounding boundary upto 5km in the years (a) 2007, (b) 2012, (c) 2017, and (d) 2022

To gauge the strength and direction of relationships among agricultural and hydrological variables within the context of the Solar Energy-Agriculture-Water (SAW) nexus, we employed the Pearson Correlation Coefficient. This analytical tool allowed us to discern patterns and trends within the LULC classes, revealing their implications for solar energy, agriculture, and water management. This approach is an effective method for nexus evaluation (Ajjur & Al-Ghamdi, 2022). Statistics were derived by tracking the area coverage of LULC classes annually from 2007 to 2022. There was a strong positive correlation between solar power and agriculture ($r = 0.877$), indicating that

the solar power plant is beneficial for surrounding agricultural areas (Table 3.1). A moderate positive correlation between solar and water ($r = 0.205$). The result suggests that solar power generation is positively affected by the availability of water in the surrounding areas. This could be due to the fact that solar panels require water for cleaning and cooling, and the availability of water could improve the efficiency of the solar panels (Shaju & Chacko, 2018). Our results suggest a relationship between LULC classes and their surrounding areas; Agricultural land area, water body extend, and solar power plants expansion benefitted from each other.

Table 3.1 Pearson correlation (r) among the classes of nexus.

	Solar	Agriculture	Water
Solar	1		
Agriculture	0.877	1	
Water	0.205	0.052	1

Canonical correlation analysis (CCA) was separately performed on the solar power park. Independent variables were LULC classes, solar power plants, agriculture, and water bodies; dependent variables were the production values in tons for cereals, millets, pulses, oilseeds, fruits, and vegetables in tons, as well as the area of cropped land, canals in hectares, and groundwater level. Required data for the analysis was acquired from ICRISAT (data.icrisat.org/dld/src/crops) (Mohanasundaram et al., 2023). It provides comprehensive collection of agricultural data related to irrigation. The groundwater level information is available in the IndiaWRIS repository (indiawris.gov.in/wris/) (Manivannan et al., 2022), was very useful in analyzing the relationship. It provided data on precise location where the GW stations were located, in the vicinity of power plants. The parameter with the greatest significance was cereals; its canonical correlation coefficient (r) of 0.804 indicated a strong correlation between cereal production and the LULC classes of the solar power plant, agriculture, and water bodies (Table 3.2). The R-squared value of 0.64 indicated that the model explained a large proportion of the variation in cereal production. Other parameters (e.g., total cropped area, millets, pulses, and oilseeds) had lower correlation coefficients and R-squared values, indicating weaker associations with LULC classes. However,

they remained statistically significant, with canonical correlation coefficients ranging from 0.46 for millets to 0.76 for pulses. Overall, the CCA results suggest that LULC classes, solar power plants, agriculture, and water bodies have moderate to strong relationships with the production values for cereals, millets, pulses, oilseeds, fruits, and vegetables, as well as the area of cropped land, canals in hectares, and groundwater level. This indicates that SAW nexus in Pavagadh solar park have good influence on agricultural sector on district level, and groundwater level in the locality.

While the insights of the correlation analysis are valuable, it is important to acknowledge its limitations. It can be attributed largely to data scarcity. Further studies with more comprehensive data can provide a more definitive understanding and potentially validate our findings.

Table 3.2 Canonical Correlation Analysis (CCA) between the nexus and the parameters.

Parameters	SAW LULC variation			
	Canonical Correlation	R-Squared	F-Value	Wilk's Lambda
Cropped area	0.66	0.44	1.08	0.55
Cereals	0.8	0.64	2.45	0.35
Millets	0.46	0.21	0.36	0.78
Pulses	0.76	0.58	1.87	0.41
Oilseeds	0.76	0.57	1.83	0.42
Fruits and Veg	0.82	0.68	2.91	0.31
GW bgl	0.60	0.37	1.77	0.62
Canals area	0.94	0.88	10.75	0.11

The utilization of land resources is a critical factor involved in planning and building societies. It directly or indirectly impacts the environment, ecology, economy, lifestyle, and other aspects of society. The recent surge in solar plant projects has led to irreversible changes in the environment. The SPI method is effective for mapping solar farms and has great potential for future efforts to achieve continuous monitoring of panels. The method solely relies on optical satellite data and can be easily implemented using widely used Landsat and Sentinel-2 images. Using SPI, the LULC classification overall accuracy increased from 81.02% (Table 3.3) to 89.72% (Table 3.4) with

Kappa coefficient increasing from 0.75 to 0.86 respectively. In all, 253 validation points were recorded with reference to high resolution Google Earth images. The SPI algorithm holds high potential in future for solar power expansion monitoring.

Table 3.3 Accuracy assessment: validation error matrix without SPI.

	LULC Classes					Producer accuracy
	Solar	Agri	Other	Water	Trees	
Solar	50	0	1	0	0	0.98
Agri	0	43	3	0	3	0.88
Other	6	16	66	0	0	0.75
Water	0	0	0	29	0	1.00
Trees	1	10	5	3	17	0.47
User accuracy	0.88	0.62	0.88	0.91	0.85	
Kappa coefficient	0.75					
Overall accuracy (%)	81.03					

Table 3.4 Accuracy assessment: validation error matrix with SPI.

	LULC Classes					Producer accuracy
	Solar	Agri	Other	Water	Trees	
Solar	50	0	1	0	0	0.98
Agri	0	47	1	0	1	0.96
Other	0	10	78	0	0	0.89
Water	0	0	1	28	0	0.97
Trees	0	6	4	2	24	0.67

User accuracy	1.00	0.75	0.92	0.93	0.96
Kappa coefficient	0.87				
Overall accuracy	89.72				
(%)					

3.4 Field visit

Agriculture is at the core of India's economy; it is affected by various factors such as climatic and weather conditions, precipitation, field planning, sowing methods, and plantation orientation. Agricultural land encroachment for the construction of solar power plants has recently increased. Farmers choose to invest in electric power production over food because power production is more profitable. This short-term benefit can have long-term impacts on the food industry. A field visit to solar power plants in Maharashtra (Figure 3.2) provided us with an opportunity to collect soil samples from below the panel structure and analyze them for any changes. We investigated the microbial populations within the topsoil (0-15 cm) of both solar panel sites and agricultural farms. Typical topsoil microbial communities consist of nematodes and protozoa (10^3 colonies), algae and fungi (10^5 colonies), and actinomycetes and bacteria (10^7 colonies). Our results (Table 3.5) revealed a significant difference in the concentration of algae and fungi, particularly in the soil beneath solar panels. The expected concentration ranges for these microorganisms are 1-50 and 100-1500, respectively (Reponen et al., 1992). This observed disparity may be attributed to the damp conditions created under the solar panels, which foster a wet, humid, and anaerobic environment compared to other locations. Such conditions could lead to an increased presence of algae and fungi within the soil (Sabaratnam & Traquair, 2002). Additionally, we found that the concentrations of nematodes and protozoa in agricultural farms were primarily influenced by the availability of nitrogen, a result of fertilizer application (Forge et al., 2020). This nutrient-rich environment promotes microbial activities related to mineralization, including nitrification, denitrification, and ammonification. The soil's parameters, including Organic Carbon (%), Phosphorus, and Boron, were also examined (see Table 3.6). A notable decrease in these parameters was observed in the soil beneath solar panels. This decline could be attributed to the limited exchange of natural gases, a crucial aspect of the nutrient cycle. The Organic Carbon content in soil is classified as medium quality when it ranges from 3-6%, whereas low quality is

defined by a range of 1-2% (Kuśmierz et al., 2023). Similarly, Phosphorus content is considered medium when it falls between 12.4 and 22.4 kg/ha, and low when it is below 12.4 kg/ha (Ravikumar, 2013). The soil under solar panels appears to have parameters indicative of low nutrient content. For Boron, a concentration above 1 ppm is regarded as adequate (Kot, 2015). These findings demonstrate the potential impact of solar panel installations on soil microbial communities. Further details study is necessary to understand the overall influence of solar structure on soil.

Many regions in India are experiencing water shortages; fluctuations in precipitation and rainfall negatively affect crop production and daily water consumption by society. Similarly, solar farms require water to clean panels effectively; without such cleaning, power plant efficiency declines. In some power plants, water is extracted from groundwater wells (Figure 3.5b). In some power plants self-cleaning robots are used. Such robots perform daily operations of cleaning without any external source of water or electricity (Figure 3.5c). Based on the field visit to Bhadla solar power park we got to know that, in most solar power plants, water is being transported from the Indira Gandhi Canal. It is located at a far distance from the power plant. While some of the power plants within the parks were using automated cleaning robots, which require no water consumption, and runs solely on their own solar power source. This shows the importance of having self-cleaning robots. The application of cleaning robots is an effective choice yet is quite expensive. Hence, some kind of incentive in the use of robots could bring positive change in water utilization.



(a) 80MW Avaada Solar power plant, Chalisgaon, Maharashtra



(b) Underground water extraction from the well



(c) Self-cleaning robots in action

Figure 3.3 Field visit to (a,b) Avaada solar power plant and (c) Hitachi solar power plant in Maharashtra India.

Table 3.5 Microbial activity of top soil from agricultural land (A) and under solar power plant site (S).

Parameters Dilution	Estimated CFU/gm		
	10^3	10^5	10^7
A	680	19	2
	*	26	0
	828	28	4
	*	9	0
	*	40	0
S	*	31	3
	*	25	0
	*	86	1
	*		

Table 3.6 Parameters content of the soil from agricultural land (A) and under solar power plant site (S).

Parameters	A	S
pH	7.9 ± 0.1	8 ± 0.1
EC	0.452 ± 0.1	0.625 ± 0.1
Organic Carbon (%)	0.41 ± 0.1	0.29 ± 0.04
Nitrogen (Kg/Ha)	357.5 ± 70.7	288.51 ± 20.8
Phosphorous (Kg/Ha)	20.26 ± 6.2	8.1 ± 2.3
Potassium (Kg/Ha)	431.42 ± 59.3	377.66 ± 18
Sulphur (ppm)	12.7 ± 3.9	12 ± 1.3
Boron (ppm)	2.15 ± 0.6	1.1 ± 0.4
Zinc (ppm)	0.77 ± 0.2	0.69 ± 0.1
Ferrous (ppm)	6.5 ± 0.9	5.2 ± 0.4
Manganese (ppm)	3.8 ± 0.7	4.8 ± 0.4
Copper (ppm)	0.18 ± 0.1	0.21 ± 0.03

3.5 Discussion

Environmental Social Impact Assessment (ESIA) serves as a critical process for systematically evaluating the potential social and environmental consequences of proposed projects or developments (Mkateko, 2021). This analysis of social, environmental, and economic impacts plays a pivotal role in aligning the sustainable development objectives pursued by international organizations, governments, and businesses worldwide (Alomoto et al., 2022). At its core, ESIA operates as a tool for identifying, predicting, and rigorously evaluating the prospective effects of a project on both the environment and the communities residing in the project's vicinity (Corvo et al., 2021). By examining these potential impacts comprehensively, ESIA contributes significantly to ensuring the sustainability of development initiatives, safeguarding against any detrimental consequences on the environment or the well-being of local populations (Dendena & Corsi, 2015). Moreover, it plays a crucial role in proactively identifying strategies to mitigate any adverse effects that might arise because of the project (Vanclay, 2020). In the context of a large-scale solar power park project in India, the application of ESIA becomes imperative (Omenge et al., 2020). The ESIA process serves as a vital mechanism for systematically identifying, predicting, and assessing the project's potential impacts on both the environment and the local communities within the project's sphere of influence (Negatu, 2017). Its objective is to guarantee the sustainability of the development endeavor, assuring that it neither harms the environment nor negatively affects the livelihoods and well-being of the people residing in the solar farm area (Scheepers, 2019). This process holds paramount importance in evaluating the sustainability of any mega project. While certain large-scale ventures like coal mines, power plants, and extensive hydroelectric projects requires official environmental and social impact assessments as a prerequisite, renewable energy projects, including solar, often proceed without such approvals (D. Ghosh et al., 2022).

Significant and unexpectedly positive progress has been observed in the vicinity of solar farm areas, particularly in relation to agricultural practices. The results (figure 3.2), clearly illustrate a substantial increase in irrigation practices since the onset of solar power plant installation. This phenomenon can be attributed to the transformative impact of solar power generation, which introduce a surge in electricity supply that can be readily diverted to support irrigation processes (Agrawal & Jain, 2019; Kelley et al., 2010). The deployment of electric motors and similar devices for groundwater extraction becomes possible, encouraging efficient water utilization in farming

(Islam et al., 2017; Nikzad et al., 2019; Shinde & Wandre, 2015; Wazed et al., 2018). Additionally, the construction of solar power plants often supports the creation of water reservoirs and canals within the region, facilitating water storage and its subsequent utilization for irrigation purposes (Kougias et al., 2016; Usmani et al., 2021). Canal top solar panels have become a popular choice of sustainable solution (Cohen & Hogan, 2018; Dixit, 2020; V. Kumar et al., 2021; Sairam & Aravindhana, 2020; Sajimon & Chacko, 2017; Vishwakarma et al., 2021). The synergy between solar power generation and the construction of reservoirs and canal systems was observed during a field visit to the Avaada solar park in Jalgaon district. Furthermore, certain solar farms, such as the Kurnool solar park, proactively develop dedicated water reservoirs to support solar energy operations (Meeena et al., 2019).

Despite observable changes in soil microbial activity induced by the presence of solar farms, the land remains suitable for agricultural purposes. The concept of agrivoltaics, encompassing the installation of solar panels on agricultural land to optimize land utilization and enhance productivity, emerges as a viable strategy (Al Mamun et al., 2022; Dinesh & Pearce, 2016; Trommsdorff et al., 2021). Agrivoltaics involves integrating crops with photovoltaic panels, which are strategically elevated to accommodate farm machinery passage underneath (Dupraz, 2023; Edouard et al., 2023; Sarr et al., 2023). The configurations of agrivoltaic systems can vary, encompassing conventional solar panels positioned atop crops or the establishment of semi-transparent PV panel greenhouses (Lu et al., 2022; Moreno et al., 2023; Torrente et al., 2024; Wydra et al., 2023). The benefits of agrivoltaics encompass enhanced land yield, reduced water consumption for irrigation due to partial shading from photovoltaic modules, and the generation of supplementary income streams for farmers, enabling reinvestment for improved competitiveness (Agir et al., 2023; Chauhan et al., 2018; Giri & Mohanty, 2022). Nonetheless, certain considerations and limitations accompany the implementation of agrivoltaic systems. These include restrictions on the size and efficiency of farm machinery that can operate within and between the solar panel frames (Gorjian et al., 2021). The coexistence of agriculture and photovoltaic power generation through agrivoltaics addresses the escalating competition for land resources between agricultural and renewable energy pursuits, which is particularly relevant in the Indian context (P. Jain et al., 2021; Poonia et al., 2022). These studies emphasize the potential for increased crop yield and improved panel efficiency, executing agrivoltaics an appealing prospect

for farmers and solar developers alike. Specifically, grape crops in India have demonstrated significant agrivoltaic potential (N. Chen et al., 2018; N. M. Kumar & Chopra, 2023; Sreekar et al., 2022). Preliminary modeling studies have indicated that the implementation of agrivoltaic systems may not only sustain food yields for grape crops but also enhance the revenue generated by farms adopting this innovative approach (Trommsdorff et al., 2022).

3.6 Conclusion

Through correlation analysis a strong interconnectedness can be seen between the components of SAW nexus. As solar power installations have increased, we observed a corresponding rise in waterbody reservoirs and increased irrigation practices in the surrounding areas. This phenomenon has contributed to a more sustainable approach to resource utilization, highlighting the positive impact of solar power on agricultural practices and water management. Furthermore, the implementation of the SPI has proven to be instrumental in enhancing the classification accuracy of our geospatial dataset. SPI has facilitated the efficient detection and monitoring of solar panels, providing valuable insights for sustainable energy planning and management. However, it is imperative to recognize that as solar power expansion continues, measures must be taken to ensure the long-term maintenance of soil quality and fertility. This involves addressing potential soil disturbances caused by solar farm development and implementing strategies for soil preservation and restoration.

Chapter 4: Land Suitability Map for sustainable resource management of agriculture land and water in the wake of solar industry

4.1 Introduction to sustainability in the context of solar energy, agriculture, and water

Solar energy presents a compelling and stable solution for advancing sustainable agricultural practices. These systems can provide the necessary electricity for essential agricultural functions, including water pumping and the adoption of water-efficient irrigation methods for crop cultivation. Furthermore, solar energy can be harnessed for post-harvest food processing and storage. By aligning solar energy initiatives with supportive policies, capacity building efforts, and the introduction of affordable on-farm irrigation water management technologies, it can effectively alleviate the strain on limited water resources while simultaneously enhancing agricultural productivity and the well-being of rural communities.

4.1.1 Importance of solar energy in promoting sustainability

Solar-based irrigation emerges as a promising, cost-effective, and transformative technology poised to elevate smallholder agriculture, strengthen household water security, and contribute to climate-smart agricultural development. While rural farmers historically considered solar-powered irrigation as complementary to rainfed agriculture, a recent study (Birhanu et al., 2023) has unveiled that approximately 20% of available land in two districts is suitable for investment in solar-based irrigation. The practical utilization of land plays a vital role in preserving the sustainability of energy, food, water resources, and natural ecosystems. Introducing solar energy development within agricultural landscapes reveals land-sparing prospects that are helpful in achieving these crucial goals. A case study in California's Great Central Valley illustrates the immense potential for solar energy development within such landscapes (Hoffacker et al., 2017). Agrivoltaics represents a symbiotic relationship where both solar panels and crops mutually benefit, enhancing their respective performances. Solar panels integrated into agricultural land not only generate renewable energy but also provide shade that benefits crop growth. This innovative technology holds the promise of enhancing food production, curbing water usage, and generating additional revenue streams. Remarkably, recent estimates (Proctor et al., 2020) indicate that

dedicating just 1% of American farmland to agrivoltaics could significantly contribute to national renewable energy targets while simultaneously conserving water and establishing a sustainable long-term food production system.

