



University of Padua

**Department of Agronomy, Food, Natural Resource,
Animals and Environment (DAFNAE)**

Second Cycle Degree M.Sc. in Sustainable Agriculture

**Pond-Based Water Resource Management in Response to Spatial-Temporal Rainfall
Variability and Drought Vulnerability in Palakkad.**

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Abstract

Agriculture in Palakkad known as the rice bowl of Kerala, India has been challenged by water-related issues due to climate-related rainfall variability. This research aims to analyse the rainfall patterns and variability in Palakkad by using daily rainfall data collected from 11 stations between 2018 and 2023. Precipitation Concentration Index (PCI) and Standardized Precipitation Index (SPI) are used to calculate rainfall variability and drought vulnerability in this region. Over the years, the region has witnessed drought and flood events. With increasing demand for food and climate change, sustainable water resource management has become important. This study integrates index maps created in ArcGIS with pond map to identify areas requiring pond-based water resource management interventions. The study reveals that Palakkad's east region, particularly in Chittur and parts of Malampuzha blocks, the Precipitation Concentration (PCI) is higher. This indicates significant rainfall irregularity. Walayar rain gauge station recorded PCI values around 20 and above for multiple years, denoting high variability. While the monsoon rainfall exhibited uniform distribution, post-monsoon values was higher in 2018 referring to inconsistencies. The Standardized Precipitation Index (SPI) further highlighted that eastern and southeastern parts of the district is drier while north and west part are wetter. This brings Chittur in the arid category. While Mannarkkad block region appeared to be wetter with SPI values greater than 2 except for the year 2023. Pond Density analysis reveals Chittur has fewer ponds in comparison with the water needs. Considering the intensive agriculture land use and erratic rainfall along with increasing water scarcity these findings suggests Chittur would face a substantial water stress in the future. In the view of climate change and increasing water demand all around the world, this study recommends restoration and construction of more ponds as a natural based solution through farm-led management initiatives. Adopting this natural-based solution supports farmers' cultivation making them resilient to the climate change impacts.

Keywords: Water, Climate change, Agriculture

1. Introduction

Water is the most important resource for agriculture. However, issues including industrialization, unpredictable rainfall patterns, and climate change have had a negative impact on water availability and management globally. Agriculture uses 70% of freshwater worldwide. The agricultural industry is extremely susceptible, since it depends on water resources. This will greatly impact places like India, where agriculture is a gamble with the monsoon season.

Kerala, a southern Indian state, is referred to as "God's own country" and the "Indian monsoon gateway". The region's humid tropical monsoon climate makes it unique. Rice is the primary farm product in Kerala, which is also a plantation state. Other cash crops include coconut, rubber, cashew, tea, and coffee, other important spice crops include black pepper, ginger, and vanilla (Thomas, 2023). Figure 1, shows extend of agriculture landscape in Kerala.

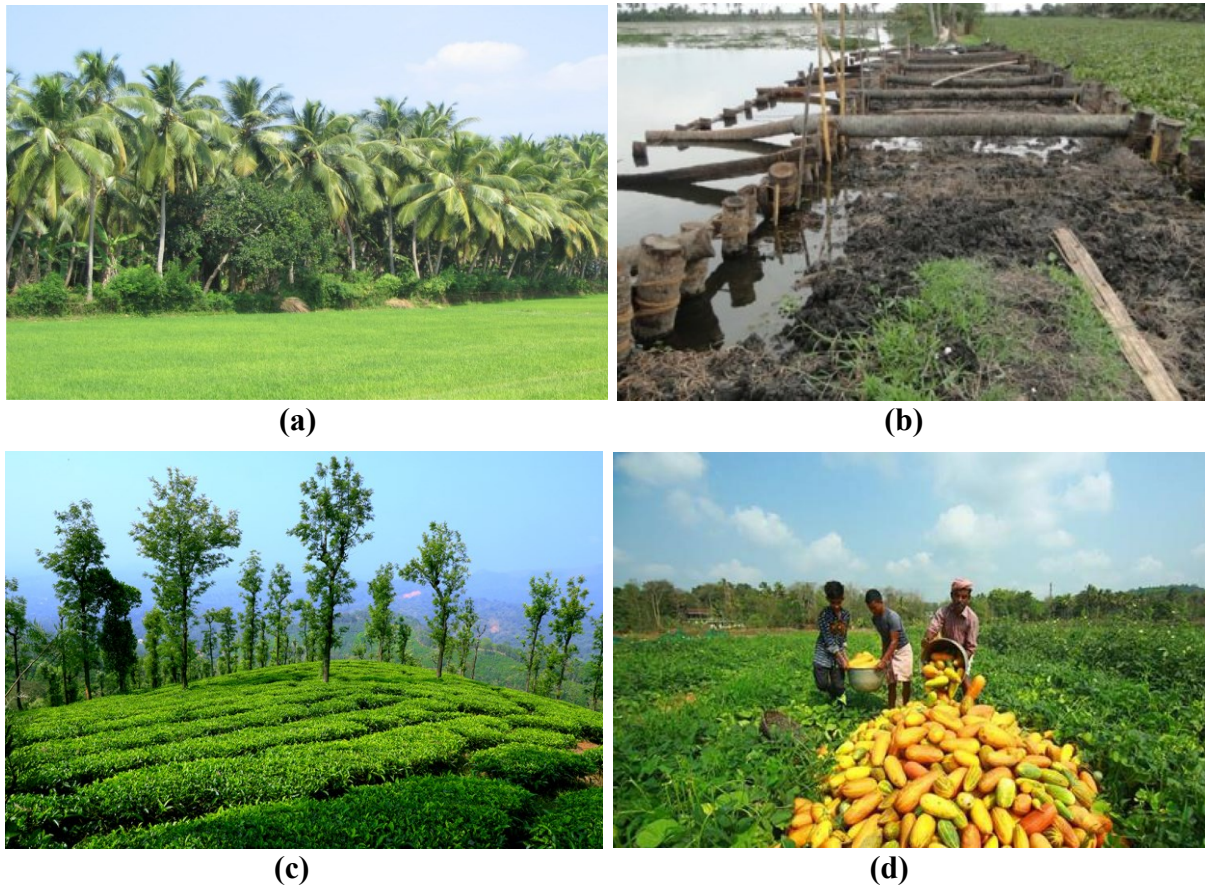


Figure 1. (a) Rice Field and Coconut Plantation in Kerala (Source: Kumar and Kunhamu, 2022), (b) Below Sea-Level Farming System in Kuttanad, Kerala (Source: FAO, n.d), (c) Tea Plantations in High Range, Wayanad (Source: Kerala Tourism Website), and (d) Vegetable Harvest in Kerala (Source: Kerala State Planning Board website)

Though the state receives ample amounts of rainfall it experiences paradoxical times of water scarcity. The state receives around 3000 mm of rainfall annually (Harithalekshmi and Ajithkumar, 2023). The rainfall season between June and September is called the Southwest monsoon and is followed by the Northeast monsoon from October to December. The rice crop season is categorized as Virippu (autumn), Mundakan (winter), and Pucha (summer). The first season is majorly rainfed as it coincides with the Southwest monsoon. The second season is mostly irrigated with a little dependence on rainfall and the last season is fully irrigated (Joji et al., 2022).

Palakkad, often referred to as the "Rice Bowl of Kerala", plays a pivotal role in the state's agricultural output, with paddy being the primary crop. Geographically the district is bordered by the Western Ghats that goes along the eastern side of the district and it has a 30 km discontinuity called the Palakkad Gap (Joji et al., 2022). Bharathapuzha River is the major source of water majorly depended by the farmers of the region. The region has many dams built, the biggest one is the Malampuzha. The monsoon or rainfall affects the inflow and outflow of the irrigation water thus affecting the rice productivity. The effect of urbanization resulted in a significant reduction (30.5%) in the rice cultivation area from 111,029 Ha to 77,121 Ha in the last 15 years in Palakkad (Agri Statistics 2021-22, 2023). Net irrigated paddy for the crop season 2022-23 is 80.20 % (Agri Statistics 2022-23). The basin consist of many rivers like Chittur Puzha, Kalpathy puzha, Gayathri Puzha and Thootha puzha.

Palakkad has a tropical and dry climate. The annual rainfall varies from 1883 to 3267 mm, of which 71 % percent of the rainfall is received during the southwest monsoon and the remaining during northeast monsoon (Das et al., 2024). The weather scenario in recent years has created many difficulties in paddy cultivation. The farmers' concerns are rising temperatures, variability in rainfall, and water scarcity during critical growth periods. Surface and groundwater irrigation is high in the rice bowls of Kerala namely, Palakkad and Alappuzha (IWMI, 2010).