However, it's essential to maintain a balance, as the complete conversion of agricultural land into solar farms could potentially reduce the land available for crop cultivation, posing a threat to food security. (*Factcheck: Is Solar Power a 'Threat' to UK Farmland?*, 2022). This is particularly concerning in regions where arable land is already scarce. Moreover, solar panels can impact local water cycles. They might reduce groundwater recharge by limiting the amount of rainwater that seeps into the ground, and affect local microclimates, potentially altering the suitability of the area for certain crops. Another concern is that the increased demand for water to clean solar panels could exacerbate water shortages in areas already experiencing water stress. This is particularly important in arid regions that are attractive for solar power due to their high solar irradiation (Supe et al., 2020). While solar power is a critical part of our renewable energy future, careful planning and management are needed to ensure that its expansion does not negatively affect agricultural practices and local ecosystems.

4.1.2 Application of GIS in sustainable management of solar energy–agriculture–water Nexus

GIS is a versatile tool that has found extensive applications within the context of the SAW nexus. One of its key roles is in identifying prime locations for solar farms. By considering factors such as solar irradiance, land use patterns, and proximity to water sources, GIS ensures that solar installations are strategically placed to maximize energy production while minimizing environmental impact (Rubio-Aliaga et al., 2017). Moreover, GIS plays a pivotal role in water resource management. It enables the continuous monitoring of water availability and quality in agricultural regions. This information, in turn, facilitates the efficient allocation of water resources for irrigation, thereby promoting sustainable farming practices and significantly reducing water wastage (Almulla et al., 2020). It contributes to land use planning, ensuring that areas suitable for solar installations are pinpointed without compromising agricultural productivity (Rubio-Aliaga et al., 2016). This delicate balance between energy development and ecosystem preservation is crucial for long-term sustainability. Furthermore, geospatial techniques are used in crop

monitoring and yield prediction by integrating remote sensing data. Farmers can make informed decisions about irrigation and crop management, leading to optimized agricultural practices and resource utilization (Azzam et al., 2023).

Additionally, other investigations have used the Analytical Hierarchy Process (AHP) method to assess renewable energy resources via a multicriteria analysis (Haji et al., 2020). Remote sensing and Geographical Information System (GIS) technologies are vital tools in providing potential sites for installation of solar power plants (Avtar et al., 2019). It can provide a comprehensive understanding of the interdependencies between water, energy, and food systems, and can help to identify solutions that promote sustainability and resilience.

Remote sensing can also support evidence-based decision-making in resource management, which is crucial for addressing the complex challenges of the water-energy-food nexus (Codjoe, 2010). This study further corroborates the strong correlation within the components of the SAW nexus using remote sensing. Previous research has focused on creating land suitability maps for solar power installation in various regions such as Egypt (Elboshy et al., 2022), Iran (Noorollahi et al., 2016), Korea (Choi et al., 2019), Mongolia (Munkhbat & Choi, 2021), and Saudi Arabia (Alhammad et al., 2022). This study adopts a similar approach but on a larger scale, integrating the sustainability of food via agricultural practices (SDG #2), water resource utilization (SDG #6), and renewable solar power generation (SDG #7). The objective of this study is to provide a valuable resource in the form of a Land Suitability Map (LSM) for optimizing the allocation of land for renewable solar energy development. This LSM is designed to serve as a strong tool for decision-makers, supporting in the meticulous planning of land allocation for future solar power projects. The study's aim is to create an LSM that aligns with the evolving nexus of solar energy, agriculture, and water resource management. By fulfilling these objectives, this research equips policymakers and stakeholders with the insights and data needed to make well-informed decisions. These decisions, in turn, are directed towards fostering a harmonious coexistence between solar energy production, agriculture, and the responsible management of water resources. The LSM thus represents a crucial step in achieving sustainability within the Solar Energy-Agriculture-Water nexus.

4.2 Materials and methods

4.2.1 Study area

India is situated in the southern part of the Asian continent, between latitudes 8° 4' and 37° 6' north of the Equator, and longitudes 68° 7' and 97° 25' east. The country experiences an average annual rainfall of approximately 1250mm, but this precipitation is highly variable (Pai et al., 2014). Some regions witness abundant rainfall, while others receive very little. The Thar Desert and the Himalayan Mountain range play pivotal roles in shaping the country's climate. Fluctuations in temperature and pressure over the Indian Ocean, the Arabian Sea, and the Bay of Bengal significantly influence the distribution and quantity of rainfall across India. The recorded highest and lowest annual rainfall in India differs by approximately 1178 cm, emphasizing the extent of this variability (Pai et al., 2014). India's rainfall shows irregular patterns throughout the year, with a distinct monsoon season prevailing over most of the country from June to September. India ranks 133 out of 180 nations around the world for its water availability (Tayal & Sarkar, 2019). Water plays an important role in the effective working of solar power plants. Apart from that, temperature is also an important factor in efficient power generation. As temperature rises the efficiency of solar panels drops significantly. In arid regions like That desert of Rajasthan, temperature goes as high as 47 deg Celsius (Supe et al., 2020). The average temperature across the country is 27 deg Celsius (worlddata.info/asia/india/climate.php). As of June 2023, India has achieved a solar power installed capacity of approximately 70 GW and has established 42 solar parks to facilitate solar plant development (Sahoo, 2016). Top eight states with highest installed capacity are Karnataka, Rajasthan, Andra Pradesh, Madhya Pradesh, Maharashtra, Telangana, Tamil Nadu, and Gujarat (mnre.gov.in/solar/current-status/). These states contribute about 86.87% of the total installed capacity of the country with Karnataka and Rajasthan comprising 18.77% and 13.98% of total power production respectively.

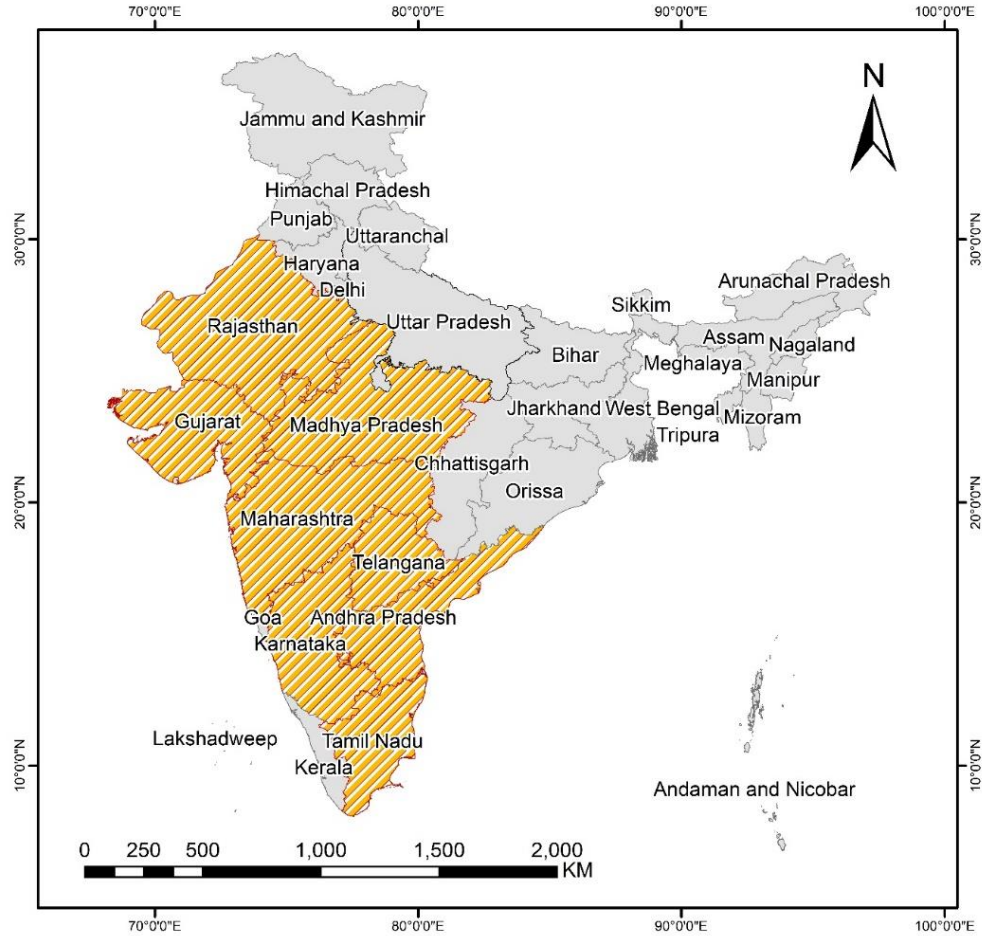


Figure 4.1 The geographic location of the study area map showing the top eight states with highest installed capacity of photovoltaic solar power

4.2.2 Data collection and preparation

We utilized diverse satellite data from various sources to extract valuable information regarding the state of land concerning solar energy, agriculture, and water. This data covered multiple years, allowing us to track changes occurring over decades. This longitudinal approach helped the observation of long-term trends in land cover alterations and enabled subsequent statistical analysis for quantification. Further details regarding the data sources are provided in following sections.

The analysis in this study used Satellite VIIRS stray light corrected Night Time Light (NTL) data, specifically for the years 2014, 2017, and 2020. This data served as a valuable indicator for

measuring changes in light intensity over this three-year period. NTL data offers a reliable representation of electricity consumption within the region, enabling us to assess the patterns of electricity usage throughout the country. This analysis also allowed us to illustrate trends in the electrification of various regions. By employing geospatial techniques, we could determine whether the implementation of solar farms had the potential to extend electrification to remote villages and communities. In doing so, we aimed to explore the role of solar energy in advancing access to electricity and promoting sustainable development in the country.

To gain a comprehensive understanding of the current state of solar farms and their impact on agricultural land and water demand, we incorporated use of diverse array of satellite dataset from various sources. Our dataset included the locations of solar farms, which were derived from the SPI dataset as discussed in Chapter 2. Additionally, we obtained Land Use and Land Cover (LULC) data for the entirety of India from the ORNL DAAC (Roy et al., 2016) for the year 2005, which is an important year for the analysis due to the onset of renewable solar energy expansion in India. To provide context and historical perspective, we compared the present-day land cover conditions with those of previous decades. For this purpose, we conducted analyses for the years 1995 and 1985, allowing us to precisely trace the evolution of land cover usage over time. For our assessment of water demand, we retrieved data from two primary sources: the Water Resources Information System (WRIS) (indiawris.gov.in) for groundwater data and the ArcGIS dataset hub (hub.arcgis.com/datasets/) for surface water data. Both groundwater and surface water are main sources of water that is used for solar power plant operations (Bracken et al., 2015). By examining these datasets, we aimed to gain insights into the water requirements and dynamics associated with solar energy production. This approach enabled us to explore the relationships between solar farms, land use, and water resources in India.

To further understand the condition of groundwater in India, we use yearly data from the GRACE (Rui et al., 2012) satellite, accessed through NASA's Giovanni GSFC platform (giovanni.gsfc.nasa.gov/giovanni/). The data from GRACE and its follow-up mission, GRACE-FO (TELLUS, 2012), provides a total picture of water stored on land (Terrestrial Water Storage or TWS), including groundwater, soil moisture, surface water, snow, ice, and water in plants. However, the common Land Surface Models (LSMs) don't cover all these aspects; they usually only model soil moisture, snow water, and water caught by plants (V. K. Singh et al., 2023). Two

particular models, the Catchment Land Surface Model (CLSM) and Noah-MP, go a step further by also modeling shallow groundwater (Deliry et al., 2022; Wang et al., 2019). When we apply a runoff routing scheme, we can additionally estimate surface water storage. In this study, we focus on Groundwater Storage (GWS), as modeled by the CLSM within the Global Land Data Assimilation System (GLDAS) (Khorrami & Gunduz, 2021). This refers to water stored below the soil layer where roots can reach, and above the bedrock. To isolate GWS from other types of water storage, we use the formula (Hu et al., 2021):

$$\text{GWS} = \text{TWS} - \text{Root Zone Soil Moisture} - \text{Snow Water Equivalent} - \text{Canopy Interception} \quad (1)$$

This formula helps us subtract the amount of water held in the soil, snow, and plants from the total water storage, leaving us with an estimate of the groundwater storage. It helps in identifying trends in water resources by showing the yearly changes in ground water as water height equivalent (cm/yr) from 2005 to 2016.

To create LSM of India, the following parameters were considered as inputs, after having discussion with experts from Solar energy sectors: (a) Agricultural Crop-land, (b) PV output potential, (c) Distance from Power Grid, (d) Land Surface Temperature (LST) and (e) Water availability index. The description of each parameter is mentioned in table 4.1. Vegetation cover and slope more than 11 degree were masked out, as these areas are considered inappropriate for sustainable solar power development. ESA World Cover map was used to get vegetation cover class, while slope data was generated using SRTM DEM. The parameters' input values were assigned between 0 to 10 as shown in table 4.2. Further, criteria weightage derived from the AHP model for each parameter was applied and processed to generate LSM. Speckles and noises were reduced using the Earth Engine neighborhood filtering kernel. Later, the result was divided into 7 layers as can be seen in the final product.

Table 4.1 Different criteria parameters used and their information.

Criteria	Description	Resolution (m)	Time of capture	Source
----------	-------------	----------------	-----------------	--------

Crop land	LULC of India recognized as crop land	10	2020	ESA (Zanaga et al., 2021)
Water availability	Water availability index	-	average	India Water Tool (indiawatertool.in)
Power grid	Distance from nearest power grids	-	2020	(Arderne et al., 2020)
LST	Surface temperature on the land	1200	Jan to May of 2018	MOD11A1 V6 (Wan et al., 2021)
PV OUT (kWh/kWp)	Long-term yearly average of potential photovoltaic electricity production (PVOUT)	920	1999-2018	SolarGIS (solargis.com)

Table 4.2 Value distribution of input parameters.

Criteria	Values					
	10	8	6	4	2	0
Crop land	No Cropland	-	-	-	-	Cropland
Water availability	0.389	0.275	0.198	0.122	0.044	-0.025
Power Grid	Within range				Outside range	
LST	< 25°C	25-30°C	30-35°C	35-40°C	40-45°C	> 45°C
PV OUT (kWh/kWp)	upto 6.038	4.8	4.45	4.1	3.74	< 3.38

4.2.3 Multi-criteria decision-making model

The Analytical Hierarchy Process (AHP) is a structured decision-making approach that is widely used in geospatial studies. It is operated by systematically ranking and comparing various options based on a set of predefined criteria (Sreenivasan et al., 2023). Within this framework, the AHP model finds effectiveness in assessing the suitability of specific locations for various purposes, like urban services planning (Parry et al., 2018) or flood risk assessment (Abdelkarim et al., 2020). The AHP model is integration GIS harnesses the power of geospatial data analysis to generate maps that vividly portray the suitability of diverse locations for distinct purposes. This synergy between AHP and GIS offers a comprehensive and data-driven perspective on spatial decision-

making. Decision-makers can systematically weigh the relative importance of each criterion, allowing for a more profound evaluation of location suitability (Malczewski, 2006). This enhances the precision and strength of decision-making processes in the context of geospatial land planning. Weightage for each parameter used in this study were derived and calculated based on inputs taken from experts who are working in the field of renewable energy solar energy sector. A meeting was setup with delegates from ‘Rajasthan Renewable Energy Corporation Limited’ (RRECL) to get necessary inputs and information for the course of this study. This meeting served as a platform for exchange of knowledge and expertise, further enhancing the credibility of the study’s findings and recommendations.

Analytical Hierarchy Process model involves pairwise comparison of various criteria. A matrix of pairwise comparison of each criterion is built based on inputs values from experts. The value scale ranges from 1 to 9. The matrix is formed by using Saaty’s method (Saaty, 2004).

$$A_w = \begin{vmatrix} 1 & p & q \\ 1/p & 1 & r \\ 1/q & 1/r & 1 \end{vmatrix} \quad (2)$$

Later the matrix is normalized by dividing it by its relative weights. A further consistency check is done following Saaty’s formula:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (3)$$

Here, n is the size of matrix that is 5, whereas $\lambda_{\max}$ is product of A_w and N_w , which is equal to 5.139. Consistency Ratio (CR) is estimated using following formula:

$$CR = \frac{CI}{RC} \quad (4)$$

Here, CR less than or equal to 0.1 is considered acceptable for pairwise comparison results. In this study, CR turned out to be 0.031, which approves the validity of the model.

4.3 Environmental Implications of Solar Farm Development

4.3.1 Electrification of villages

Figure 4.2 presents an RGB composite of Night Time Light (NTL) data for the years 2014, 2017, and 2020. This visual representation clearly showcases the evolution of light intensity over this six-year period. Notably, shades of blue and green indicate a visible increase in light intensity throughout this time frame. While light indicates high light intensity throughout the time-period. It usually represents the area having high electricity consumption with focused socio-economic activities (Mellander et al., 2015). Upon visual interpretation of the figure, the prevalence of these blue and greenish shades becomes evident, particularly in the northern part of the country. This includes areas covering parts of Bihar and Uttar Pradesh states. These findings align with the results of the survey (A. Sharma et al., 2020), which highlight the potential for solar mini-grids to provide a viable solution for electricity access, especially in regions where a dependable power supply is highly valued by rural enterprises. The visual evidence supports the statistical insights from the survey, highlighting the significant role that solar energy can play in enhancing electricity access in these areas.

Electricity transmission has made significant advancements, allowing for the efficient transport of electricity over long distances with minimal transmission losses (Humpert, 2012). Modern transmission systems can achieve distances of up to 100 kilometers with negligible losses (Yamaguchi et al., 2019). Figure 4.3 provides insight into the average light intensity in and around solar farm areas, covering a radius of 100 kilometers, over the six-year period from 2014 to 2020. There is an obvious increase in light intensity observed across all states of the country. This upward trend signifies the substantial impact of solar farm installations on expanding electrification nationwide, spanning various states. It emphasizes the role of solar energy in extending access to electricity, thereby contributing to the broader electrification efforts in the region. However, while an upward trend in light intensity is observable within the vicinity of solar farm boundaries, it may not exclusively correlate with the installation of photovoltaic (PV) solar infrastructure. A comprehensive investigation is imperative to ascertain the precise influence of PV solar installations on the electrification of the regions.