The agricultural production in the Palakkad region is dependent on the monsoon rainfall. George and Athira 2024 analyzed the historical rainfall data of the region from 1901 to 2013 and found a significant reduction in the annual rainfall and an increase in the frequency of occurrence of extreme events (George and Athira, 2020). The region experienced 6 extreme rainfall events after the year 2000 which has been identified based on the trend in Standardized Precipitation Index (SPI) value (Department of Environment and Climate Change, Kerala,

2022) and there has been an increase of 1°C in the average temperature over this period of 35 years (Sreeshna et al., 2023). Changing patterns in the temperature and rainfall patterns have adversely impacted the agricultural production of the region. The rice production has reduced by 17% in this period (George and Athira, 2020).

The Precipitation Concentration Index (PCI) and Standardized Precipitation Index (SPI) are valuable tools for analyzing rainfall variability and drought vulnerability, respectively (Lu et al., 2017; Thomas et al., 2016). By employing these indices, this study examines the spatiotemporal patterns of rainfall in Palakkad to identify risk areas. Additionally, the study integrates pond density analysis to identify the areas with limited number of ponds to meet the increasing water need. This approach is proposed as Natural-based solution for water resource management, aiming to enhance agricultural resilience and long-term water security in the region.

Through this research, we aim to bridge the gap between climate variability and water resource management, offering actionable insights for sustainable agriculture in Palakkad. The findings underscore the importance of rediscovering traditional water systems, such as ponds and adopting innovative, location-specific strategies to combat water stress and ensure food security in the face of climate change.

2. Literature Review

2.1 Impacts of Climate Change on Food Production: A Global Perspective

Climate change is a pressing concern that the world is facing and requires urgent action. The Intergovernmental Panel on Climate Change defines it as a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period typically decades or longer (IPCC, 2022). Climate change can lead to changes in frequency, intensity, spatial extent, duration, and timing of weather and climate extremes resulting in unprecedented extremes (IPCC, 2012). However, extreme events can also occur due to changes in El Nino-Southern Oscillations. Nevertheless, it is crucial to note that the average temperature rise is 1.20° C for a period ranging from 2014- 2023 (WMO, 2024).

Different sectors of society including the economy, health, biodiversity, and forests would experience these impacts (Ojumu et al., 2020). Within this, the susceptibility of agriculture is concerning due to its heavy dependence on climatic variables and weather conditions (Musser

and Patrick, 2002). Agriculture is impacted due to the fluctuations in global temperature and precipitation patterns that result in extreme climate events and natural disasters (Lobell et al., 2011). In the last decade, agriculture alone absorbed 26 % of the overall impact caused by natural disasters at different scales (FAO, 2021). This has also affected the global food security and the agriculture sector will experience more losses in the coming years (Monteleone et al., 2023).

Food production can have impacts at various levels. The rising temperature has mixed results. However, the effect in warm region are causing detrimental effect already. Positive trends in yields are also observed, but they tend to decline after reaching a certain optimal level (Lobell et al., 2011). On the other hand, the changing precipitation pattern and high temperatures eventually can increase the demand for irrigation and decrease the water availability (Elliott et al., 2014). The rising temperature and precipitation can also impact the soil organic carbon interfering the fertility of the soil. The extreme events such as drought and floods can lead to soil erosion and nutrient leaching threatening long-term productivity (Lal, 2013).

Pests and disease proliferate due to conducive conditions for proliferation thereby causing crop damage in an indirect way. About 10- 25 % increase in pest is possible to happen from every degree rise in Celsius (Deutsch et al., 2018) increasing chances of extensive damage. Nutritional decline in crops especially staple crops like rice and wheat also attribute to impact of climate change. The protein and nutrient concentration in crops posing severe implications on the public health and food security (Myers et al., 2014). And the most important implication is the production and price of the food affecting the food security in developing countries. The reduced yields, increased demand and resulting high price will affect the accessibility. Other climate-induced impacts can affect production which can lead to export restrictions also (Porter et al., 2014).

Climate change's impacts on agriculture are multi-dimensional, affecting temperature and precipitation patterns, water availability, pest prevalence, soil health, crop quality, and food prices. The aggregate effect threatens global food security, particularly in regions already vulnerable to food shortages.

2.2 Rainfall Variability in Kerala over the years

Kerala receives heavy rainfall that ranges around 3000 mm during the rainy season also called as the Monsoon season. The rainfall occurs in Kerala as a result its geographical position in the

western windward slopes of the Western Ghats (Thomas and Prasannakumar, 2016). The windward slope also has many river drains. The hydrology and water availability of the region is hence determined by the Indian summer monsoon (Lakshmi et al., 2024).

The monsoon mainly consists of two seasons. The first season is the Southwest Monsoon starting from June till September and followed by the Northeast Monsoon starting from October to December. The season starts over the Kerala coast on 1st of June and advances along the west coast of the country, covers all of the country and withdraws on 15 October which is then replaced by the Northerly continental airflow called the northeast monsoon. The season is very crucial for the economy of Kerala as it affects the regional climate. Hence, any variability in the season is very crucial for the state. Understanding the rainfall pattern as well as drought characteristics in the state plays an important role in the watershed development and management. A previous study conducted reveals that there has been variability in the rainfall. This analysis conducted with the last century's data indicates that 1871-72 to 2011-2012 rainfall in Kerala showed a decreasing trend with the southwest monsoon. At the same time, post-monsoon and winter showed an increasing trend resulting in a monsoon-driven climate seasonality, concentrating rainfall in the half part of the year. The temporal variation of SPI for 3-month scale also indicated that the period 1871-72 to 1911-12 and 1971-72 to 2011-12 have witnessed more intense short-term droughts. And these drought patterns were related to rainfall concentration. The reducing trend of the rainfall during southwest monsoon contributed to short-term meteorological droughts, while the increasing rainfall (with less irregularity between months) during other seasons helped to reduce the drought severity (Thomas and Prasannakumar, 2016).

Further rainfall variability for the period 1989 to 2018 was analyzed in another study. The highest southwest rainfall in this period was 2654.8 mm in 2007 and the highest annual rainfall of 3518.9 mm in 2018. Also, the last 30 years, the highest rainfall of June (1063.6 mm), July (963.6 mm), August (822.4 mm) and September (522.5 mm) are received in 1991, 1997, 2018 and 2007 respectively. Similarly, the lowest rainfall of June (430.3 mm), July (318.5 mm), August (231 mm) and September (50 mm) are received in 2012, 2002, 2016 and 1991, respectively. The lowest southwest monsoon rainfall was 1352.3 mm and the annual rainfall was 1870.9 mm in 2016 (Guhathakurta et al., 2020). Since 2018, Western Ghats have experienced extreme rainfall events that significantly affected agricultural productivity threatening food security (Lakshmi et al., 2024). Events of Mini-cloud bursts (MsCB) have resulted in severe rainfall. The normal monthly rainfall amount was poured in one or two days

or within a few hours. July and August of 2018 and 2019 received the highest rainfall (50 mm in 2 hours on August 8, 2018) leading to flash floods. Also, cyclones are increasing in frequency and intensity in the Arabian Sea. The Northeast Monsoon of 2021 culminated in heavy rainfall and floods (Dhanya and Jayarajan, 2024). In 2019, the state saw the highest departure from normal rainfall which was 217 % for August for Palakkad and 123 % for the state exacerbating the flooding conditions (Mehrishi et al., 2019).

Rainfall variability in Kerala has shown varied trends in different periods, resulting in both droughts and floods. With shifting patterns, water management in these areas poses a challenge and is very important for the agriculture sector.

2.3 Impact of Droughts and Floods on Agriculture in Palakkad

Hydro-meteorological hazards for example flood and drought have negative impacts in short, medium and long term (Onuma et al., 2021). In case of floods there could be consequences on the soil that may result in the loss of beneficial fungi important for nutrient mobilization due

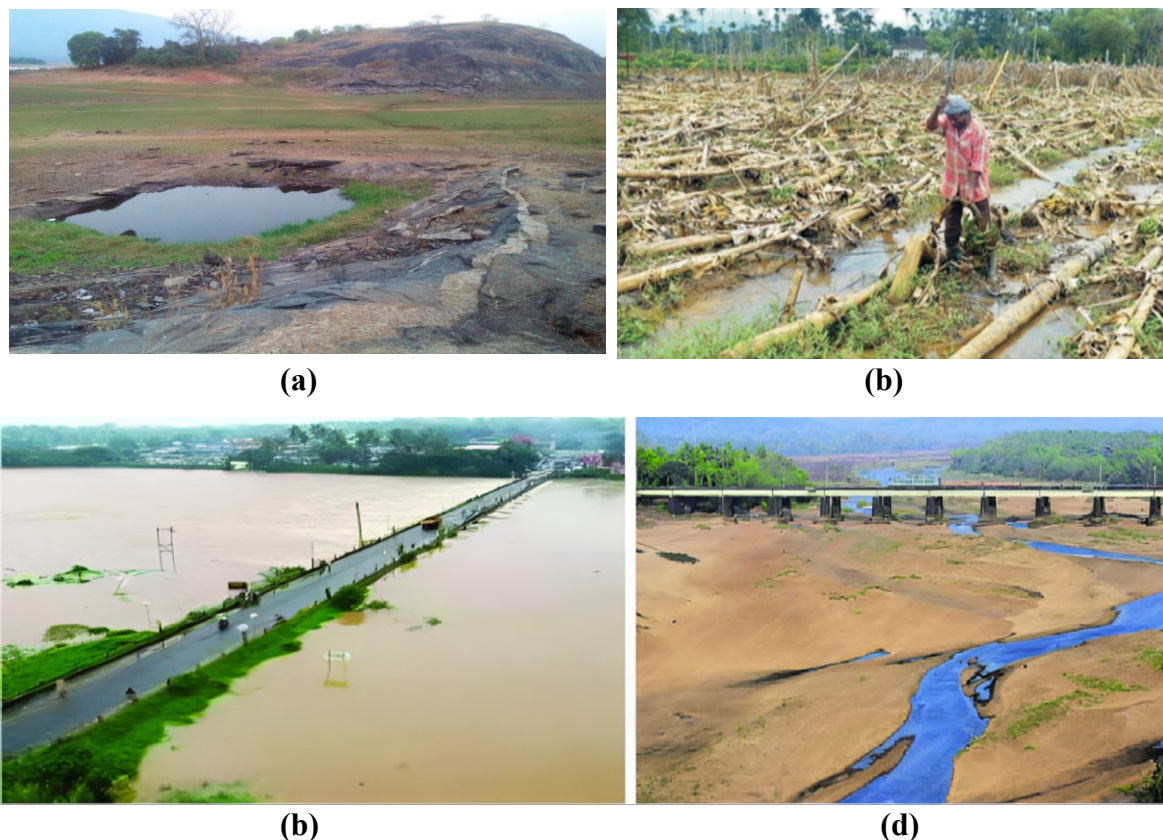
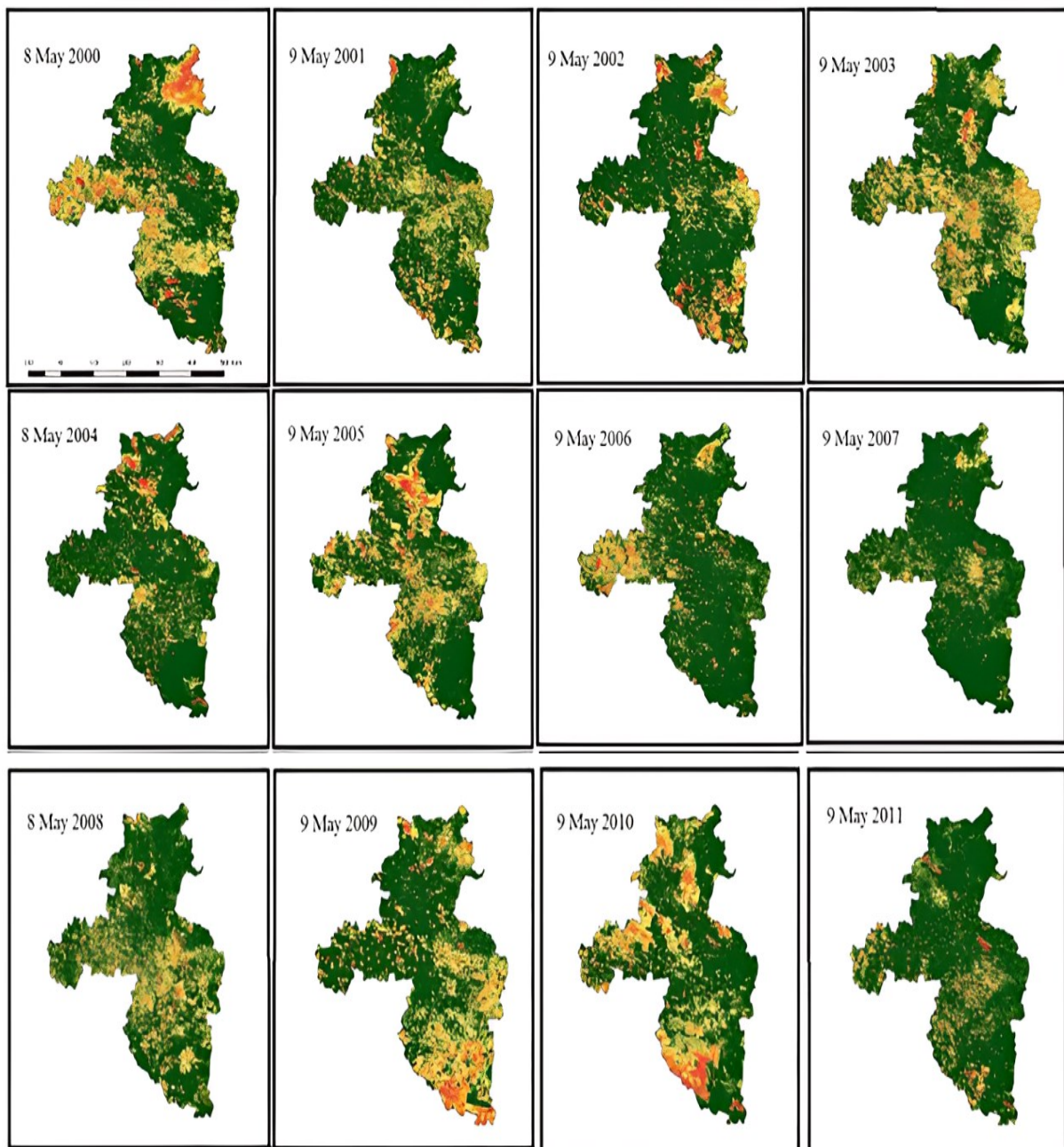


Figure 2. (a) Malampuzha Reservoir in Palakkad experiencing drought situation (Source: Kerala State Disaster Management Authority, 2017), (b) Destroyed Plantain field (Source: N (Source: National Institute of Disaster Management, 2018), (c) Bharathapuzha River during Monsoon and Summer season (Source: Amala and Kolathayar, 2021)

to erosion of agricultural soil and deposition of sand and debris. A similar effect was evident At the economic level, the flood loss reported was INR 41.80 Billion and damage was INR 29.75 Billion after the 2018 flood. Palakkad district especially the crop sector damage estimated was INR 1.086 Billion. The loss of livestock in the area was also substantial. The



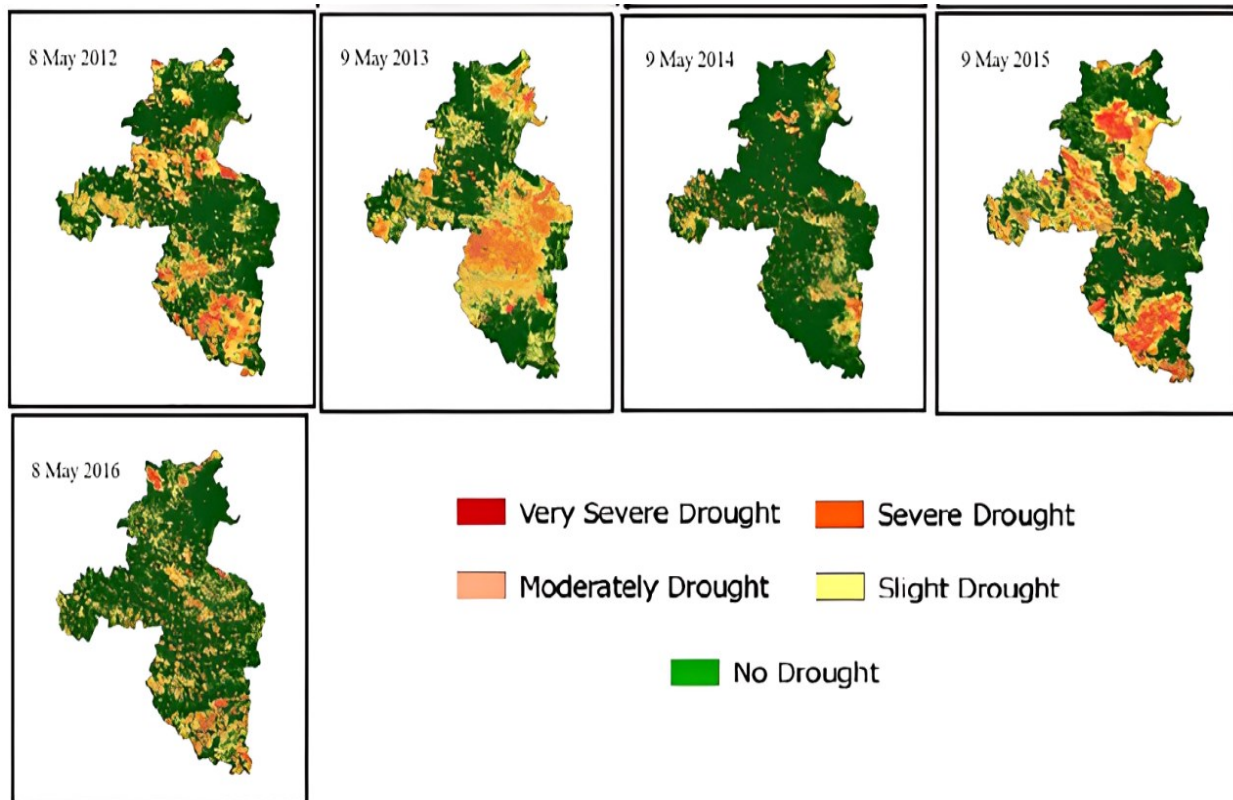


Figure 3. Drought map of Palakkad over a period of 2000-2016 for the 1st bi-week of May (Gopinath et al., 2020)