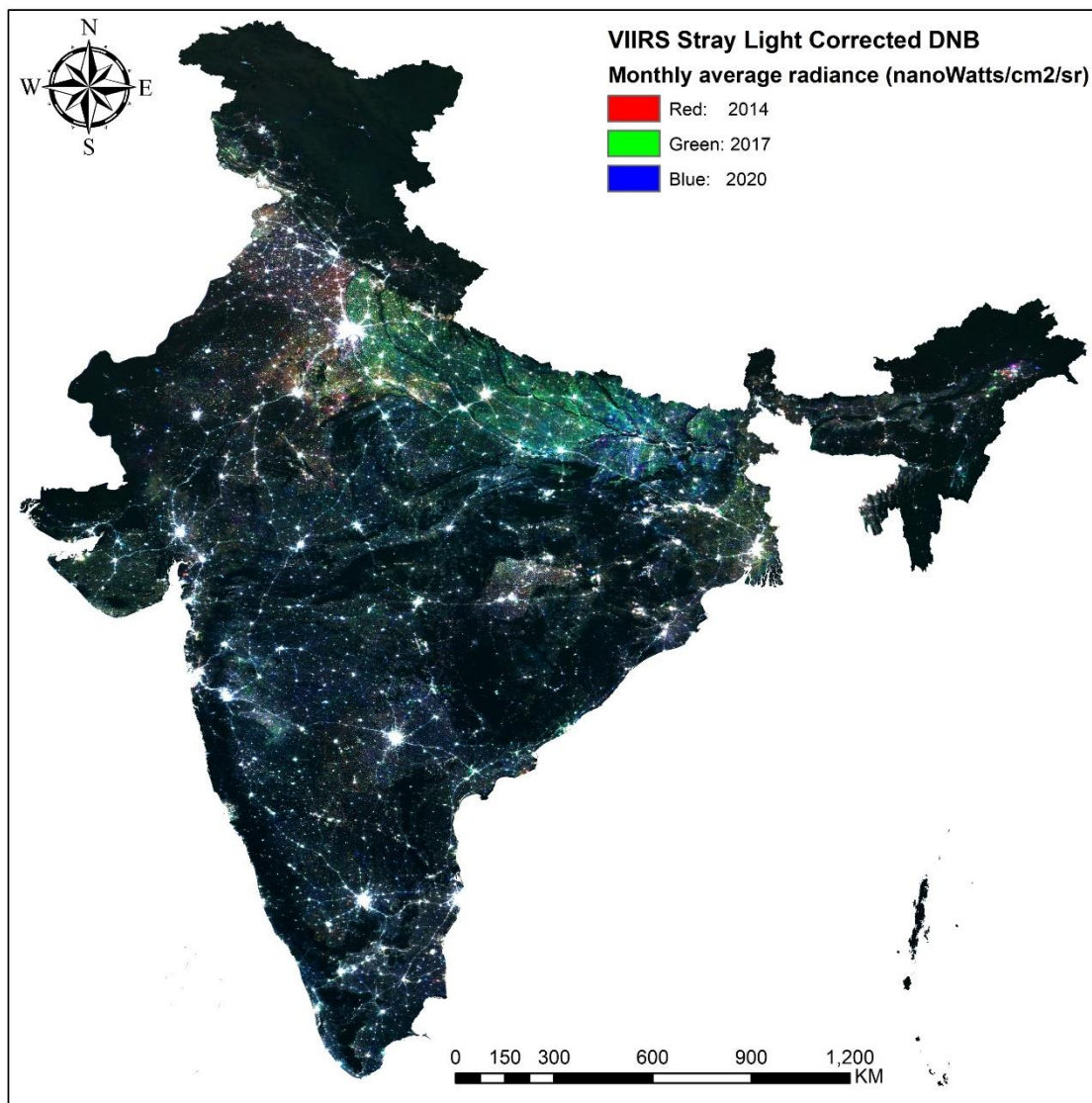


Figure 4.2 VIIRS derived Night Time Light RGB Map of years 2014, 2017, and 2020, Indicating the change in electricity consumption in the span of six years.

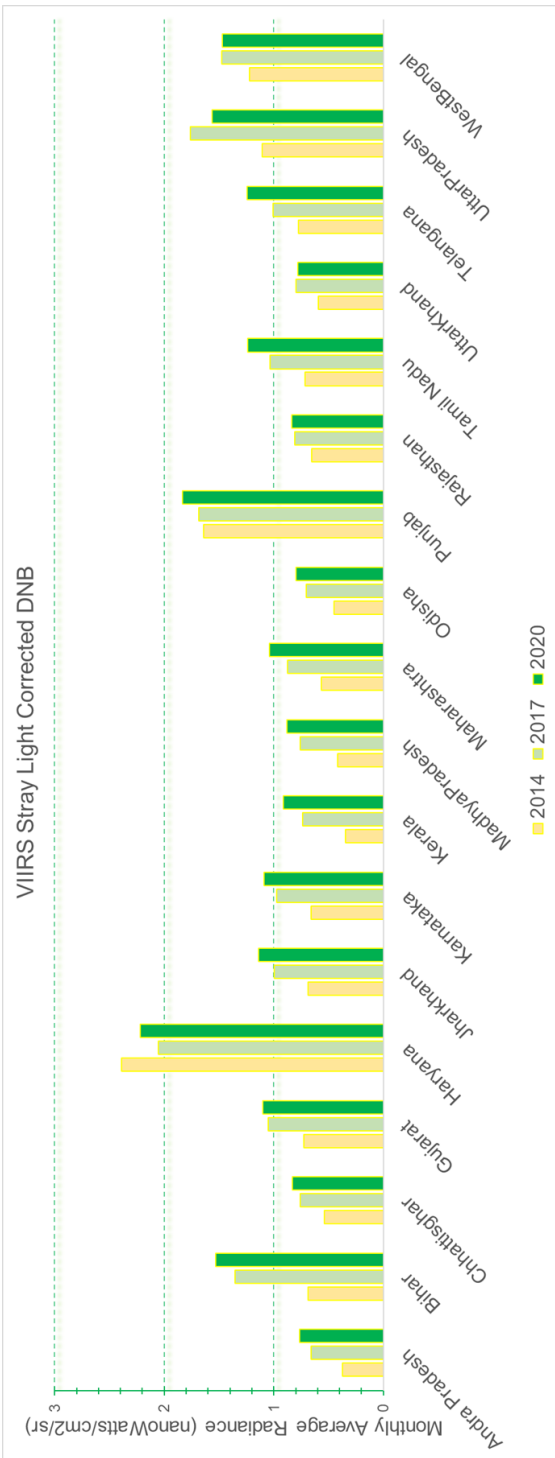


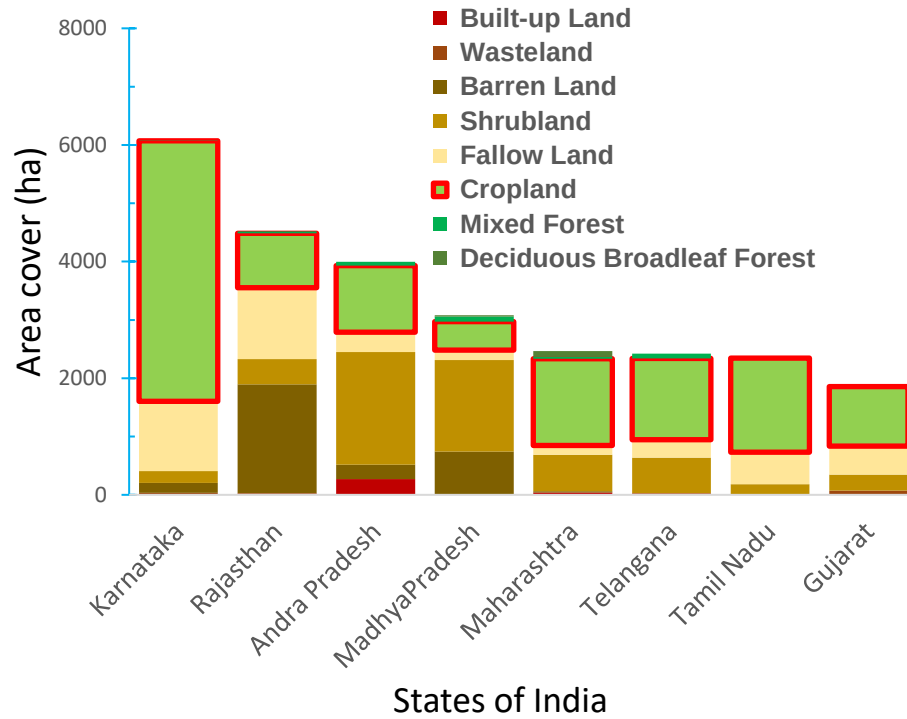
Figure 4.3 State-wise distribution of VIIRS derived average Night Time Light within 100 Km boundary of existing solar farms of years 2014, 2017, and 2020.

4.3.2 Land use changes

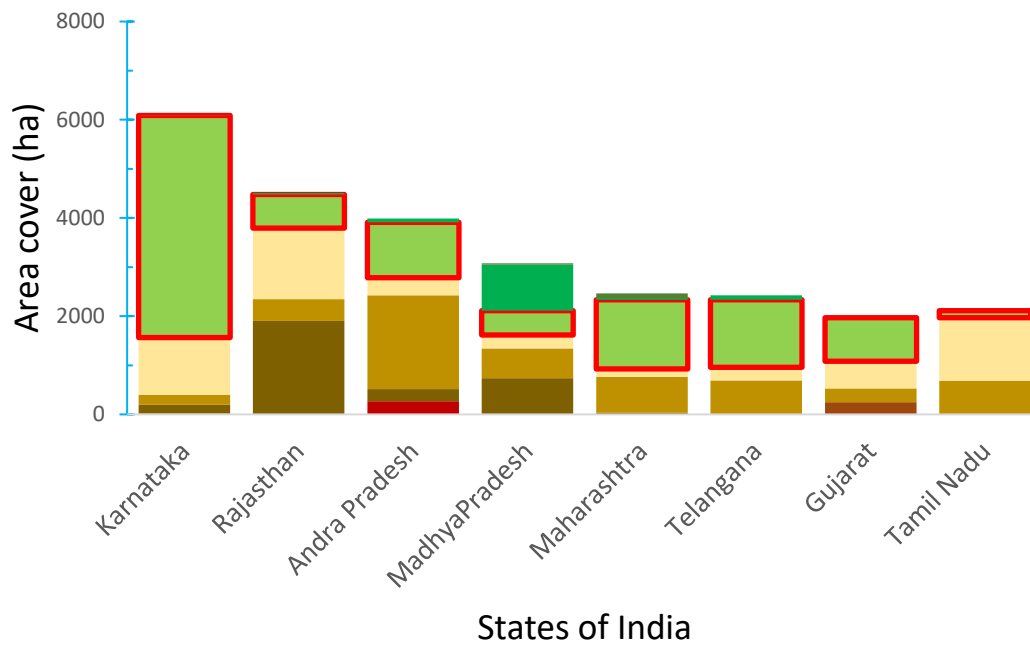
Figure 4.4 statistics are derived by processing the Land Use Land Cover (LULC) map of India in 2005, obtained from the Oak Ridge National Laboratory Distributed Active Archive Center of the National Aeronautics and Space Administration (Roy et al., 2016). The map divides the landscape of India into 19 classes (Annexure C). Because India is an agrarian country, a substantial portion of its land is dedicated to agricultural purposes. We used this information to analyze changes from agricultural land into solar power plants. Therefore, we projected the identified solar farms onto the LULC map. We found that a large portion of land that is now used for solar farms was previously used for agricultural crops. Figure 4.4 presents a state-by-state depiction of Land Use and Land Cover (LULC) changes, measured in hectares, revealing a predominant trend of agricultural cropland conversion into solar plants across virtually all states. The eight states featured in the figure are those with the highest installed solar capacity in the country, collectively accounting for 86.87% of the nation's total solar power generation (State-Wise Installed Capacity of Renewable Power as on 31.03.2023., 2023).

Analyses of LULC maps from previous years, specifically from 1995 and 1985 (Annexure C), revealed a similar pattern. This pattern indicates the general trend that agricultural land that was previously used for food production has since become a popular choice for solar energy production, highlighting the encroachment of agricultural land.

(a) 2005



(b) 1995



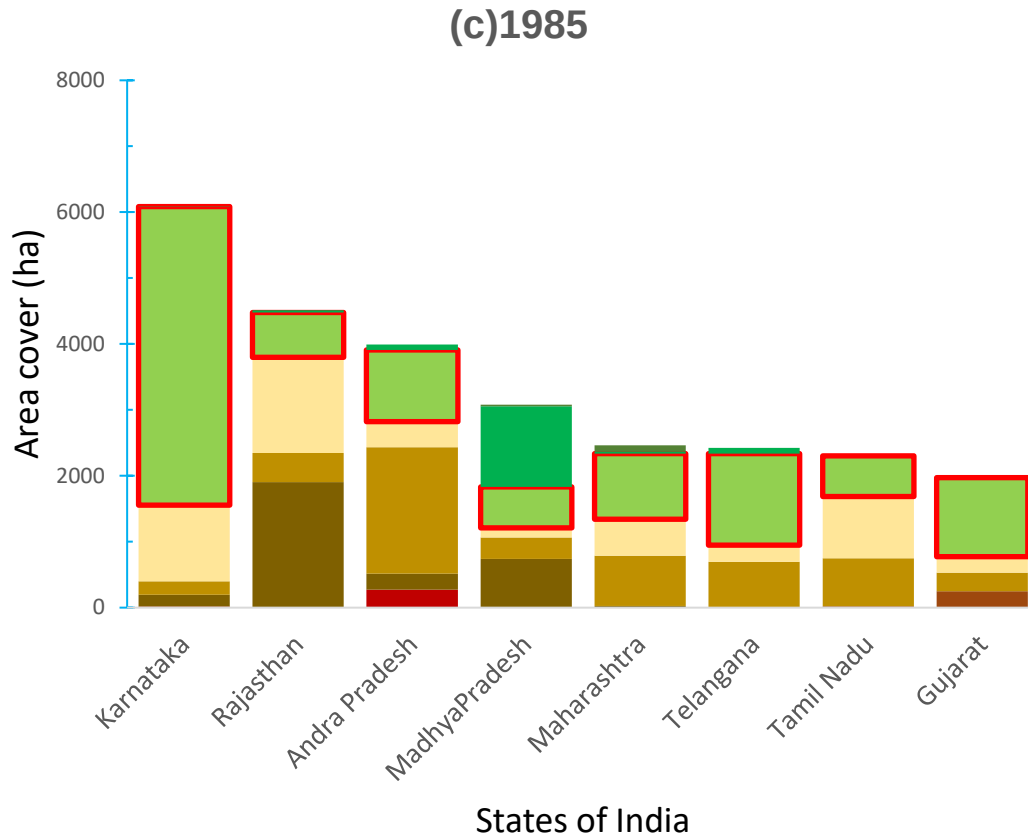


Figure 4.4 LULC change caused by Solar power plant installation for (a) 2005, (b)1995 and (c)1985 and the states mentioned here are top 8 states with highest solar power installed capacity.

In the context of agricultural practices, soil preparation techniques such as ploughing, leveling, manuring, and weeding play a crucial role in maintaining land quality. When land is leased for solar power installations for extended periods, these routine procedures may be neglected, potentially leading to a decline in land quality (Larry G, 2022). The Indian government's 'KISAN URJA SURAKSHA EVAM UTTHAN MAHABHIYAN (KUSUM) Yojana' schemes promotes the expansion of solar power, with many farmers choosing to lease their land to companies for periods up to 25 years (Jethani, 2019). The 'Saur Krushi Vahini Yojana (SKVY)' scheme offers attractive financial incentives and straightforward eligibility requirements for landowners, providing them with a stable income source (Manjunatha et al., 2022). However, long-term solar panel installation on agricultural land may have unintended consequences on land quality, rendering it unsuitable for future farming activities. The absence of regular soil treatments may

result in weed proliferation, which could adversely affect the land's organic content and overall fertility (Bashagaluke et al., 2018). This potential trade-off between solar energy expansion and agricultural land preservation highlights the need for a balanced and sustainable approach to land use planning in the context of solar power development.

4.3.3 Water resource availability

4.3.3.1 Groundwater level change

When compared with other primary power generation sources such as thermal and nuclear, solar photovoltaic (PV) power generation is significantly more water-efficient. However, the challenge lies in the fact that these solar power plants are often situated in water-stressed areas. The majority of the water requirements for these plants (approximately 60%) are fulfilled by groundwater accessed via borewells, while the remaining demand is met through surface water sources, including rivers, canals, and lakes (*Role of Water in Long-Term Performance of Solar PV Plants*, 2019). Developers generally prefer to utilize groundwater as it is freely available, resorting to surface water only when necessary, which typically involves reliance on local contractors. In addition to the quantity of water, the quality of water required also greatly influences the actual water usage. For instance, reverse osmosis (RO) treated water is recommended for cleaning solar panels. However, the RO process itself results in a significant amount of water wastage. Thus, both the quantity and quality of water are essential considerations in the operation of solar power plants (*Role of Water in Long-Term Performance of Solar PV Plants*, 2019). Access to reliable water resources is critical to the operation of solar power plants. Figure 4.5 shows groundwater levels in India, which considerably vary throughout the country because of differences in land type. Projection of the solar farm locations onto the groundwater map revealed that areas with the highest installed capacity are located in regions with low groundwater depths, intensifying water strain in the area. Regions experiencing severe ground water scarcity include Rajasthan, Madhya Pradesh, and Andhra Pradesh.