value of total crop production lost for Palakkad was INR 1.199 Billion (UNDP). Considering the extensive paddy fields in Palakkad, agriculture was adversely affected due to water logging. The harvest-ready rice-standing crops were the worst hit. Before 2018, the state witnessed floods in 1961 and 1924 causing life and properties. Though the state has humid tropical climate it has always experienced drought that have left adverse effects on agriculture sector. Figure 3 illustrates drought maps of Palakkad for years. Overall, drought area percentage of Palakkad is 47.22 % and the drought years were 2000, 2009, 2013, and 2015 (Gopinath et al., 2020). These can have negative impact on the surface water sufficiency impacting irrigation in dry years and drought periods. The decrease in surface water availability inevitably leads to a rise in groundwater exploitation which has resulted in a range of ecological issues, including continuous decline of groundwater table and decreasing streamflow, reduced well yield and increased irrigation energy consumption as well as cost (Zhang et al., 2024).

In Palakkad according to Kerala State Resource Board, the annual extractable ground water recharge is 584.10 MCM and existing gross ground water extraction is of the order of 331.37 MCM. The stage of ground water extraction is 56.73%. Two blocks in the district, are ‘Critical’ (Chittur & Malampuzha), 2 blocks are ‘Semicritical’ (Pattambi and Thrithala) and 9 blocks are ‘Safe’.

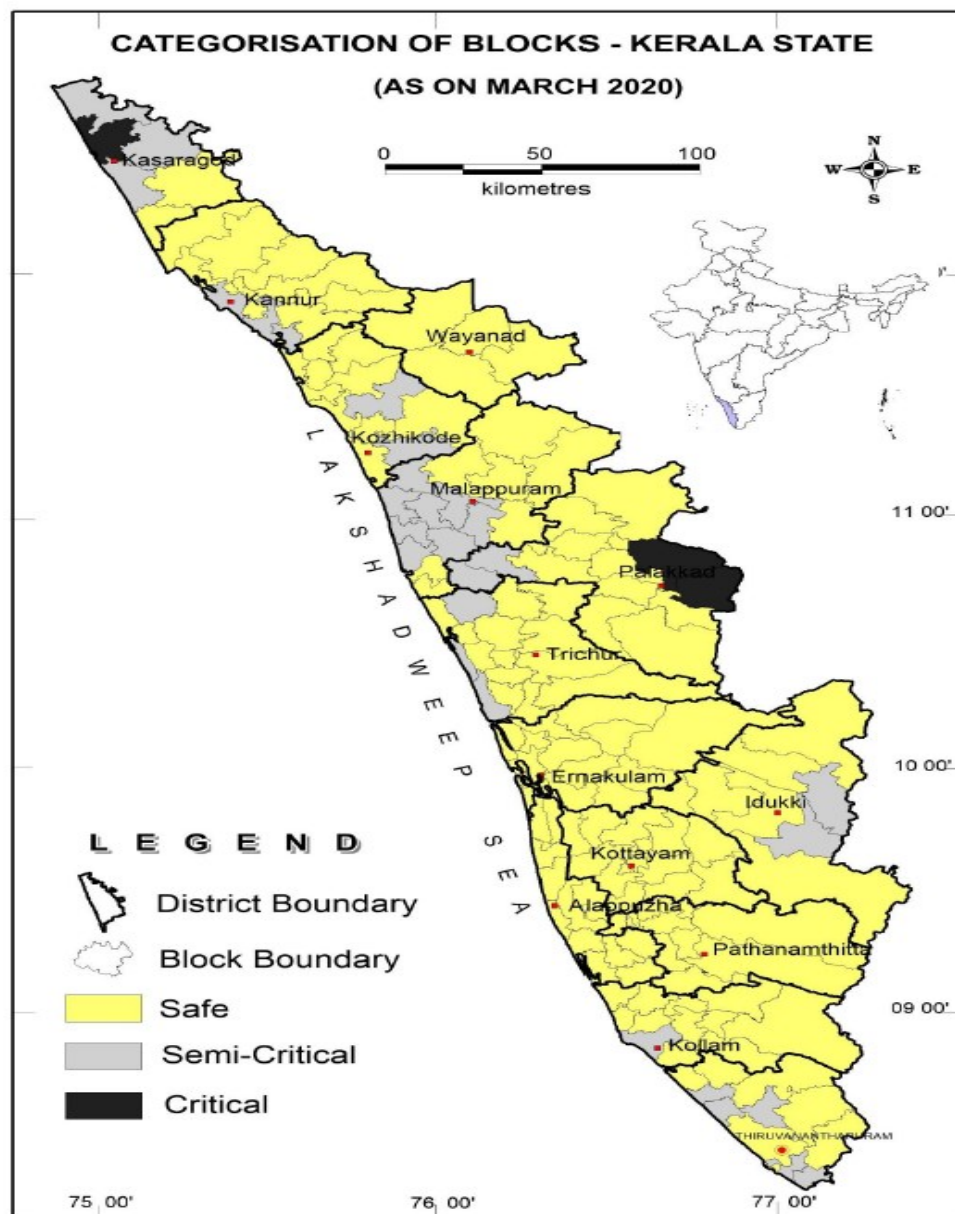


Figure 4. Categorization of Blocks in Kerala based on stage of ground water extraction as per March 2020 (Source: Ground Water Resource Board, 2020)

The in-storage groundwater resources of the phreatic zone (unconfined aquifer) is 547.50 MCM, and the semi-confined zone is 475.02 MCM. The total groundwater resources of the

district is 1606.62 MCM. Groundwater extraction in Palakkad is predominantly for irrigation, utilizing a variety of well types, including dug wells, bore wells, and shallow tube wells (Central Ground Water Board, 2020). On the other, hand there has been a shift in paddy cultivation to other commercial crops. Demand- supply gap of rice is widening faster in Kerala making it a food deficit state with an increasing dependence on neighbouring states for food grains. These states are already water-scarce than Kerala. Hence, dependence on these states will increase the pressure on natural resources especially groundwater (Mehrishi et al., 2019), demanding sustainable rice cultivation in the state.

2.4 Pond-Based Water Resource Management: Natural-based Solution

The concept of Natural-based solutions is defined by the International Union for the Conservation of Nature as the “Actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges such as climate change effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” (IUCN). Due to its multifunctional characteristics, the concept has been much promoted internationally, especially in the European Union, Latin America and the Caribbean, China and the United States of America (Bartrons et al., 2024).

Small water bodies like ponds and pondsapes are Natural-based Solutions whose potential is underutilized. Because they can play a significant role in strengthening ecosystems and build resilience to climate change. According to Williams et al., 2010, ponds can be defined as lentic water bodies between 1 m² and <2 ha in area, and pondsapes (a network of ponds and their surrounding terrestrial matrix) are a significant freshwater resource in the landscape. In the world, there are an estimated 547 million–3.19 billion ponds, although there is significant uncertainty surrounding pond numbers at national and international scales in many regions.

However, ponds can offer considerable opportunities to mitigate threats freshwater habitats face and reverse the decline of freshwater biodiversity globally through management and conservation (Hill et al., 2021). They can act as a multifunctional Natural-based Solution, delivering multiple Nature Contributions to People (NCPs) to address climate-related challenges and Sustainable Development Goals. A previous study analysed natural-based solutions actions in 93 ponds of 24 countries. The results revealed that most ponds/ pondsapes were at the place where there was no water body before followed by actions like restoration

and management. The actions happened mainly in rural areas as they face unique challenges concerning land use and climate change especially in the agricultural sector and with water management. In agricultural landscapes, these creations can act as natural retention basins, buffering water flow and preventing its rapid discharge into rivers or water bodies thereby reducing flood risk. They can also regulate the water quantity, mitigating flood risks, and

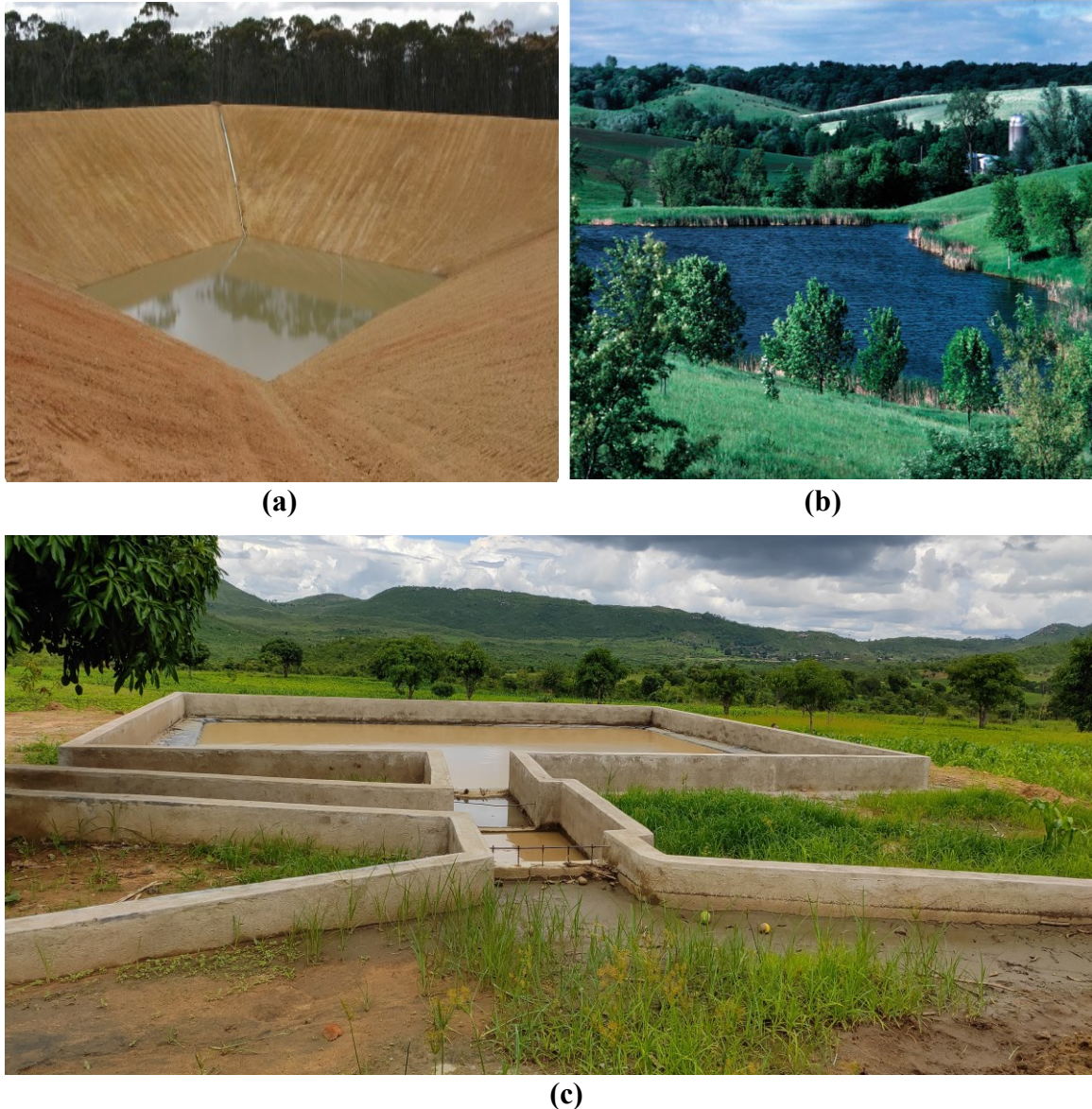


Figure 5. (a) Farm dams in Australia (Source: Department of Primary Industries and Regional Development Website) (b) Farm pond in America (Source: U.S. Department of Agriculture Natural Resources Conservation Service (n.d.)) (c) Farm pond for rainwater harvesting in Malawi (Source: FAO, 2022)

ensuring water availability during droughts. Furthermore, the NbS indirectly support climate change adaptation by preserving microclimates, buffering temperature fluctuations, and providing vital habitats for diverse species, enhancing ecosystem resilience. Simultaneously, these actions offer recreational, cultural, educational, and well-being benefits to local communities impacted by climate change. Despite their potential, the capacity of ponds and pondscapes for climate change mitigation through carbon sequestration and storage remains unknown, requiring further exploration. At the same time, the other positive aspects of Natural-based solutions are that they are more cost-effective and provide additional benefits such as food and water provision, clean air, water and soil, and recreational and aesthetic functions.

Also, such natural water retention ponds organized into networks can improve connectivity and enhance their benefits by addressing water issues due to climate change while preserving environmental quality and agricultural productivity. However, certain challenges have to be addressed such as land use conflicts and maintenance needs, and secondly, the carbon sequestration potential needs to be explored in this scenario (Bartrons et al., 2024).

Recently, the world has come across many water supply-related problems limiting economic activities. The expansion of agricultural areas due to constant population growth increases water demand. Alternate water supply sources that can be used for agriculture and human consumption are a growing need. The studies have estimated increased intensity and frequency of droughts and reduced water availability in developing countries. Water collection and storage in rainwater harvesting (RWH) systems is becoming a successful strategy to mitigate the effects of climate change (Márquez et al., 2021).

2.5 Precipitation Concentration Index and Standardized Precipitation Index for Rainfall and Drought Analysis

In recent years, on a global scale, there have been marked climatic variations that have influenced the spatio-temporal behavior of meteorological variables such as precipitation. The frequency, intensity, and duration of extreme events are important to understand when formulating adaptation and mitigation strategies in the future. Considering the case of rainfall its intensity and distribution along with geomorphology are among the other aspects that determine the sensitivity of the territory to meteorological hazards triggered by excessive levels of rainfall.

In the case of rainfall, precipitation concentration is considered to better understand the pattern. Precipitation Concentration is a measure of the temporal distribution of precipitation in a location. This can be characterized using models like the Gini Index (GI), the concentration index (CI) and the Precipitation Concentration Index (PCI) that assess the unequal distribution of precipitation (Morbidegli et al., 2021). The concept was introduced by Oliver (1980) and developed by De Luis et al (1997) to understand the homogeneity of total precipitation among months of different scale. This can be studied on an annual and seasonal scale (Salameh, A.A., 2024).

Drought has been a major natural hazard in the world with significant cost to the ecosystem, agriculture and human societies (Cook et al., 2018). Wilhite and Glantz (1985) stated that drought generally forms when a region lacks enough rainfall for an extended period, leading to water scarcity. In zones experiencing persistent severe drought, the factors and physical mechanisms affecting drought are highly complex. This can be under developed water conservation projects and inadequate disaster resilience, excessive cutting of forest resources resulting in severe soil erosion and destruction of vegetation, altering water cycle system, and also abnormal atmospheric circulation leading to irregular precipitation. Other reasons for drought are water scarcity, high water use, and unplanned use of water resources. Previous studies have demonstrated that drought is primarily the result of insufficient rainfall and increase in temperature. Thus, for a specific region and timescale drought characteristics can be assessed based on precipitation and temperature (Kartal, 2023).

The Standardized Precipitation Index (SPI) is a widely used index to characterize meteorological drought. SPI is closely related to soil moisture on short timescales, while at longer timescales, the SPI can be related to groundwater and reservoir storage. They can be compared across regions with markedly different climates. SPI quantifies observed precipitation as a standardized departure from a selected probability distribution function that models the raw precipitation data. These data are typically fitted to a gamma or a Pearson Type III distribution, and then transformed to a normal distribution. The SPI values can be interpreted as the number of standard deviations by which the observed anomaly deviates from the long-term mean. The SPI can be calculated for differing periods of 1 to 36 months, using monthly input data. For the operational community, the SPI has been recognized as the standard index that should be available worldwide for quantifying and reporting meteorological drought. Concerns have been raised about the utility of the SPI as a measure of changes in drought associated with climate change, as it does not deal with changes in evapotranspiration, and this

limits its ability to capture the effect of increased temperatures (associated with climate change) on moisture demand and availability (National Center of Atmospheric Research (NCAR, n.d).

2.6 Role of GIS and Remote Sensing in Water Resource Management

Geographical Information System is described as a digital dataset management system used to gather and process spatial data collected from different sources (Pradhan et al., 2024). On a broader scale, the idea of GIS is to manage the built and natural environments and to provide a framework to enable decisions for the better use of Earth's resources.