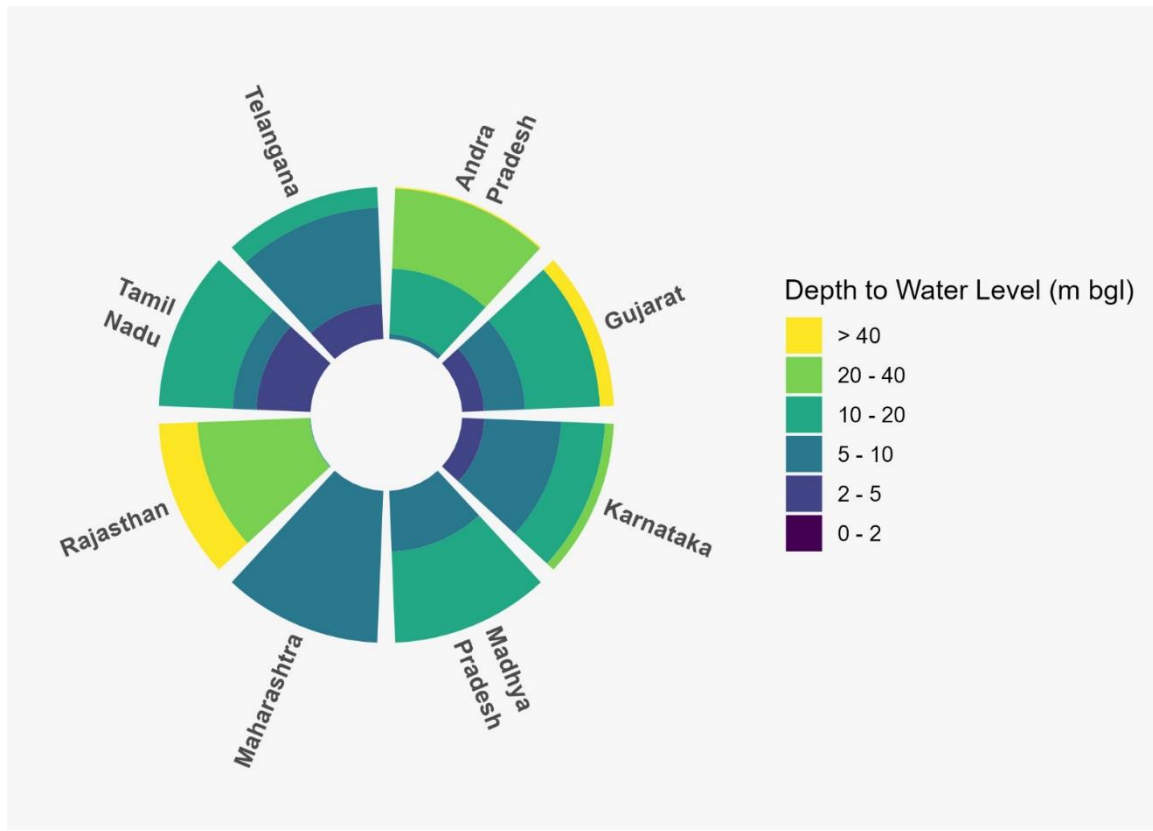
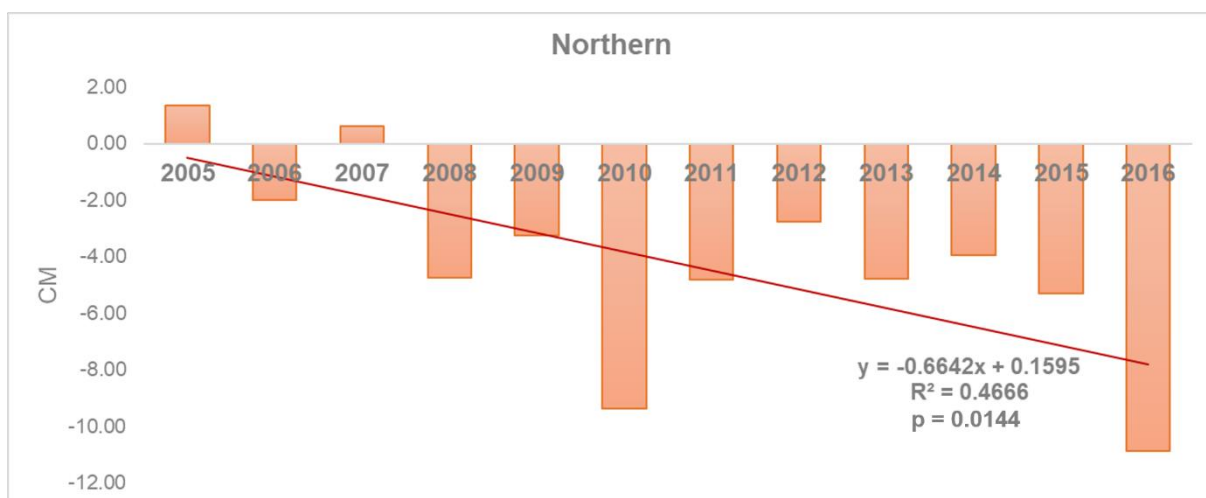
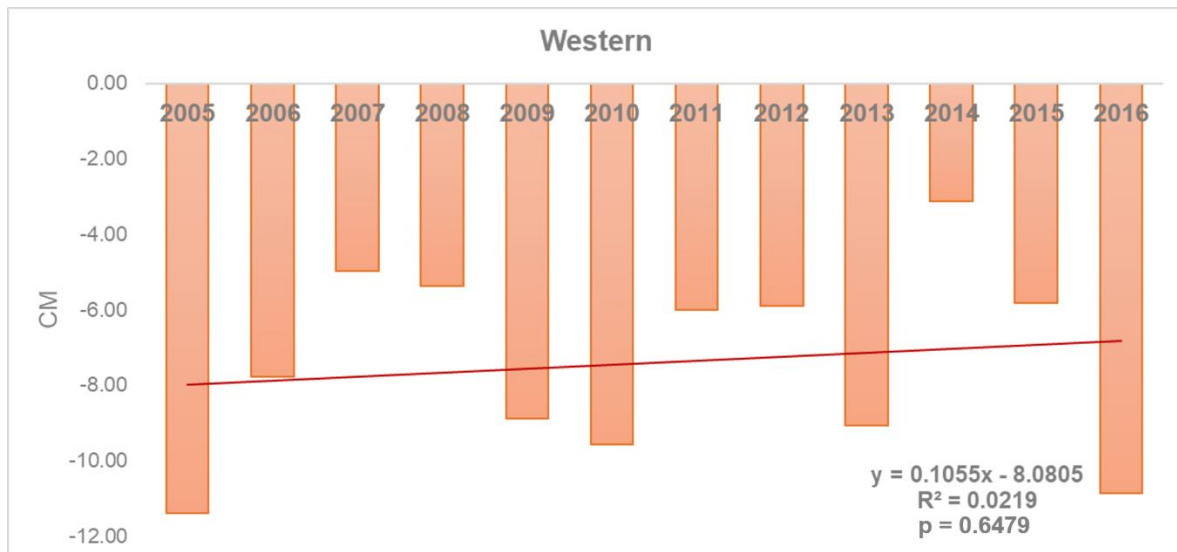
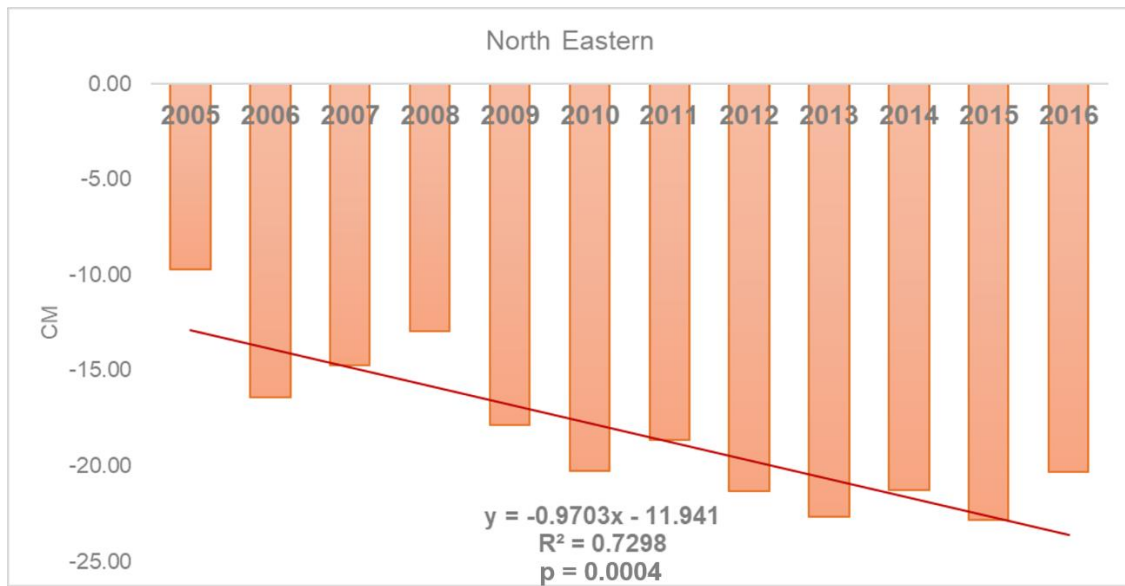


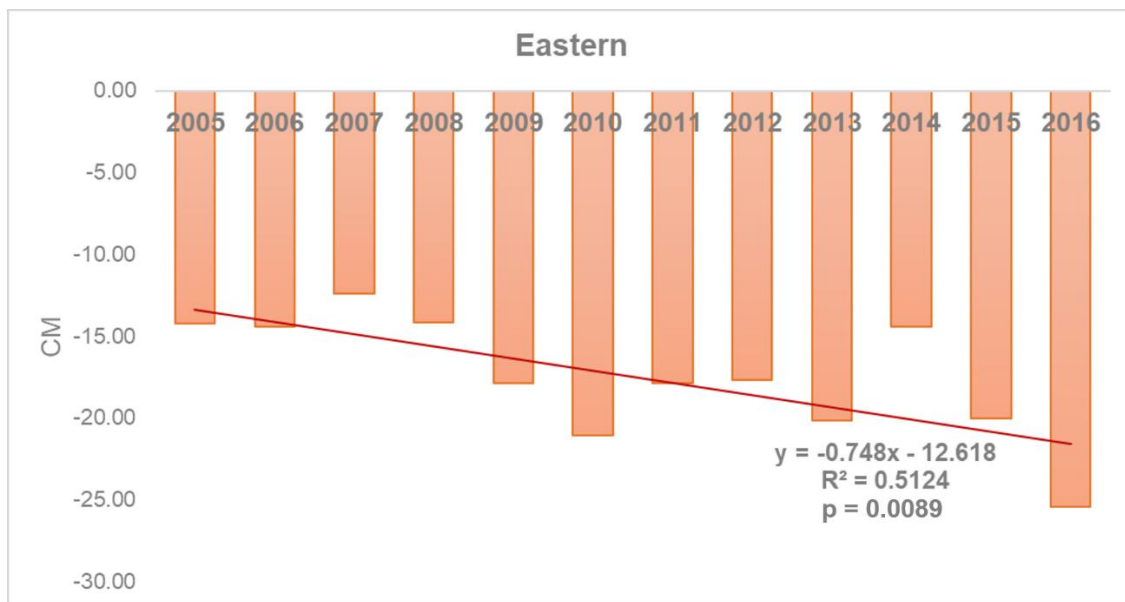
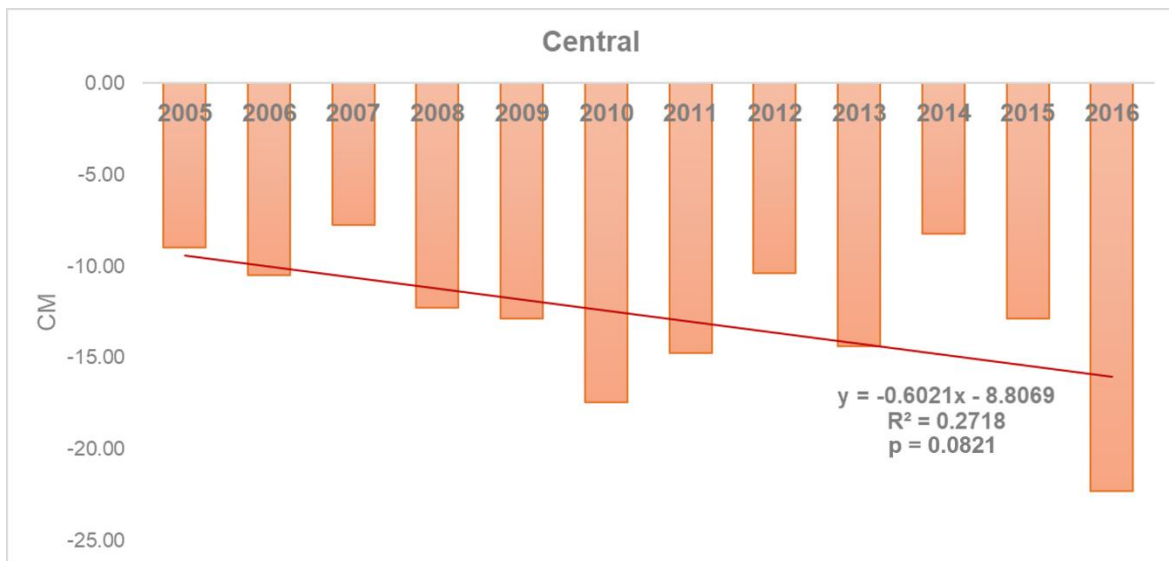
Figure 4.5 State-wise groundwater level distribution over solar farms.

Groundwater storage underwent comprehensive analysis using GIOVANNI GLDAS CLSM025 data spanning from 2005 to 2016. To facilitate the investigation, India was divided into six distinct regions: Northern, North Eastern, Western, Central, Eastern, and Southern. This regional categorization was essential for in-depth analysis. The figure 4.6 portrays the annual changes in water thickness, measured in centimeters (cm), for each of these regions, complete with trend lines and corresponding equations. A striking pattern emerges across most regions, characterized by a consistent decline in groundwater thickness. This downward trend signifies an ongoing reduction in groundwater resources, raising concerns about long-term sustainability. Of particular concern is the Northern region, where groundwater thickness has experienced a pronounced decrease. Similarly, the North Eastern region, Central region, and Eastern region exhibit substantial declines in groundwater thickness. Notably, the North Eastern region stands out with the highest r-square value of 0.7298, emphasizing the severity of the groundwater depletion challenge in this area. Ground water storage in India is critically being affected. Groundwater irrigation stands as the

prevailing method employed throughout India (Gandhi & Bhamoriya, 2011). However, the alarming decline in groundwater (GW) storage poses a significant threat to the sustainable development of the water-energy-food nexus within the country (Gandhi & Namboodiri, 2009; Nair & Indu, 2021). India has faced severe dry spells in the years 2002, 2004, 2009, and 2012, exacerbating the challenge of groundwater management (Nair & Indu, 2021). The southern Indian state of Tamil Nadu is one of the largest agricultural producers, heavily reliant on groundwater for irrigation (Amarasinghe et al., 2009). Surprisingly, the impact of increased irrigation resulting from the intensification of agricultural activities has not received comprehensive spatial and temporal research attention (Saha & Ray, 2019). Groundwater depletion is become apparent at a rate of 21.4 km³ per year, which surpasses the annual recharge rate (19.81 km³ per year) attributed to an annual rainfall of 1016 mm per year (Chinnasamy & Agoramoorthy, 2015). Particularly affected are districts such as Dharmapuri, Vellore, and Thiruvannamali, which have experienced intense groundwater depletion. While the observational record remains limited, the available evidence strongly suggests that unsustainable groundwater consumption for irrigation and other anthropogenic purposes is the primary reason behind this issue (Dangar et al., 2021). Urgent measures are necessary to ensure sustainable groundwater utilization. Failure to address this challenge quickly could result in reduced agricultural output, potable water shortages, and widespread socioeconomic pressures affecting the region's 114,000,000 residents (Rodell et al., 2009).







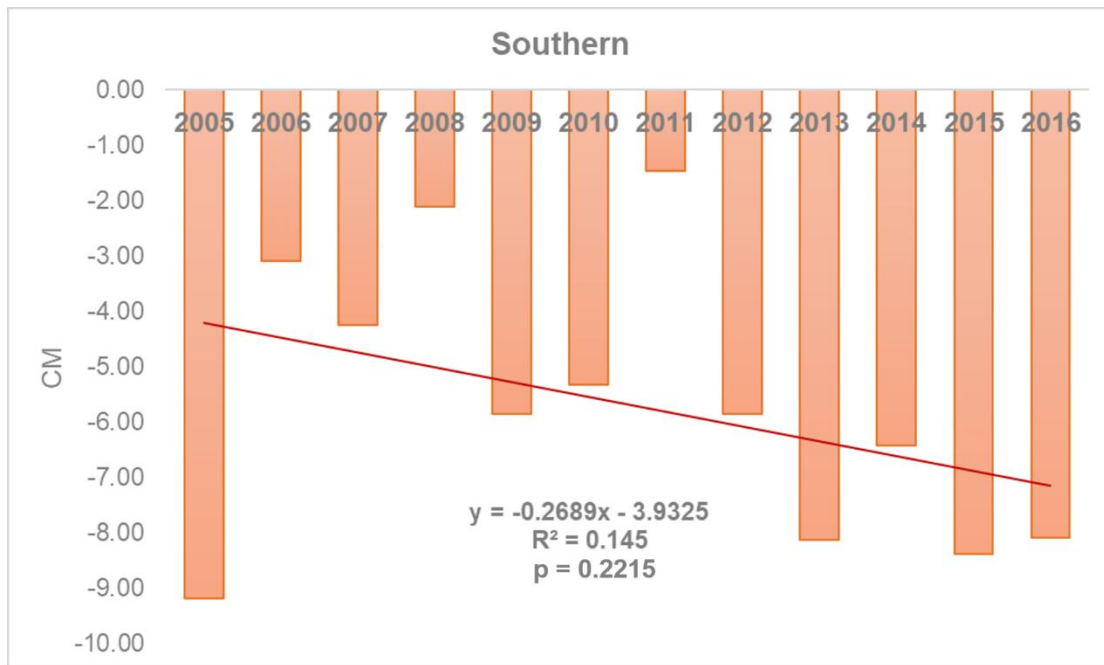


Figure 4.6 Giovanni GLDAS CLSM025 derived annual groundwater level thickness change in centimeters among the six regions of India.

4.3.3.2 Surface water proximity

Figure 4.7 indicates the numbers and percentages of power plants located within a 5-km radius of these surface water bodies. The regions Madhya Pradesh, Maharashtra, and Rajasthan have minimum presence of power plants. In particular, Madhya Pradesh had no power plant located within 5 km of surface water bodies, consistent with our observations regarding groundwater content (Figure 4.5). This suggests that solar farms situated in the state of Madhya Pradesh are likely to place a significant demand on regional water resources. Overall, the installation of large solar power plants is exerting increasing pressure on water management conditions throughout the country.