In the water field, the GIS links geographical information like water basins with graphical information such as rainfall, and water level height to conduct analysis benefiting reservoirs and also study groundwater, seawater intrusion, and drought monitoring large watershed characteristics and parameters linked to watershed can be effectively managed with the capabilities of GIS in data processing and manipulation thereby giving a visual representation. This is discussed as hydrologic and hydraulic models in different papers that help in forecasting drought, flooding, irrigation management and water quality (Bashar et al., 2023).

One of the applications of GIS is Surface Water Hydrologic Modelling for representing the effects of rainfall-runoff on surface water resources. Water supply and sewer systems modelling for generating an economical and efficient operating network is another application of GIS. Further, erosion investigation, identification and prioritization of polluted regions are possible through water quality and watershed protection modelling. Groundwater modelling uses the technology for protection, resource investigation and engineering design is also an important application of GIS in water field (Arezoo et al., 2021).

Considering irrigated agriculture, efficient management of land and water resources necessitates a deep understanding of climate, soil, land use, crops, water availability, water distribution network, and management practices. GIS has been used for integrating this spatially distributed data. The use of geo-referenced databases enables efficient data exchange, integration from multiple sources, and seamless interaction with models and decision-support tools. A study was conducted in Apulia region in Italy, where GIS-based irrigation management was developed to customize GIS applications to model irrigation scenarios, thereby helping to determine optimal cropping patterns, estimate water needs, and identify potential water deficits or surpluses, facilitating comprehensive analysis and decision-making (Todorovic and Steduto,

2003). GIS technology is invaluable in the context of increasing water needs, climate change and agricultural irrigation, providing necessary tools to analyse and predict patterns for effective management and planning.

2.7 Traditional Water Resource Management Techniques

Conventional water resource planning in developed countries followed the top-to-bottom approach. In developing countries, the experts and decision-makers plan without public participation. Earlier water resource project plans did not consider the environment. However, in recent times, integrated resource planning and management has become participatory, technically and scientifically informed, and is being implemented at the lower level. The framework for this action is catchment, basin, or aquifer level, natural units by which nature



Figure 6. (a) Traditional Water Harvesting system Surangams (Source: Yesubabu et al., 2024) (b) Traditional pond in Kerala (Source: FAO website)

manages water. Stakeholder engagement is a key point in this approach where the community addresses local issues in a coordinated and integrated way. Environmental impact assessment is an important part of the water resource plan with an emphasis of society on the quality and aesthetic integrity of the environment for planning (Matondo, 2002). Kerala receives an appreciable amount of rainfall. However the groundwater potential is limited. The dug wells function as the common extraction structures and they are in large numbers. Drying up of dug wells and salinity in coastal areas are the major concerns these days. The state has a lot of traditional water harvesting techniques and ponds are one among that. Before the onset of monsoon, the rainwater is channelled to these structures where they serve function as a storage structures (water harvesting) and source of water for agriculture practices, especially paddy

cultivation. Over time these traditional water harvesting structures in Palakkad and other districts of Kerala State were reclaimed or converted for buildup purposes. Many of these structures are silted up and water storage capacity has been drastically reduced. They are also part of the tradition linked to the religious customs in the state. Similarly, in Kasaragod (northernmost district of Kerala) surangams (tunnel wells) are the traditional water harvesting structure (Balooni et al., 2010).

Several scientific studies have been done to assess the effectiveness of regional and local water harvesting techniques in Kerala. A previous study, conducted by the Indian Institute of Technology (IIT) in Delhi, analysed the groundwater recharge under the influence of water harvesting systems in a small village in Kerala (Liji 2020).

2.8 Socioeconomic Impact of Climate Change-Induced Water Scarcity and Extreme Rainfall on Farming Communities

Freshwater is essential to life, agriculture, and industry (Ingrao et al., 2023). Climate change and natural hazards are now major global concerns, affect the quality of life and well-being, with rural populations particularly vulnerable to mental health impacts from climate variability (Berry et al., 2010; Qi et al., 2015). Developing economies, with a heavy dependence on temperature and precipitation, are highly susceptible to these changes (Schmidhuber and Tubiello, 2007).

Key livelihood assets such as financial and social capital, natural resources, and education are compromised by recurrent climate-induced droughts. These assets' vulnerability to factors like low income, small landholdings, soil infertility, and reliance on weather-dependent livelihoods calls for integrated intervention strategies by government and NGOs (Tofu et al., 2023). In India, where most farming relies on rainfed systems, climate change is accelerating an agrarian transition that pushes many to leave agriculture altogether (Matthan, 2023).

India's 2017-18 Economic Review highlights the financial toll of extreme weather on agriculture, with weather shocks reducing farm income by 4% to 13.7% across seasons. Despite advancements in agricultural practices, 52% of Indian farms remain rainfed, leaving them vulnerable to the unpredictability of weather (Economic Survey India, 2017-18). As the agriculture sector supports 42.3% of the population and contributes 18.2% to GDP, the repercussions of these vulnerabilities are widespread.

Agricultural instability further strains rural livelihoods, with unskilled laborers losing employment opportunities and farmers facing financial hardships that lead to postponement of major life events, like weddings, due to economic strain. Drought-stricken regions report increased social conflict and even suicide due to high indebtedness and financial pressure. Erratic rainfall exacerbates these issues, causing crop losses that fuel food insecurity and rural indebtedness as farmers rely on loans to recover from successive failed harvests (Sahoo and Bhattacharya, 2022).

In Kerala's Palakkad district, the Crop Production Loss Index is the highest in the state, with water-intensive crops like paddy, arecanut, and mango suffering from fluctuating cultivation areas and annual natural calamities (Giridhar et al., 2022). Limited water resources and disrupted traditional land management due to land reforms have further hindered agricultural productivity (Krishnan and George, 2009). Nationwide, rainfall variability from excessive rains causing floods to extended droughts continues to destabilize agricultural productivity, community well-being, and socio-economic stability (Gupta et al., 2020).

2.9 Water Governance and Policy in Kerala

Kerala receives abundant water through rainfall every year. The average rainfall is reported as 3000 mm. 69 % of the annual rainfall is received during the Southwest Monsoon and 16 % during the Northeast Monsoon. The water after rain gets drained quickly due to the physiographical pattern and topography into the sea and the total runoff of all rivers adds to around 70,300 million cubic meters. The region has 44 rivers.

The large water storage structures called dams serve the purposes of irrigation, and drinking water supply and are also used for hydroelectric projects. Though, they have caused disturbance to the flow of river by converting it into a series of pools divided by dry stretches, the dependence on them remains substantial. Groundwater is also a major water source in the state where the 80 % water usage is in rural area for domestic and 50 % for irrigation activities. Kerala Water Authority (KWA) covers 52.30% of the population through their water supply schemes. KWA and KRWS (Kerala Rural Water Supply and Sanitation Agency- Jalanidhi) are the two main agencies distributing drinking water in Kerala in urban and rural areas respectively. The local self-government is vested with considerable powers concerning the

governance of water resources in Kerala according to Kerala Panchayat Raj Act 1994 (FAO, n.d.).

Furthermore, water policies are also an important factor in determining water use. The National Water Policy, of 2002 emphasizes on integrated water resources management, prioritizing most importantly environmental needs while advocating for conservation, pollution prevention, and stakeholder involvement. However, Kerala has been trying to bring out a change with decommodification idea through its policies. The 2008 State Water Policy (hereafter SWP) of Kerala stated water as a vital component for the survival of life. Furthermore, the SWP explicitly considered “water as part of the ecosystem for the benefit of all and not as a commodity for the profit of a few” (Kerala State Water Policy, 2008). The policy kept equity and sustainability over and above “productive management” and emphasized public health over growth requirements as water use priorities. The policy identified that local self-governments important role in perspective planning and sustainable water resource management.

Furthermore, it suggests that fully replacing traditional systems with piped water supply may not be necessary, as long as the safety of those water sources can be assured (Kerala State Water Policy, 2008).

3. Material and Methods

3.1 Study Area

The study area is Palakkad district, one of 14 districts in the Indian state of Kerala. The region is known as the ‘Rice bowl of Kerala’ since rice is the majorly grown crop. The district lies between 10° 21’ and 11°14’ North latitude and 76° 02’ and 76° 54’ East longitude (Aparna and Basil, 2013). The extent of the region is 4480 sq. km. Administratively the district is divided



Figure 7. *Rice field in Palakkad during Winter Season*

into 13 Blocks and 88 Panchayaths. Rice being an important crop, the area of cultivation goes to an average of 10,000 hectares of paddy cultivation, especially in Alathur, Nenmara, Kollengode, Chittur, and Kuzhalmannam (Chinnu et al, 2023). Geographically the district is bordered by the Western Ghats that goes along the eastern side of the district and it has a 30 km discontinuity called the Palakkad Gap. The maximum temperature of the study area varies from 32.3°C to 41°C and the minimum is 22.2° C to 25.3° C (Joji et al., 2022). State receives around 3000 mm of rainfall annually (Harithalekshmi and Ajithkumar, 2023). The Bharathapuzha River is the major source of water on which the farmers of the region depend.

The basin has many dams built, the biggest one is the Malampuzha. The monsoon rainfall affects the inflow and outflow of the irrigation water thus affecting the rice productivity.

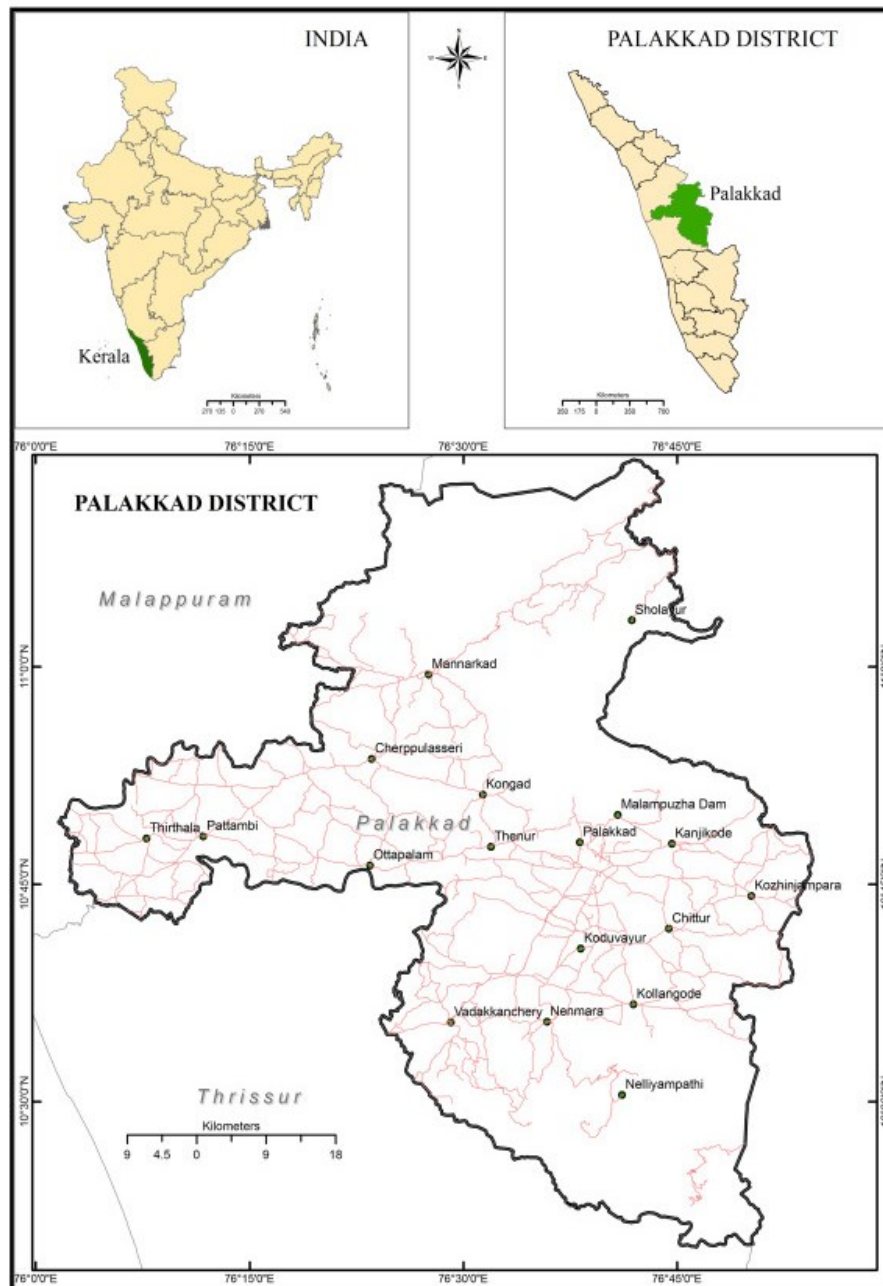


Figure 8. Study Area Palakkad (Kerala State, India) (Source: Dhanya and Jayarajan, 2023)

This study area in India has both natural and artificial ponds that serve different purposes. The local government body-owned ponds are called public ponds and are mainly used for agriculture, drinking, and other domestic purposes. The private ponds are owned by individuals or private owners and are used for agricultural activities and domestic uses. Temple ponds are

located within the premises of temples and are used for rituals. Farm ponds called Kokkarnis are common in Southern parts of Palakkad and are used mainly for farming and water percolation. Quarry ponds near quarry sites are used for fishing, farming, recreational purposes etc. Community ponds owned by different communities in the society and used also for agriculture purposes. Flower ponds are used for the cultivation of lotus and lilies. Colony ponds are found in residential areas mainly for drinking purposes. Though ponds are of different types in Palakkad, India the important use of these structures is agriculture irrigation. Before the construction of reservoir, ponds were the major source for irrigating fields. The ponds/tanks of Palakkad spread area of 1-2 acres and very large ones with a spread area of 3-4 acres. The ponds in Palakkad district are mainly used for agricultural purposes. In Palakkad and other districts of Kerala State the most common traditional harvesting structures such as ponds were totally reclaimed or converted for buildup purposes. Currently many of these structures are silted up and water storage capacity drastically reduced (Lekshmi, 2019).

Generally people of the area divert the rainwater to the tanks / ponds before the sowing season and they clean the channel before the onset of monsoon. The tanks/ponds function as storage structures (water harvesting) and sources of water for agriculture practices especially paddy cultivation (Joji, 2018).



Figure 9. Farm pond (Source: Kerala Soil Survey and Soil Conservation Department)



(a)



(b)



(c)



(d)

Figure 10. (a) Kokkarnis, (b) flower pond, (c) quarry pond and (d) public pond in Palakkad
(Source: Lekshmi, 2019)

3.2 Data Used

The Daily Rainfall data in mm of 11 stations was collected from the Irrigation Design and Research Department (IDRB), Trivandrum, Kerala for the analysis. Panchayath-wise consolidated pond Excel dataset was collected from Minor Irrigation Department, Palakkad. Waterbodies data accessed from Water Bodies Census Report 2023, Kerala State.

Place	X	Y
Chittady	76.52	10.582
Chulliyar	76.765	10.593
Eramayur	76.569	10.655
Kanjirapuzha	76.538	10.993
Koduvayoor	76.65	10.691
Malampuzha	76.683	10.834
Mangalam	76.536	10.517
Pokkunni	76.798	10.618
Pothundy	76.625	10.545
Thrithala	76.128	10.804
Walayar	76.849	10.839

Table 1. Rain gauge stations of the study area and their coordinates.

3.3 Software and models used in the study

Software/Model	Source	Use
Precintcon Package	R Studio	Precipitation Concentration Index calculation
Macro	Excel	Standardized Precipitation Index, Seasonal PCI
ArcGIS 10.3.1	ESRI	Interpolation, analysis and creating maps
QGIS		Creating Shapefiles

Table 2. Software / Models used for the study and their functions

3.4 Precipitation Concentration Index

Precipitation Concentration Index is an effective measure of temporal inhomogeneity of annual precipitation.

$$PCI_{annual} = \frac{\sum_{i=1}^{12} P_i^2}{(\sum_{i=1}^{12} P_i)^2} \times 100 \quad (1)$$

In the present study the PCI proposed by Oliver (1980) and developed by De Luis *et al* (1997) was used for the calculation of the annual PCI as indicated by the equation. Here, p_i is the monthly precipitation in month i and is calculated for each studied station and each year throughout the observation period. According to Oliver's study if the value is <10 the monthly precipitation distribution of the year is relatively uniform, between 11 and 20 the precipitation of the year is seasonal and greater than 20 indicates a precipitation distribution in the year to be abnormally concentrated and monthly variation of precipitation having significant differences (Meng et al., 2023). Precipitation Concentration Index (PCI) is a remote-sensing-based drought-monitoring technique that represents abnormalities in climatic signs and spatiotemporal deficits in precipitation (Ravichandran et al., 2022).