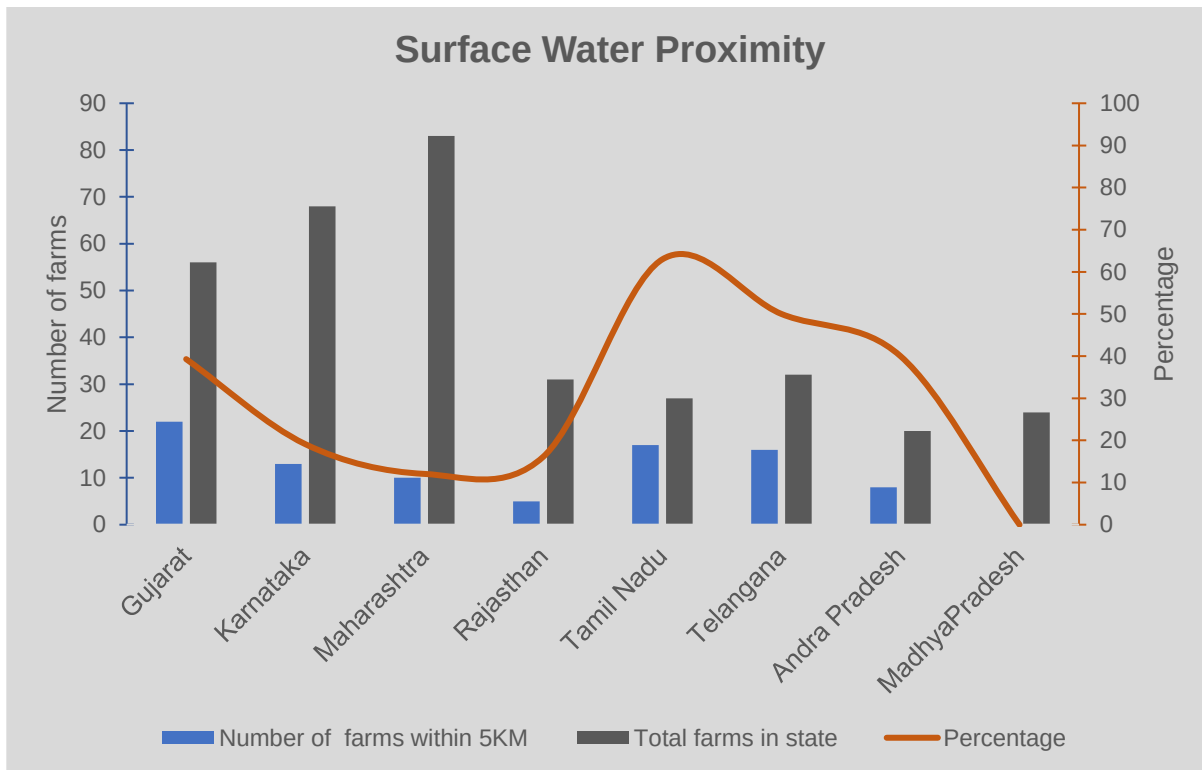


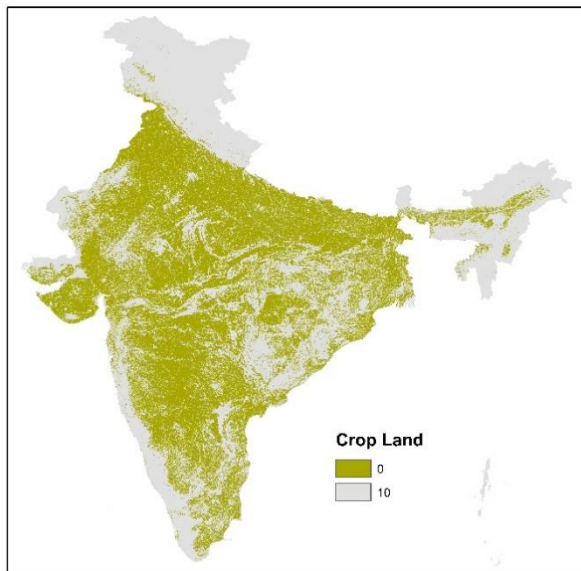
Figure 4.7 State-wise distribution of number of Solar farms within the proximity of surface water source

4.4 Generation of Land Suitability Map (LSM)

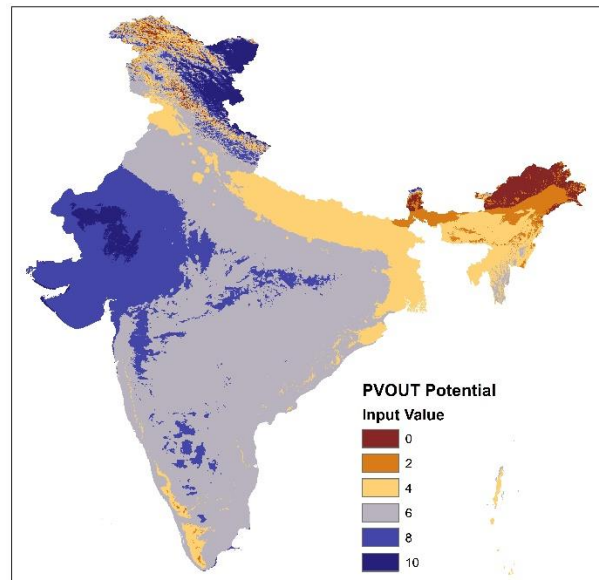
4.4.1 Selection of parameters for LSM generation

It is challenging to grant permission for solar power plant installation because such plants can have negative impacts on agriculture and water resources. There is a trade-off among the food, energy, and water sectors with respect to land use. Proper guidelines from a central management body are essential for sustainable planning. Currently, the government determines state-wise solar power potential estimates based on land availability and sunshine. On a broader scale, land type and natural resources should also be considered. The determination of suitable locations for solar farms involves the consideration of several critical parameters. One of these key factors is the PV potential output, which estimates the solar energy available in a given region. This information is essential for effective site selection planning. Another important parameter is the distance from the power grid; proximity to the grid can significantly reduce construction costs associated with

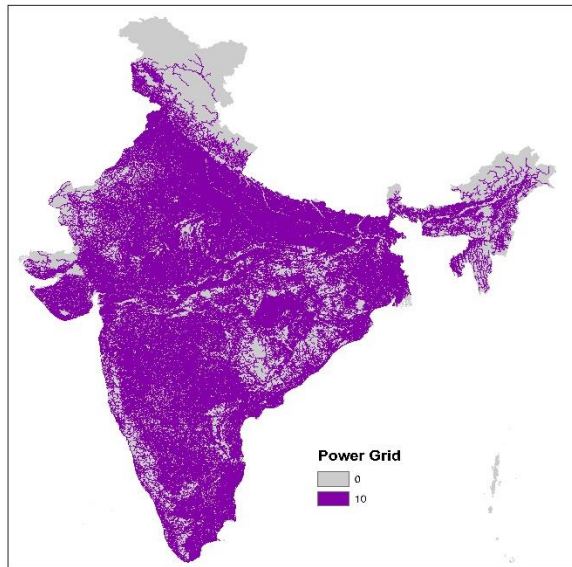
transmission lines, making it a crucial consideration during the planning phase. Furthermore, temperature plays a crucial role, as higher temperatures can have a significant drop in the efficiency of solar panels. Therefore, temperature levels are carefully assessed to optimize solar farm performance. Additionally, the land use land cover category, specifically focusing on agricultural crop land, is of great importance. This study emphasizes the importance of avoiding land encroachment to ensure sustainable food security alongside power generation. Equally significant is the assessment of water availability, which is essential for ensuring water sustainability in the region. Raster images (as shown in Figure 4.8) were obtained from various sources (as detailed in Table 4.1) and subjected to preprocessing, including conversion to normalized values (as presented in Table 4.2), to prepare them as input variables for the Analytical Hierarchy Process (AHP) model.



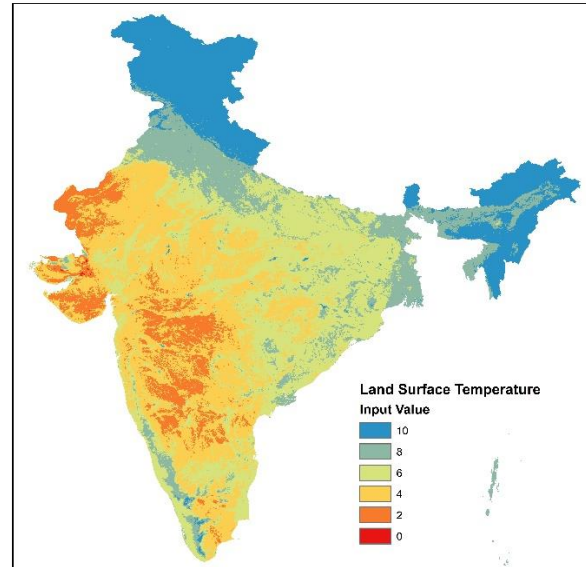
(a) Agricultural crop land



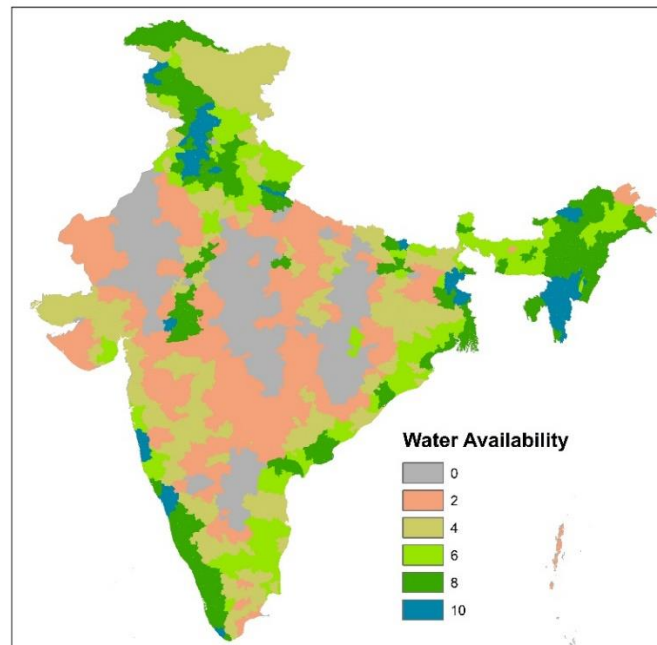
(b) PV OUT



(c) Power Grid



(d) LST



(e) Water availability

Figure 4.8 Rasterized input environmental parameters: (a) Agricultural Crop Land, (b) PV Output Potential, (c) Power Grid, (d) Land Surface Temperature, and (e) Water Availability.

4.4.2 Integration of AHP with Geo-spatial parameters

The AHP model played a crucial role in assigning weightage values to these parameters and processing them according to AHP model calculations. The criteria weightages, as depicted in

Figure 4.9, offer insights into the prioritization and importance assigned to each parameter in the decision-making process for solar farm site selection.

	PV	C	W	LST	PG	Criteria Weights
PV	1	3	7	5	9	0.52
C	0.333	1	4	2	7	0.24
W	0.143	0.25	1	0.5	3	0.08
LST	0.2	0.5	2	1	5	0.13
PG	0.111	0.143	0.333	0.2	1	0.04
Sum	1.787	4.893	14.333	8.7	25	

Figure 4.9 AHP matrix derived from discussion with experts

The final product a land suitability map (LSM) of India (figure 4.10), is a high-resolution (100m) georeferenced raster image of India, which can support future planning in the solar energy sector. It shows with seven categories that range from least suitable to most suitable. LSM aims at the sustainability of water resources, and agricultural production in the region. According to the resultant LSM, Rajasthan state has highest suitable land availability for solar power generation. The most suitable land category area comprises more than 70 thousand square kilometers within the state, which is way more than enough for achieving target of 280GW by the year 2030. Most of the solar power plants currently located are coming under moderately suitable region with 29.6% cover (Table 4.3).

Solar panels installed on slopes have adverse effect on ecological system. Accumulation of soil mounds from solar panel installation on slopes led to landslide during heavy rain causing destruction in the region (“Japan to Reevaluate Solar Development Regulations After Cause of Landslide in Atami Revealed to Be Improper Upstream Construction,” August, 21). Infrastructure on flat land is preferable. Solar panel structure on surface water systems like canals could reduce

water loss due to evaporation (Jin et al., 2023). Previous studies discuss the use of Solar radiation zone map prepared by TERI based on the IMD database as an important material for planning (A. Sharma, 2011). Other studies considered the terrain and infrastructure development aspect for solar power installation (Mahtta et al., 2014). However, all these datasets give a coarse idea of the solar resources available on land. LSM generated in this study provides high resolution map with 100m resolution. This map incorporates various sustainability factors, primarily focusing on SDG #2 (Zero Hunger), #6 (Clean Water and Sanitation) and #7 (Affordable and Clean Energy). Additionally, we have taken care to minimize potential impact on other ecologically significant areas like forests. This approach ensures a balanced consideration of multiple environmental and sustainability aspects in our study.

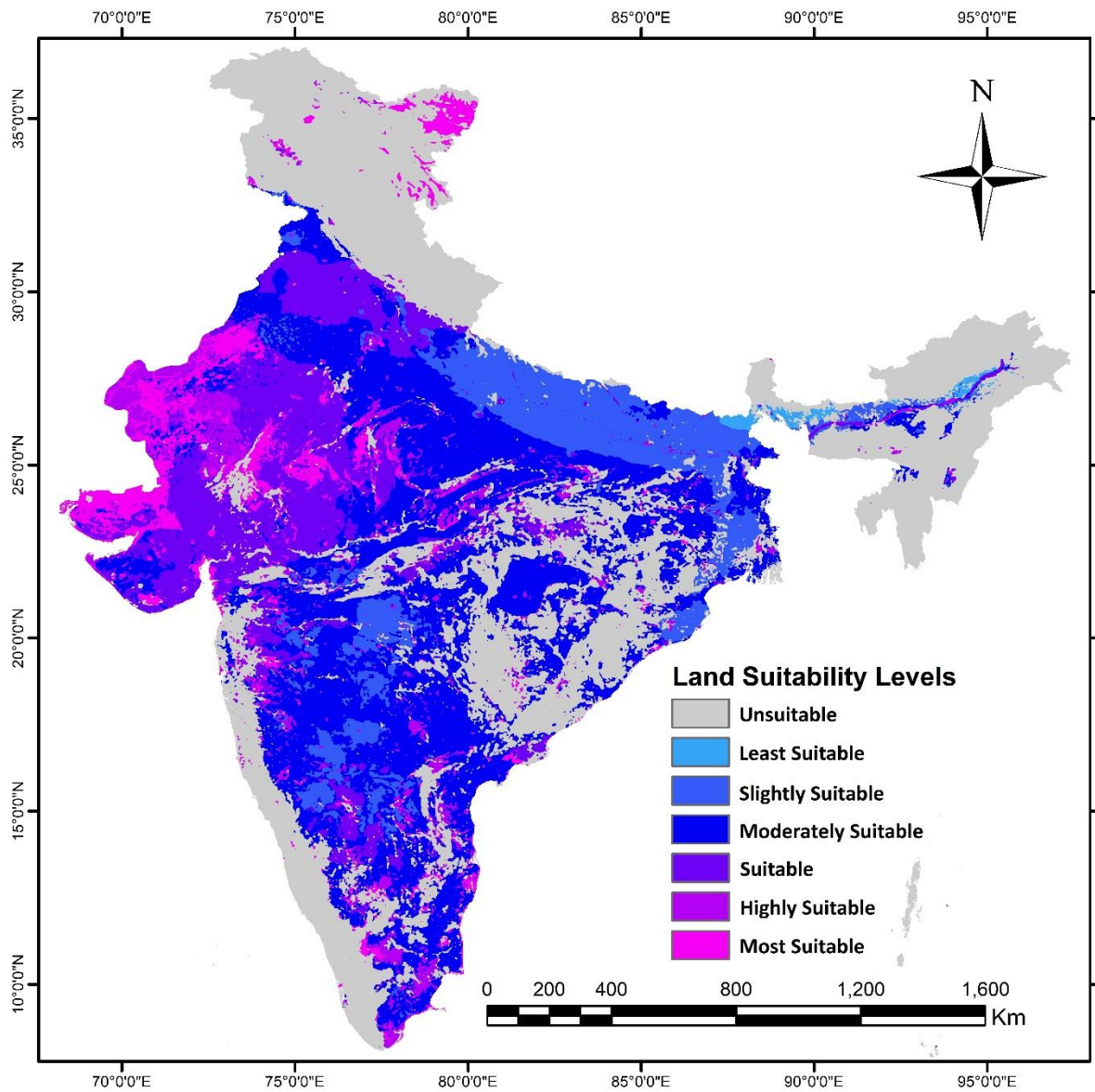


Figure 4.10 Land Suitability Map for solar farm installation in the study area.

Table 4.3 Percentage distribution LSM categories in India.

LSM Categories	Percentage cover
Unsuitable	36.13
Least Suitable	0.42
Slightly Suitable	9.84
Moderately Suitable	29.6

Suitable	13.5
Highly Suitable	5.09
Most Suitable	5.42

4.5 Discussion

The distribution of solar farms in India exhibits variations across different regions, with certain areas accommodating a more concentrated presence of solar installations compared to others (Yenneti & Day, 2016). Rajasthan stands out as one of the leading states in India when it comes to solar energy production, presenting a significant number of large-scale solar farms and solar parks (Meena et al., 2014; D. K. Sharma et al., 2014). This prominence is attributed to the state's abundance of sunlight and a favorable policy environment that supports solar development (Sukhatme & Nayak, 1997). Tamil Nadu actively embraces solar energy, featuring numerous solar farms and installations, with the state government implementing various incentives to adopt solar power generation (Nesamalar et al., 2017; Rohankar et al., 2016). Karnataka has made noteworthy investments in solar power projects, including solar farms and solar parks, establishing itself as a leader in solar capacity expansion (C. M. S. Kumar et al., 2023). Andhra Pradesh and Telangana have also achieved substantial progress in solar energy development, marked by numerous solar farms and power plants (Prakash et al., 2022). Madhya Pradesh diligently works toward increasing its solar energy capacity, with several ongoing solar projects and the establishment of solar parks (M. Verma et al., 2023), while Maharashtra's growing solar energy sector is characterized by the presence of several solar farms and rooftop installations (Deshmukh & Chandrakar, 2022). Furthermore, several other states across India have initiated their own solar energy projects and installations, collectively contributing to the nation's overall solar capacity. These solar farms can vary significantly in size, encompassing small-scale rooftop installations to large-scale utility solar farms and solar parks.

The growing global demand for renewable energy, particularly solar power, fuels interest in solar farm development (Gielen et al., 2019). Developers are keen to meet this demand by identifying suitable land for solar installations, which may include agricultural land (Dias et al., 2019). Local zoning and land use regulations sometimes permit or encourage such land conversion for renewable energy projects, with regulations varying by region and prioritizing energy generation

over agricultural use (Chang & Lin, 2023). While solar farms offer significant benefits such as clean energy generation and employment opportunities, they also raise concerns regarding land use and environmental impacts (Hernandez et al., 2014). Potential issues include the reduction of arable land for food production, soil disturbance due to topsoil removal, disruption of local ecosystems and habitats, and alterations to the visual landscape (Guerin, 2017).

Agricultural land encroachment by solar farms is a phenomenon driven by various factors (Kim et al., 2021). It occurs when large-scale solar energy projects are established on land that was previously designated for farming or other agricultural purposes. This process involves the conversion of agricultural land into solar farms, which includes clearing existing vegetation, removing topsoil, and installing solar panels, mounting structures, and electrical equipment (Turney & Fthenakis, 2011). The motivation behind this transformation can be attributed to several factors. Solar farm development is financially lucrative for both landowners and developers (Gilliland et al., 2020). Government incentives, subsidies, and favorable regulatory policies often make it economically attractive to convert agricultural land for solar energy generation. As a result, landowners opt to lease or sell their land to solar farm developers to generate income (Gazheli & Di Corato, 2013). Moreover, the suitability of agricultural land for solar panel installations is a driving force. Agricultural land is often flat and wide, making it ideal for accommodating solar panels (Dower, 2018; Günen, 2021). Additionally, solar farms are typically situated in regions with high solar irradiance, which often overlap with areas abundant in agricultural land (Amjad & Shah, 2020).

To address these concerns, some regions have established guidelines and regulations that aim to strike a balance between solar energy development and the preservation of agricultural land and environmental considerations (Chel & Kaushik, 2011). These measures may include land remediation requirements after solar farm decommissioning, land set-asides for agriculture, and ecological impact assessments. Ultimately, the extent and impact of agricultural land encroachment by solar farms are contingent on local policies, economic factors, and the priorities of landowners, developers, and communities (Pascaris et al., 2022). Furthermore, the issue of land disputes and encroachment poses a significant challenge to sustainable energy development in India (Yenneti et al., 2016; Yenneti & Day, 2016). Conflicts over land use can arise, particularly in densely populated areas with limited available land. It is essential to adhere to international

conventions and declarations related to indigenous rights and biodiversity to ensure responsible and sustainable land use practices in the context of renewable energy projects.

India, with just 4% of the world's water resources and a population representing 18% of the global populace, faces severe water stress (Goyal & Surampalli, 2018; Ray & Ray, 2011). Despite possessing an extensive river network, the country faces shortages of safe drinking water and irrigation resources (Asthana & Shukla, 2014; Chakraborti et al., 2019; Dhawan, 2017; Garg & Hassan, 2007; R. Kumar et al., 2005). In 2010, India harnessed a mere 20% (761 cubic kilometers) of its water resources, with some of it derived unsustainably from groundwater sources (Galkate et al., 2022). Access to improved water sources in India has improved significantly, rising from 72% in 1990 to 88% in 2008 (J. Singh, 2012). India's annual utilizable water resources stand at 1123 billion cubic meters, comprising 690 billion cubic meters of surface water and 433 billion cubic meters of groundwater (Gupta & Sharma, 2023). The primary consumer of this resource is the irrigation sector, utilizing 78% of the total water reserve, followed by the domestic sector (6%) and the industrial sector (5%) (Vohra & Franklin, 2021). Unfortunately, the overexploitation of groundwater has led to its depletion, despite being a crucial source for both irrigation and domestic water supply in rural and urban areas (D. K. Singh & Singh, 2002). India receives approximately 4,000 billion cubic meters of average annual precipitation (Bhat, 2014), with 3,000 billion cubic meters occurring during the monsoon season (June-September) (S. K. Jain et al., 2007). However, the distribution of available water resources does not align with population distribution (Bhat, 2014), resulting in large areas facing water scarcity and drought conditions. Interstate river distribution has generated conflicts among Indian states, compounding the water management complexities. The study's findings also revealed that water resources in areas near solar farms are in a critical condition. It is essential to explore alternative methods for cleaning solar panels.

4.6 Conclusion

Given the significant challenges related to water availability, effective water management measures are crucial in the context of operating solar power plants. The Land suitability map mentioned earlier represents an initiative aimed at ensuring the thoughtful planning of solar energy resource installations while considering the implications for the agriculture and water sectors. This chapter is an amalgamation of various factors, including land type, terrain characteristics, vegetation

cover, and climate conditions, and resource availability. By integrating these factors into a single map, it allows decision-makers to identify and prioritize areas that are most suitable for a particular land use, while avoiding areas that may be less suitable or environmentally sensitive.

Chapter 5: Discussion

The Solar Panel Index (SPI) discussed in chapter 2, is a method used to effectively map solar farms, providing insight into the distribution and extent of solar energy infrastructure. In the context of the SAW (Solar Energy-Agriculture-Water) nexus analysis at Pavagadh, SPI may be employed to assess the spatial distribution and impact of solar energy installations on agricultural lands and water resources in the region. By utilizing SPI data alongside other relevant datasets, researchers can analyze the interplay between solar energy development, agricultural activities, and water availability in the Pavagadh area. The Land Suitability Map (LSM) complements the SPI and SAW nexus analysis by providing information on the suitability of different land types for solar energy development. LSMs incorporate various factors such as land cover, slope, and vegetation cover to identify areas that are most suitable for installing solar panels. Overall, SPI, SAW nexus analysis, and LSM are interconnected components of the research framework aimed at understanding the complex interactions between solar energy development, agriculture, and water resources. These tools enable researchers to assess the spatial distribution of solar energy infrastructure, analyze its impacts on agriculture and water availability, and identify suitable areas for future solar energy development, ultimately contributing to informed decision-making and sustainable resource management in the Pavagadh region.

5.1 Disaster risk

Natural disasters worldwide have significantly impacted the renewable energy sector. Research (Zhao et al., 2022) indicates that these disasters hinder energy innovation by affecting economic development levels, trade openness, and infrastructure quality. In India, a disaster-prone country, natural disasters have been found to reduce both renewable and nonrenewable energy consumption due to economic damage exceeding the country's reconstruction capacity (Rakshit, 2021). The National Disaster Management Authority reports that 8% of India's total geographical area is susceptible to cyclones, and 12% to flooding (Parida et al., 2018). The effects of natural disasters on energy infrastructure can be disruptive, leading to grid collapses and failures, which are unfavorable to the economy (Uja, 2020). The vulnerability of energy infrastructure to natural disasters emphasizes the importance of resilience and adaptation efforts in the face of climate

change. Overall, natural disasters, along with other crises, emphasize the importance of building resilient energy systems and transitioning towards sustainable energy sources to mitigate risks and ensure a reliable energy supply in the face of future challenges (Zakeri et al., 2022).

Natural disasters, such as storms, have significantly impacted solar power plants. These events can cause physical damage to solar installations, leading to disruptions in energy generation. Hailstorms, tornadoes, hurricanes, and earthquakes have damaged solar installations (Van Reyk, 2023). Solar panels are particularly vulnerable to hail damage, and the increasing frequency of extreme weather events poses a significant risk to solar projects. Moreover, solar power plants can face challenges related to grid stability during storms. Solar energy "tripping" events have occurred due to faults on the grid or other factors, resulting in unexpected shutdowns of solar capacity. These facilities are not immune to the destructive forces of nature. Natural disasters, especially storms, pose significant risks to the operational efficiency and physical integrity of solar power installations (Jasiūnas et al., 2021). Tropical cyclones, characterized by strong winds and heavy rain, can cause extensive damage to solar panels and support structures (Amin et al., 2021). Hail can physically damage the solar panels, reducing their operational efficiency or rendering them inoperative. Similarly, heavy rainfall and flooding can damage the electrical systems and foundations of solar power plants, despite solar panels being designed to be water-resistant (Ketjoy et al., 2022). Storms can lead to direct physical damage to solar panels, including cracking, breaking, or complete detachment from their mounting systems. Such damage requires costly repairs and significantly reduces the plant's power generation capacity. Even minor damage or soiling from storms (e.g., mud deposition after heavy rains) can reduce the efficiency of solar panels (Maghami et al., 2016). Regular maintenance and cleaning are essential, especially in regions prone to such weather events. Storms can disrupt the operations of solar power plants by damaging infrastructure, leading to power outages and loss of revenue. The logistics of repairing or replacing large numbers of solar panels can also be challenging and expensive (Majdi et al., 2021; Shimura et al., 2016).

For example, Hurricane Maria heavily damaged Puerto Rico's emerging solar farms, which had become a significant source of renewable energy for the U.S. territory (Aros-Vera et al., 2021; Kwasinski et al., 2019). The second-largest solar farm in Humacao, providing nearly 40% of the island's solar-produced electricity, suffered significant damage with newly added panels ripped

from their foundations. Another major project, the "Ilumina Project" near Guayama, also experienced damage (Hill, 2020). Additionally, a smaller solar field attached to Humacao's sewage treatment facility, providing 60% of its energy, was nearly destroyed (Ceferino et al., 2023).

Storms can affect solar power plants in India in various ways. The impact of storms on solar energy generation can be influenced by factors such as aerosol loading, cloud cover, and extreme temperatures. One research (S. Ghosh et al., 2023) indicates that India has experienced a substantial impact on its solar power potential due to aerosol and cloud attenuation, with estimates suggesting a loss of 29% of the Global Horizontal Irradiance (GHI) potential between 2001 and 2018. There are some countermeasures that can be adopted, including developing more robust mounting systems and using hail-resistant materials to enhance the resilience of solar panels. Regular monitoring of solar panels and infrastructure to detect any damage early on allows for prompt repairs and maintenance to prevent further deterioration during storms. Developing comprehensive emergency response plans that outline procedures for addressing storm-related damage quickly and efficiently can minimize downtime and ensure the continuity of energy generation.

Storms can be a significant threat to solar power plants, affecting their physical integrity and operational efficiency. However, through careful planning and engineering innovation, the resilience of solar power infrastructure can be improved to withstand such natural disasters (Aly, 2023). The broader implications of storms on solar energy generation and infrastructure in India highlight the importance of resilience planning and risk mitigation strategies for the country's growing solar sector. Addressing these challenges requires a comprehensive approach to enhance the reliability and sustainability of solar power plants in the face of extreme weather events.

5.2 Solar pumping for irrigation

Solar pumps have become a boon for irrigation in India, providing farmers with a dependable, affordable, and eco-friendly option (Rathore et al., 2018). These pumps alleviate the financial strain of electricity expenses, cut down on carbon emissions, and aid in preserving groundwater reservoirs. Studies show that the integration of solar-powered irrigation systems has lightened the daily workload for farmers, boosted agricultural output, and raised income levels (Ramli & Jabbar,

2022). Furthermore, coupling solar pumps with micro-irrigation methods like drip irrigation has led to significant water conservation, improved energy efficiency, and enhanced crop yields (D. S. Kumar & Palanisami, 2010; Priyan & Panchal, 2017; Sivanappan, 1994). Government schemes such as PM-KUSUM and PM-KSY seek to encourage farmers to switch to solar water pumps, thereby promoting sustainable farming practices and supporting the country's Net Zero mission by 2070 (Kynta, 2020; Shah & Rai, 2021).

Solar pumps differ from traditional pumps in several aspects, including cost, efficiency, and environmental impact. In terms of cost, solar water pumps entail a higher initial investment due to solar panels and associated components, but they offer long-term savings by harnessing free solar energy (Chandel et al., 2015). On the other hand, traditional pumps necessitate ongoing payments for electricity or fuel. In terms of efficiency, solar pumps excel by utilizing renewable solar power, resulting in lower operational costs and reduced maintenance needs compared to traditional pumps. They are also more reliable, with fewer moving parts and simpler operation, and they have a minimal environmental footprint, emitting no harmful pollutants, unlike traditional pumps. Out of the total 29.93 million agricultural pumps in India (Karmarkar, 2023; Shastri et al., 2021), approximately 20 million are grid-connected, 10 million run on diesel, and around 3.9 million operate using solar energy (Mantri et al., 2020). Solar pumps have proven instrumental in reducing farmers' daily burdens, enhancing productivity, and boosting incomes. A paper (Buisson et al., 2021) examines the impact of access to electric pumps on agricultural outcomes in West Bengal. Electric pump owners cultivated larger areas of rice, achieved higher yields and value added compared to diesel pump owners and water buyers. They also provided irrigation water to non-owners, benefiting smaller farmers. The government aims to cut carbon emissions by 32 million tonnes through solarized irrigation, with off-grid solarization potentially reducing transmission and distribution losses by up to 20% (Karmarkar, 2023; Shukla et al., 2023). Solar pumps provide a reliable energy source, economical irrigation solution, and environmental benefits, particularly benefiting remote areas with limited electricity access (Supe et al., 2024). Despite challenges such as awareness gaps and reluctance to transition, initiatives like PM-KUSUM and PM-KSY strive to incentivize farmers to embrace solar water pumps and micro-irrigation techniques for sustainable agricultural practices.

5.3 Current scenario of solar farm distribution

In recent years, India has seen a surge in the installation of solar power on a larger scale. Most of this renewable energy comes from massive solar farms located in the deserts of Rajasthan or Gujarat, often as public-private partnerships run by utility companies (Meena et al., 2014). The table 5.1 displays the distribution of current solar farms across different types of land suitability as recommended by the Land Suitability Map (LSM) of India. The largest portion, accounting for 37.55%, falls under moderately suitable land. A significant portion of existing solar farms is also located in land categorized as Suitable (16.03%), Highly Suitable (16.37%), and Most Suitable (19.35%) according to LSM. Only a small fraction of land is considered Unsuitable to Slightly Unsuitable. Overall, this suggests that the nation's solarization program has allocated land moderately well, according to the LSM presented in the study. In future planning, using LSM as a decision-making tool could further enhance the efficiency of land allocation for solar projects.

Table 5.1 Distribution of currently located solar power plant according to LSM generated from this study.

LSM Categories	Percentage cover
Unsuitable	1.97
Least Suitable	0.00
Slightly Suitable	8.74
Moderately Suitable	37.55
Suitable	16.03
Highly Suitable	16.37
Most Suitable	19.35

The residential rooftop solar market in India is experiencing rapid growth, with cumulative installed capacity set to rise significantly from 2 GW in FY2022 to an expected 3.2 GW by FY2023, indicating a nearly 60% year-on-year increase (Kristoff, 2022). States like Gujarat, Haryana, and Maharashtra are becoming key locations for residential rooftop solar installations due to favorable policies and incentives. According to India MNRE (pib.gov.in), the estimate of rooftop solar in India after the implementation of the PM-Surya Ghar Muft Bijli Yojana is to add 30 GW of solar

capacity in the residential sector. India's rooftop solar sector is positioned for substantial expansion, offering the potential to meet a significant portion of the country's residential electricity demand.

The insights gained from India's study in balancing solar energy expansion with agricultural and water needs provide valuable methods for other nations grappling with similar challenges. Policymakers and stakeholders globally can leverage the study's recommendations to implement integrated planning approaches, optimize resource utilization, and ensure the harmonious coexistence of renewable energy, food security, and water management. Ultimately, this research contributes to the global discourse on sustainability, offering practical solutions to foster resilient and equitable development across diverse geographic and socio-economic contexts.

Chapter 6: Conclusion and Recommendations

6.1 Summary of Findings

This research presents a novel index, the Solar Panel Index (SPI), which utilizes a combination of multispectral bands to efficiently detect solar panels. This index has demonstrated its effectiveness in Land Use and Land Cover (LULC) classification, achieving an impressive accuracy of 89% when incorporated into the machine learning training model. The research has also generated a comprehensive map depicting solar farm locations and their estimated installed capacities across the country, which can be instrumental in informing spatial energy distribution planning. SPI has shown strong classification capabilities at various threshold values across different regions. The differing environmental conditions in various locations have influenced SPI's performance.

Analysis performed in this research study has revealed that more than 40% of solar power plants have been constructed on land traditionally used for agricultural crop production. Also examined water resource availability in the regions surrounding these installations, highlighting the importance of the solar-agriculture-water nexus in sustainable development. Field visits to solar power plants provided a thorough understanding of their operation and impact on natural resources such as land and water. Additionally, valuable insights were gained from expert consultations, which guided our research in identifying critical factors affecting the functioning of solar power plants and achieving overall sustainability. These insights proved particularly valuable in understanding the complex interplay between solar energy production, agricultural land use, and water resource management.

The study culminated in the creation of a high-resolution (100m) Land Suitability Map (LSM) for the entire country of India, emphasizing the elements of SAW nexus. This map has the potential to serve as a valuable resource for effective land use planning those accounts for the interconnectedness of these three crucial components. Notably, the state of Rajasthan emerged as the most promising region for solar power installation.

6.2 Conclusions drawn from the findings

The study has effectively demonstrated the utility of the SPI method for mapping and monitoring solar panels across India. This innovative approach, harnessing open-source optical satellite data, offers valuable insights into the distribution and expansion of solar farms within the country. Furthermore, the research study has introduced the significant impact of solar farm expansion on agricultural land and water demand. The growing encroachment of agricultural areas for the establishment of solar power plants is a concerning trend with potential long-term consequences for India's crop lands. It's pertinent to observe that solar farms, rely on water resources for the maintenance and cleaning of solar panels. This dependence creates a potential competition for water resources, particularly in regions already facing water scarcity issues. The study highlights the emerging trade-off between land utilization for solar energy production, agricultural purposes, and water supply emphasizing the complexity of the challenge at hand.

6.3 Limitations and recommendations for further studies

The study introduces SPI, a method using optical data that is easily accessible. However, its accuracy may vary with different sensors and factors like panel orientation, dust, and degradation over time. The research analyzes solar farm encroachments on agriculture and water resources at a state level, but local level study could yield detailed information with diverse regional outcomes. The study did not consider the socioeconomic effects of land use changes on food security and livelihoods. The study's recommendations for sustainable resource management discussed in the subsequent section are theoretical and need policy-level considerations, potentially involving unexplored challenges and trade-offs.

Further research endeavors are essential to dig deeper into the SAW nexus. It is imperative to conduct long-term and field-based studies that meticulously assess the sustained impacts of solar farm expansion on agriculture, food production, and water resources in specific regions of India. These studies should encompass continuous monitoring over several years, or even decades, to comprehensively comprehend the evolving trends and potential mitigation strategies. Additionally, detailed investigations are necessary to examine the effects of shading caused by solar panels and the resulting changes in microclimates on crop yield and quality. Such studies can offer valuable

insights into the specific crop types and growing conditions that are most susceptible to these changes. Furthermore, a more extensive analysis of soil quality assessment is imperative to gain a profound understanding of soil conditions. Ground-level field studies are indispensable to validate the outcomes of geospatial-based analyses comprehensively.

There is a persistent need to get on research and development initiatives aimed at formulating sustainable land-use planning models and guidelines. These models must effectively balance the competing interests of agriculture, solar energy, and other land uses. The main goal should be to optimize land utilization across diverse sectors while minimizing adverse environmental impacts. Furthermore, to strengthen the knowledge base, it is beneficial to conduct comparative analyses that compare the experiences and outcomes of solar energy development in India with those of other countries confronting similar challenges. These comparisons should focus on identifying best practices and drawing lessons from international experiences.

6.4 Policy recommendations for sustainable resource management

The policy guidelines proposed in this paper aim to support the long-term sustainable development of the solar energy industry while addressing the challenges of the SAW nexus. By incorporating the insights and recommendations presented in this study, decision-makers can more effectively balance the demands on land and water resources while advancing the sustainable growth of the solar energy sector. The comprehensive and strategic approach to sustainable resource management in the SAW nexus involves adopting an integrated and holistic approach to planning and decision-making. This approach considers the interdependencies and trade-offs between different sectors, and seeks to optimize resource use, reduce waste, and enhance resilience. The following policies are recommended to promote sustainable resource management:

- I. Encouraging integrated planning approaches that consider the interdependencies between water, energy, and food systems, and promote collaboration among stakeholders.
- II. Promoting education and awareness among farmers on possibilities of land degradation resulting from the long-term deployment of solar panels.

- III. Developing regulatory frameworks that promote sustainable resource management practices, such as water-use permits or energy efficiency standards for buildings.
- IV. Establishing land leasing agreements with solar developers that prioritize non-agricultural land such as barren land or degraded forests, for solar development to reduce pressure on agricultural land.
- V. Integrate trainings and procedures in the local plans that can encourage solar developers to use water more efficiently and promote sustainable water management practices.
- VI. Promoting and incentivizing use of robotic cleaning system for solar panels that can replace water usage and cut-short labor cost.

This approach can support economic growth and social development in the solar industry. By taking a comprehensive and integrated approach to resource management, it is possible to achieve a more sustainable and equitable future for all stakeholders involved in the solar, agriculture, and water nexus. Implementing rigorous policies of this nature can effectively prevent land encroachment in other countries too (Cerullo et al., 2023; Li et al., 2023; Schaefer & Thinh, 2019). By enacting effective water management policies and offering incentives for the deployment of cleaning robots, with proactive steps can have control over the water resources, thus mitigating potential stress and scarcity issues (Ammari et al., 2022; Elamim et al., 2023; Habib et al., 2023; Musie & Gonfa, 2023). These policies can help to balance the needs of different stakeholders and promote the sustainable use of natural resources, while also supporting economic and social development goals.

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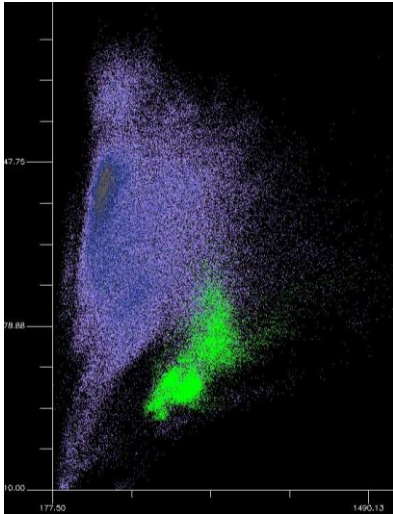
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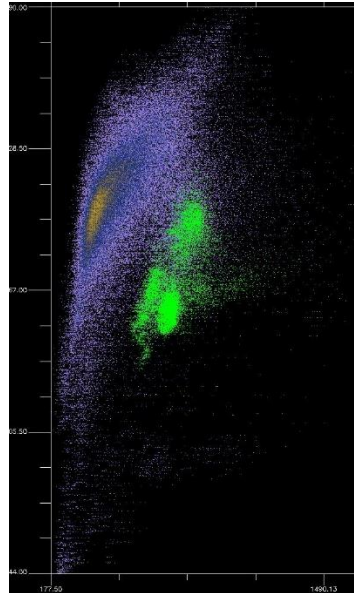
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Annexures

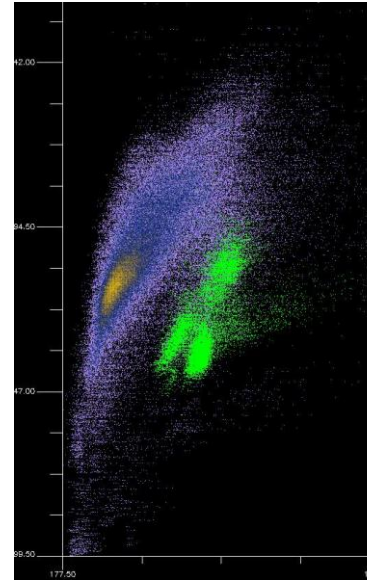
Annexure A1: Scatter plots of Sentinel-2 multispectral bands, highlighting solar panel area in green.



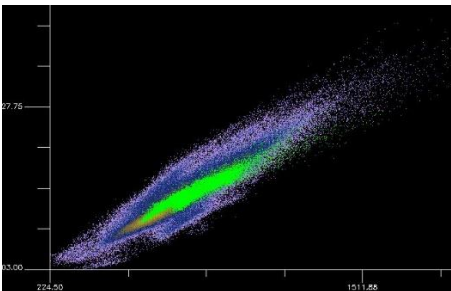
Band 2 (Blue) – Band 8 (NIR)



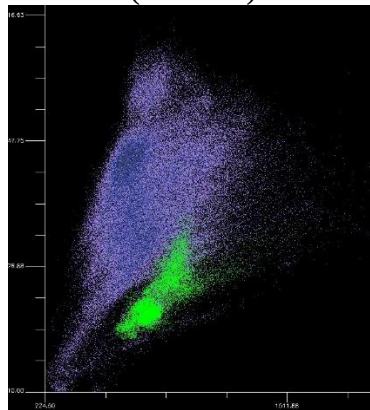
Band 2 (Blue) – Band 11 (SWIR-1)



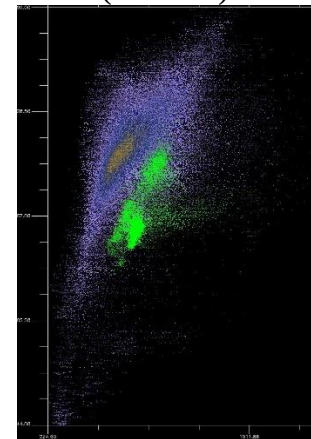
Band 2 (Blue) – Band 12 (SWIR-2)



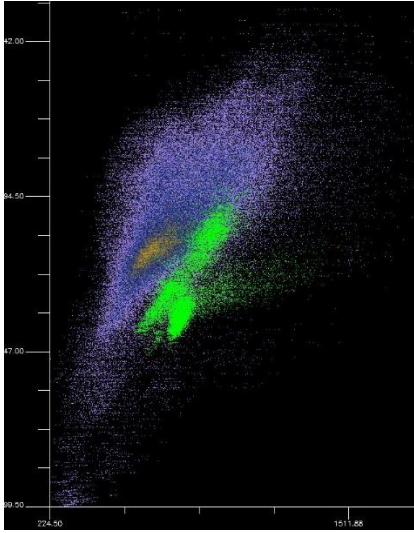
Band 3 (Green) – Band 4 (Red)



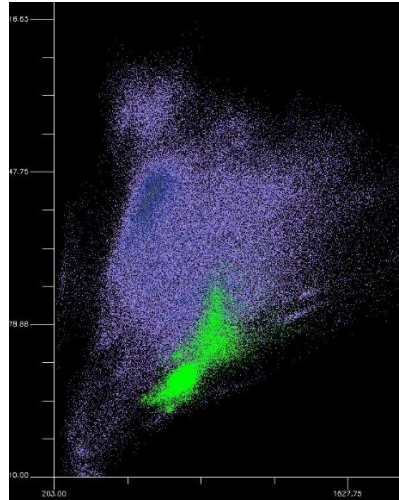
Band 3 (Green) – Band 8 (NIR)



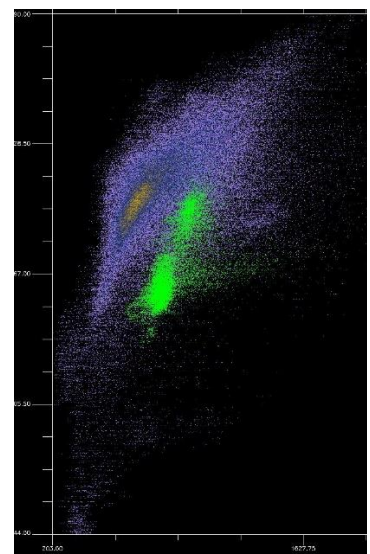
Band 3 (Green) – Band 11 (SWIR-1)



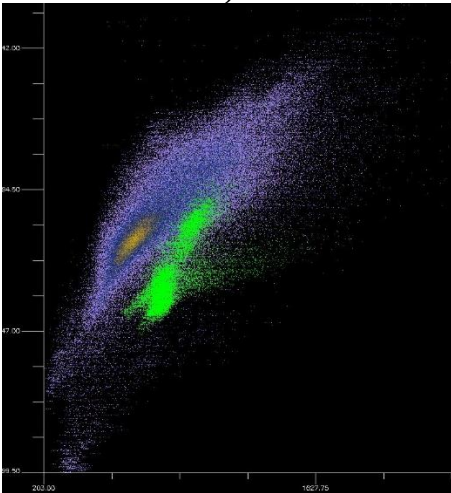
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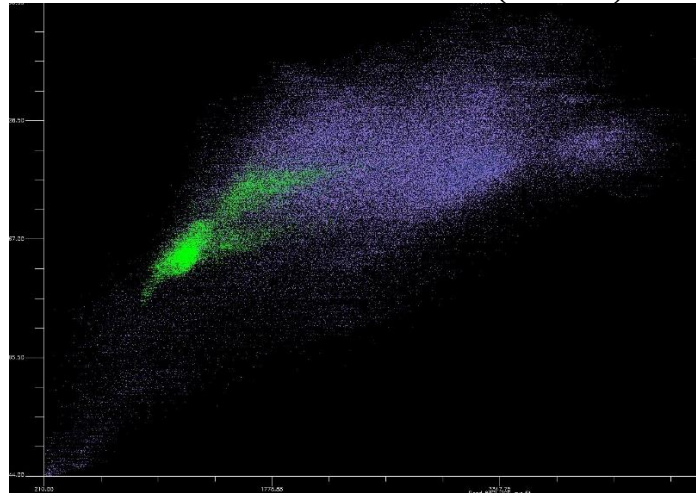
Band 4 (Red) – Band 8 (NIR)



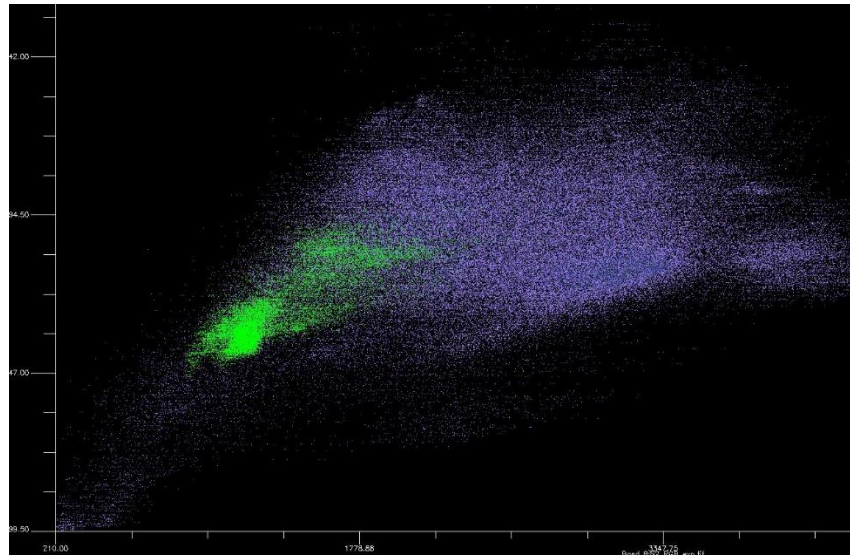
Band 4 (Red) – Band 11 (SWIR-1)



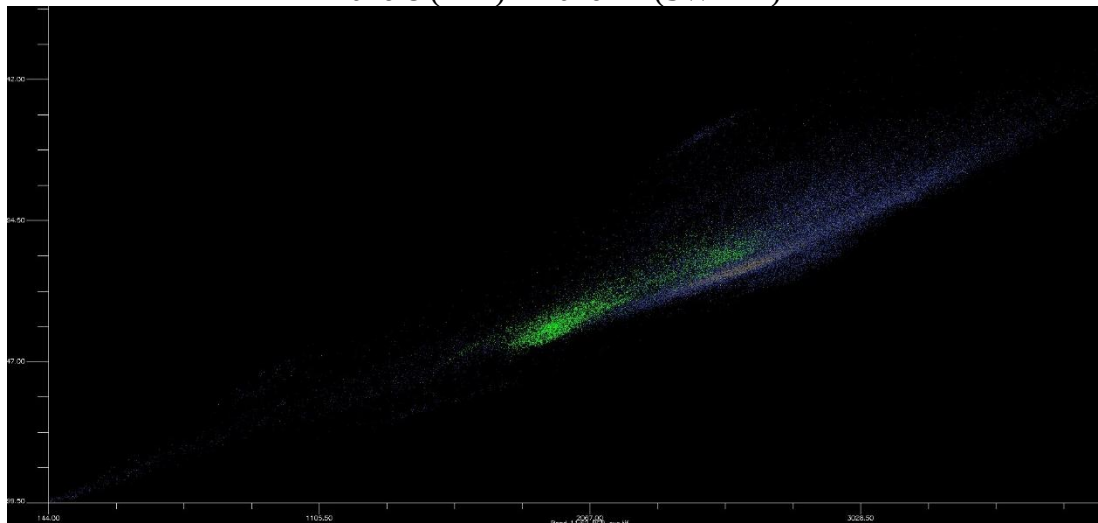
Band 4 (Red) – Band 12 (SWIR-2)



Band 8 (NIR) – Band 11 (SWIR-1)



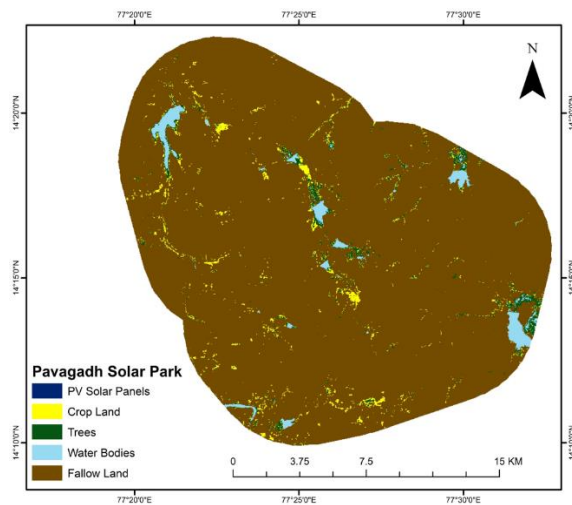
Band 8 (NIR) – Band 12 (SWIR-2)



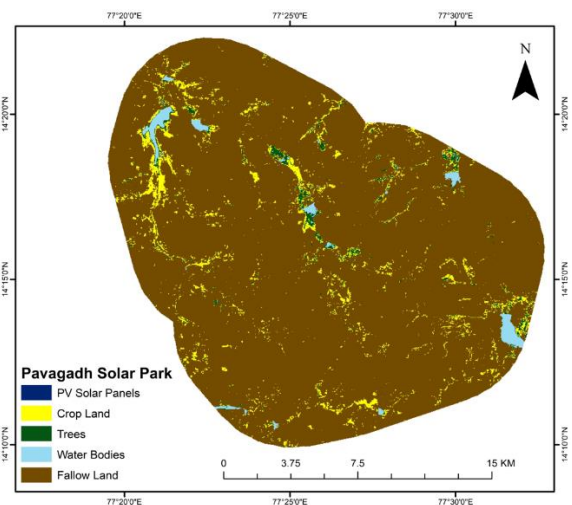
Band 11 (SWIR-1) – Band 12 (SWIR-2)

Annexure B:

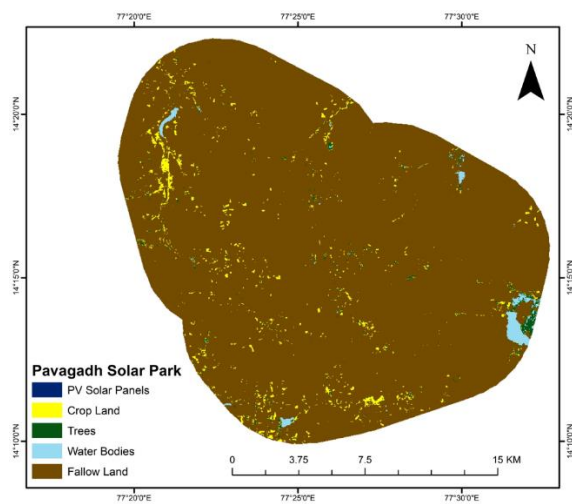
Figure. B1. LULC of Pavagadh solar park area and its surrounding boundary upto 5km.



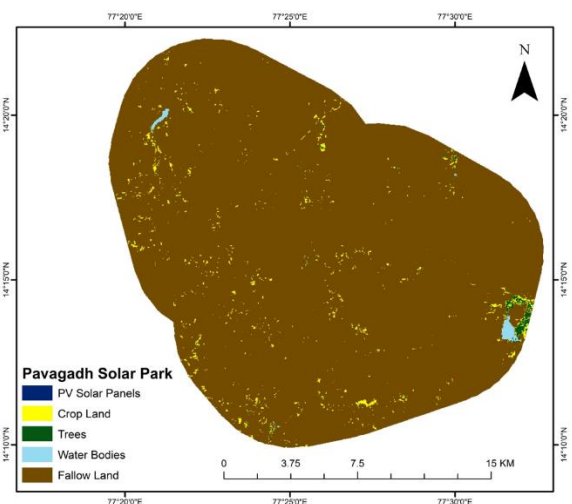
2008



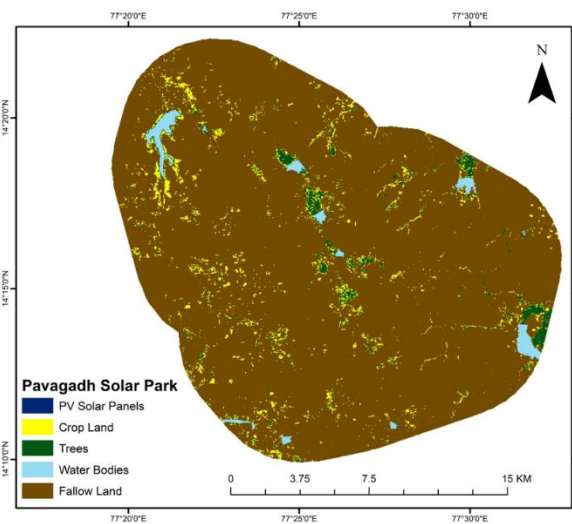
2009



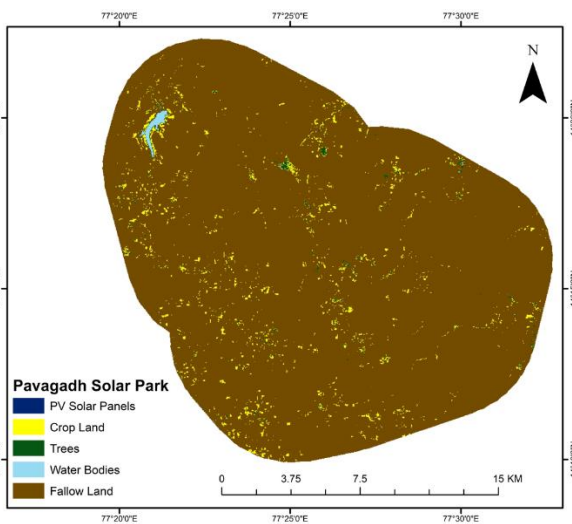
2010



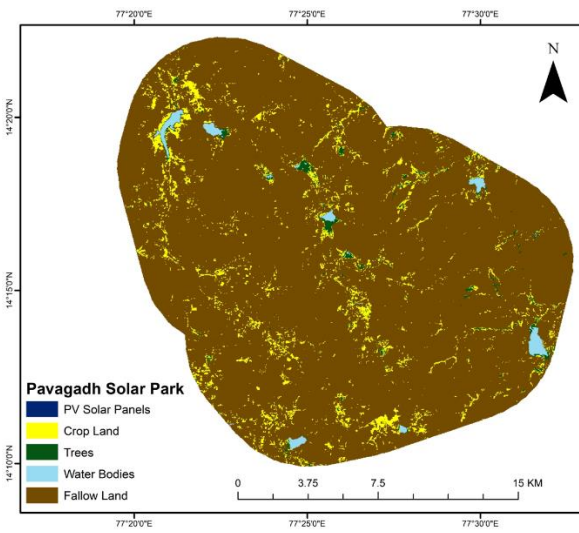
2011



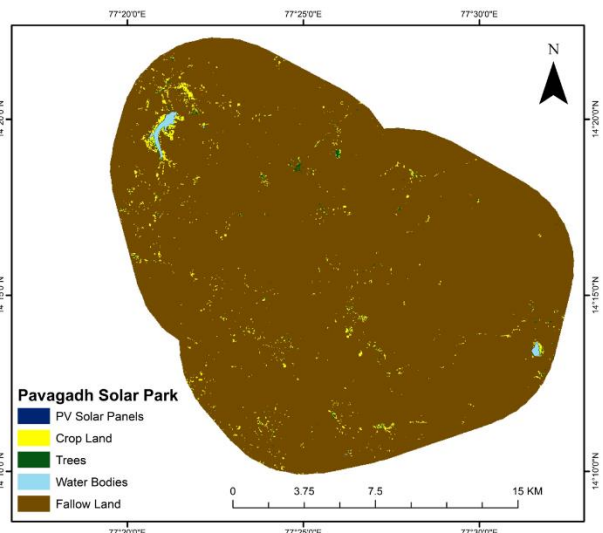
2013



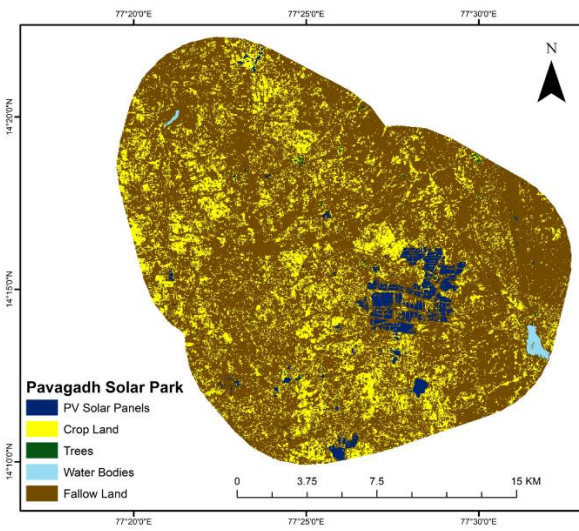
2014



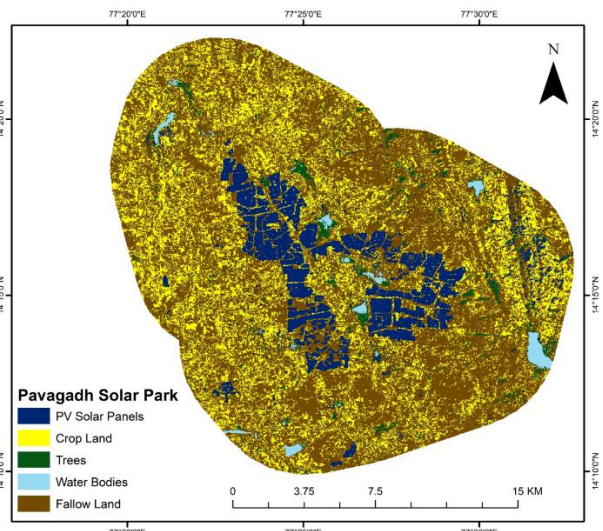
2015



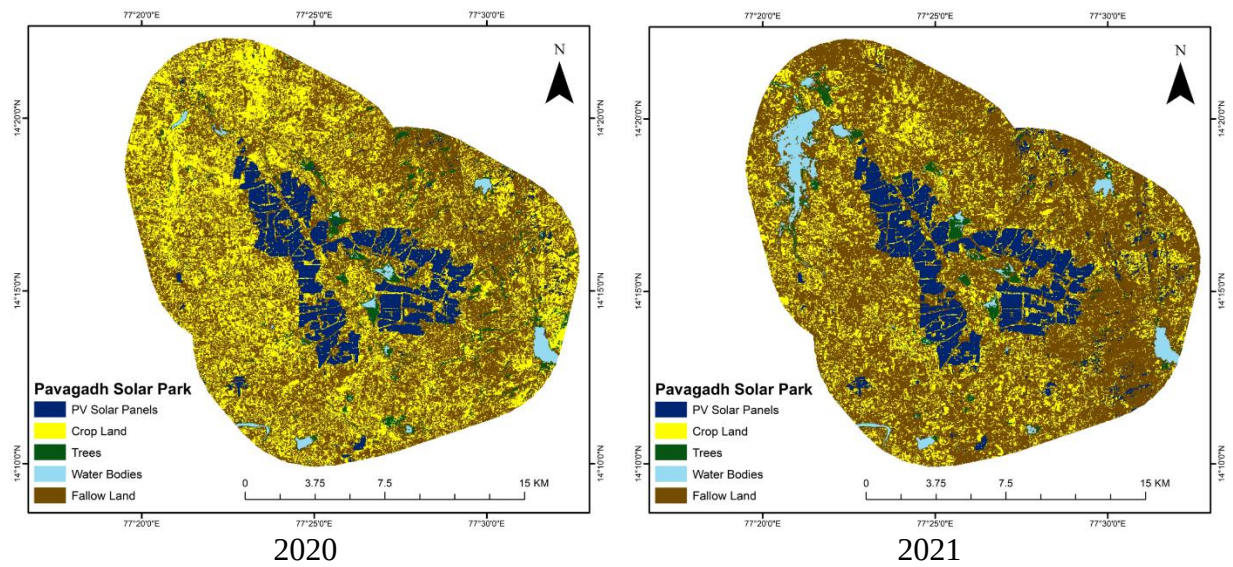
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2018



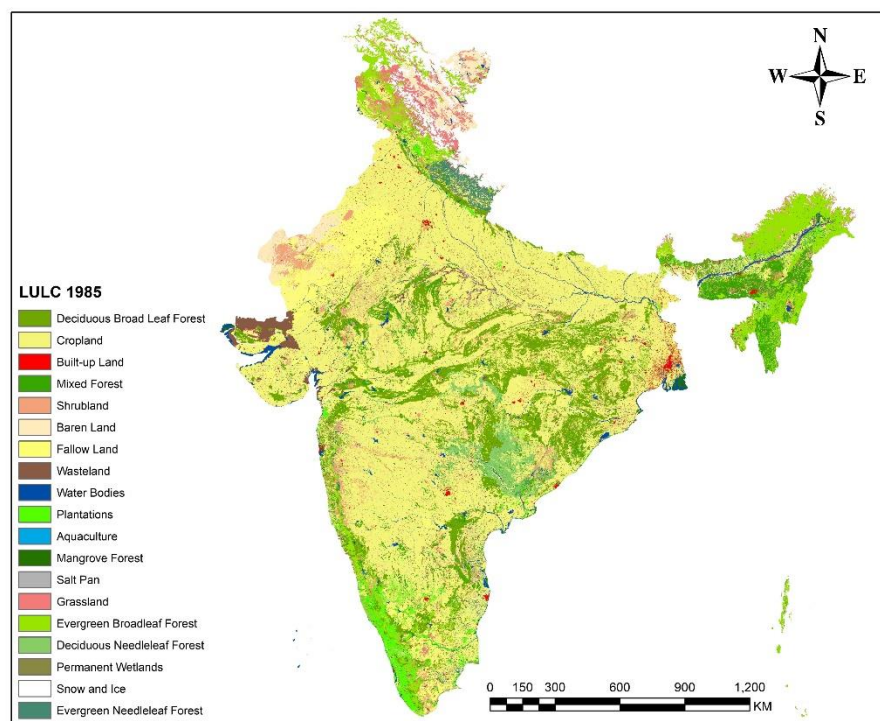
2019



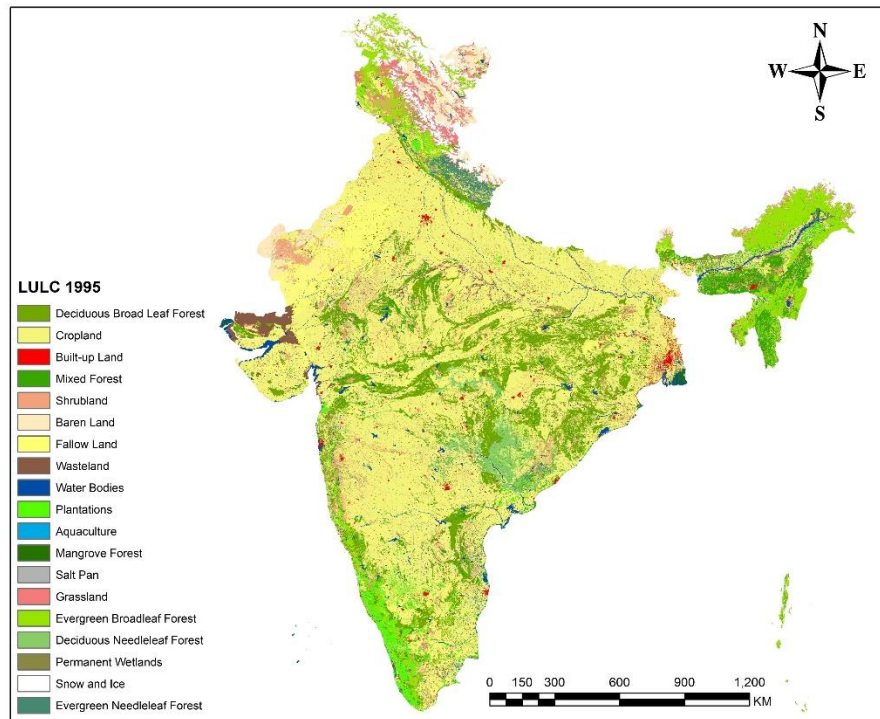
Annexure C:

Figure. C1. Landsat series generated 100-m resolution LULC map by ORNL DAAC (Roy et al., 2016)

(a) 1985



(b) 1995



(c) 2005

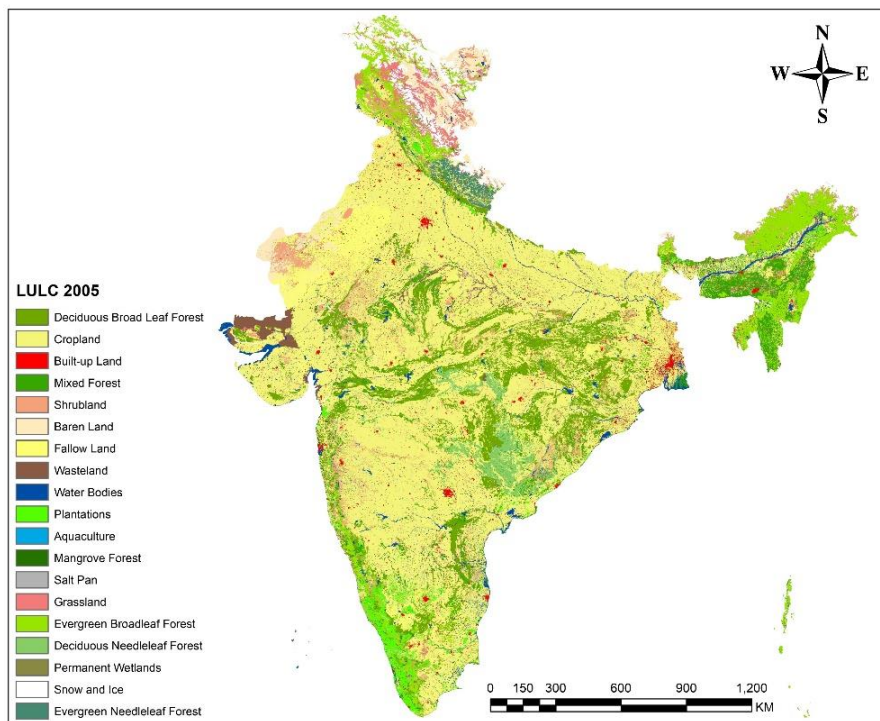


Figure. C2. Groundwater map (indiawris.gov.in)

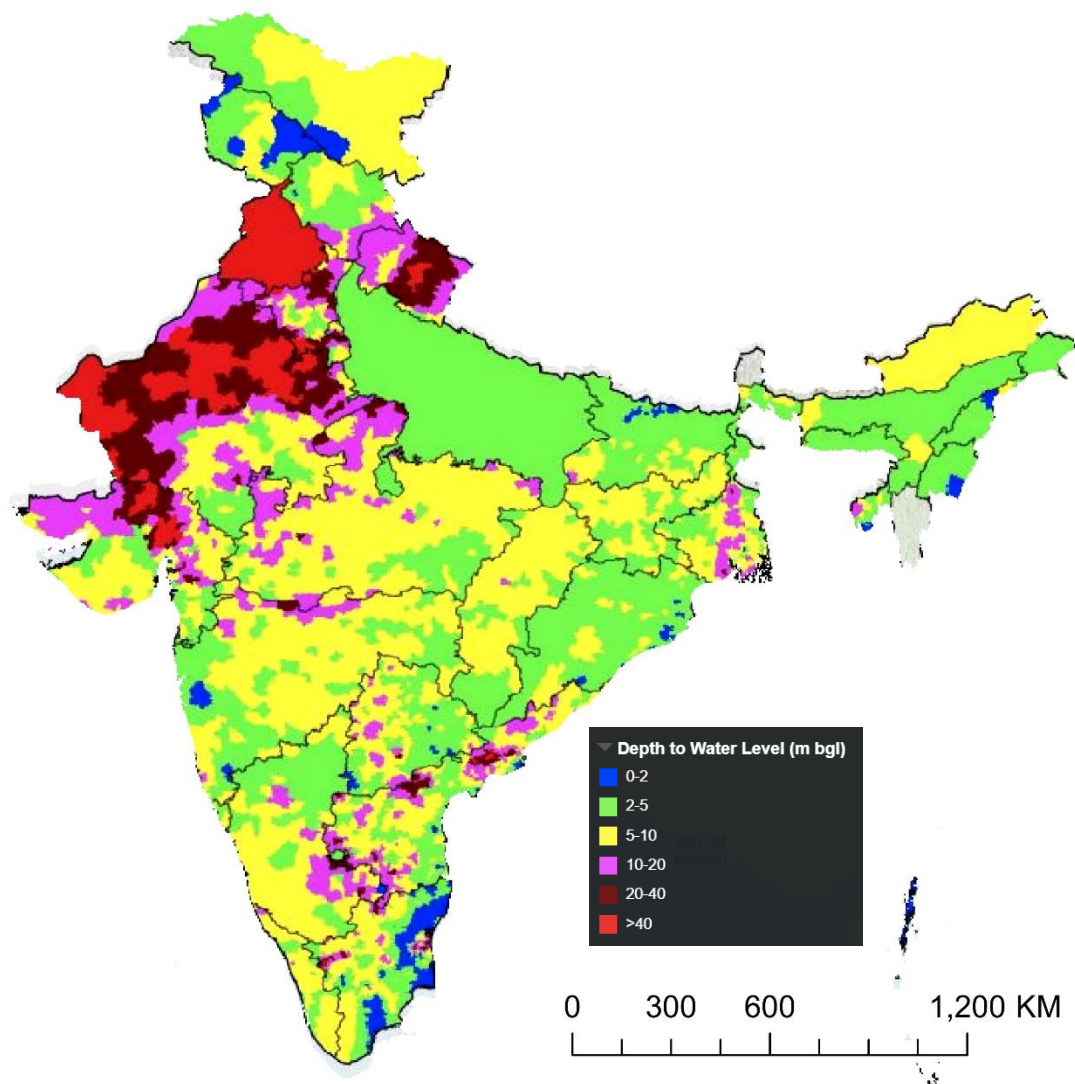


Figure. C3. Surface water map (hub.arcgis.com/datasets/)