$PCI \leq 10$	Uniform monthly precipitation distribution (low precipitation concentration)
$10 < PCI \leq 15$	Moderate precipitation distribution
$16 < PCI \leq 20$	Irregular precipitation distribution
$PCI > 20$	Strongly irregular precipitation distribution (high precipitation concentration)

Table 3. *Precipitation Concentration Index values and their implications on rainfall concentration (Oliver, 1980).*

3.4.1 Seasonal Precipitation Concentration Index

The seasonal precipitation for the monsoon months is calculated following the India Meteorological Department Scheme of Classification. According to this scheme the seasons are winter (January-February), summer (March-May), Indian summer monsoon (June-September), and post-monsoon (October- December) (IMD Glossary). The PCI calculated at the seasonal scales are in winter (PCI_{WIN}), pre-monsoon (PCI_{PRM}), monsoon (PCI_{ISM}) and post-monsoon (PCI_{POM}) according to the equation 2, 3, 4, and 5. The equations are

$$PCI_{WIN} = \frac{\sum_{i=1}^2 p_i^2}{(\sum_{i=1}^2 p_i)^2} \times 17 \quad (2)$$

$$PCI_{PRM} = \frac{\sum_{i=3}^5 P_i^2}{(\sum_{i=3}^5 P_i)^2} \times 25 \quad (3)$$

$$PCI_{ISM} = \frac{\sum_{i=6}^9 P_i^2}{(\sum_{i=6}^9 P_i)^2} \times 33 \quad (4)$$

$$PCI_{POM} = \frac{\sum_{i=10}^{12} P_i^2}{(\sum_{i=10}^{12} P_i)^2} \times 25 \quad (5)$$

3.4.2 Estimation of the Precipitation Concentration Index (PCI)

Precipitation Concentration Index (Annual) was calculated from the rainfall data from eleven stations. For this, the daily data was converted to monthly data through a pivot table. Then these data were rearranged so that they could be used for easy calculation in the R programme. Using the Precintcon package following Oliver's (1980) equation the PCI values were generated. Afterward, the average PCI for the 6 years was calculated. The PCI values generated were further organized into an Excel spreadsheet in Comma-separated values (.csv) format. XY to Points tool was used to incorporate the values into the study area map in ArcGIS. The inverted Distance Weighted Interpolation method was used to get the pattern of rainfall for these years from the points. Similarly, the Seasonal Precipitation Concentration Index was also calculated following the equation.

3.5 Standardized Precipitation Index

Standardized Precipitation Index is the indicator used worldwide for detecting and characterizing meteorological droughts and their severity using drought classes.

Sl.no	Drought Class	SPI values
1	Extremely wet	> Or = 2.00
2	Severely wet	1.50 – 1.99
3	Moderately wet	1.00 – 1.49
4	Mildly wet	0 – 0.99
5	Mild drought	-0.99 - 0
6	Moderate drought	-1.49 - -1.00
7	Severe drought	-1.99 - - 1.50
8	Extreme drought	< Or = 2.00

Table 4. Standardized Precipitation Index values and drought class (McKee & other, 1993)

It was devised by McKee and others (1993). The SPI is used because it is standardized and allows a reliable comparison between different locations and climates. It can be used for shorter or longer timescales that can reflect lags in the water cycle response to precipitation anomalies (Moreira et al., 2015). The negative values indicate drier regions and positive values indicate wet areas.

The normal probability distribution is considered here as it is computationally easier to calculate and maybe more accurate. The equation for the SPI Index is:

$$SPI = \frac{P - \bar{P}}{\sigma} \quad (1)$$

SPI, is the standardized precipitation index, *P* is the precipitation amount and σ is the standard deviation for the same period.

3.5.1 Estimation of the Standardized Precipitation Index (SPI)

To estimate the Standardized Precipitation Index (SPI), rainfall data was first organized for SPI calculation, and a macro was developed in Excel for streamlined processing. SPI values were then calculated using the specified equation, with results for six years saved as comma-separated values. These data points were mapped in ArcGIS using the XY to Points tool, and Inverse Distance Interpolation was applied to analyse the six-year pattern.

3.6 Ponds Density Analysis

Ponds are small and shallow waterbodies with a maximum surface area of 5 ha, a maximum depth of 5m and < 30 % coverage of emergent vegetation. Ponds will have light penetration to the sediments if water clarity permits and can be permanent or temporary and natural or human-made (Richardson et al., 2022).

Farm ponds is defined as water impoundments used for agricultural or domestic farm uses and enjoyment. According to National Resource Conservation Service- USDA (NRCS) they are water impoundments made by constructing a dam or by excavating a pit or dugout. Therefore, there are two general types of farm ponds, largely determined by topography. One is embankment ponds are formed by impounding water behind a dam built across a watercourse. Secondly, the excavated ponds, as the name implies, are constructed by removing soil to create a pond basin at an elevation below the surrounding ground level. Unlike embankment ponds, they are typically constructed on relatively level areas where a source of water may be more limited (Tuttle, 2003).

Details of ponds in Palakkad, India was collected from the Minor Irrigation Department, Palakkad. This data consisted of details of ponds, coordinates and usage.

3.6.1 Ponds Mapping Process

The collected data was organized in spreadsheets and saved as comma-separated values, then incorporated into ArcGIS. Using the Kernel Density tool, the density of ponds in Palakkad was analysed, and a corresponding map was generated. This pond density map was then compared with SPI and PCI maps to examine correlations.

4. Result and Discussion

4.1 Rainfall in Palakkad and their spatiotemporal variability

The detailed analysis of the rainfall data of the Palakkad district indicates that the average rainfall for the analysis period was 2219.69 mm. During this period (2018-2023) the minimum and maximum rainfall was recorded in 2023 (977.3 mm) in Walayar station and 2018 (3443.2 mm) in Malampuzha respectively. The irregularly high rainfall amount observed in the stations for the year 2018 represents the Mini-cloud burst event happened, resulted in the flood disaster. This year Kerala experienced high rainfall in the second and third week of August, resulting in an unprepared flood disaster that was exacerbated by the opening of 35 hydropower dams (Suresh et al., 2024). Rainfall analysis on a seasonal scale gave further insights into the winter rainfall in the stations that ranged from 1.8 mm in 2021 (Chittady) to 65 mm in 2021 (Walayar). The pre-monsoon showers range from 41.6 in 2019 (Walayar) to 687.8 mm in 2021 (Malampuzha). The Indian monsoon summer rainfall of the stations varied from 524 mm in 2023 (Walayar) to 2759.9 in 2018 (Malampuzha). And the post-monsoon rainfall was 78.8 mm in 2020 (Chittady) and 1252.42 mm in 2021 (Kanjirapuzha). The seasonality of rainfall in Palakkad was visible from the rainfall analysis.

Figure 11 shows the sum of rainfall for each month for 6 years. From the graph it is evident that July, August and September experience the highest rainfall, emphasizing the monsoon's intensity during the period.

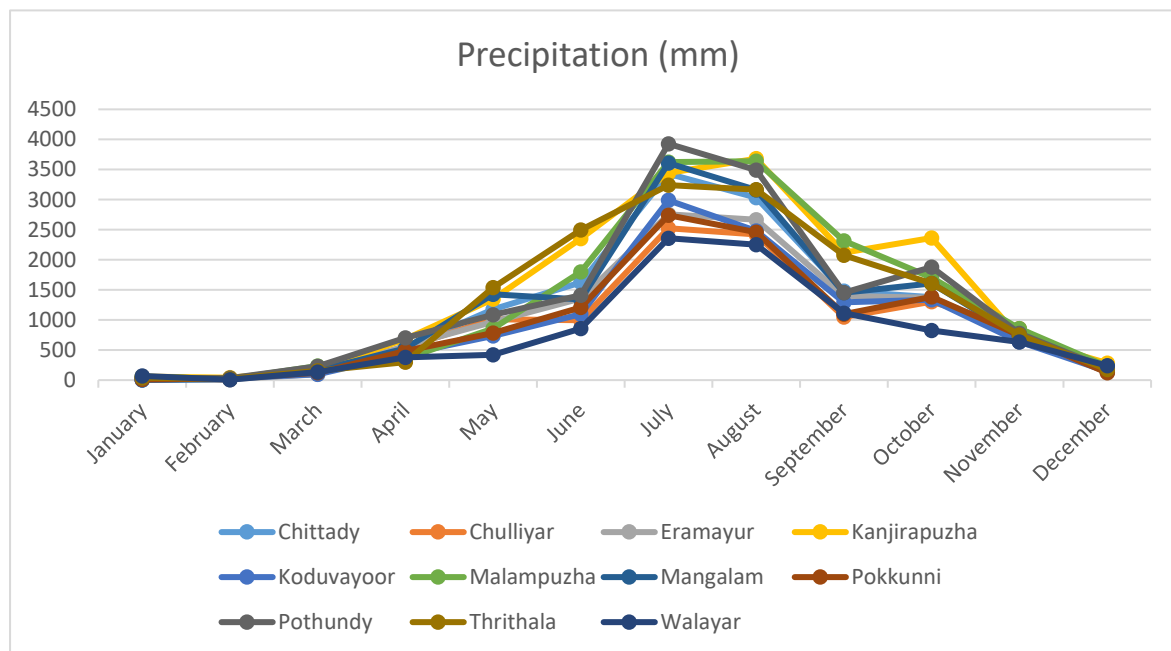


Figure 11. The sum of each month's rainfall of 6 years for all the stations in the study area

Walayar recorded the lowest cumulative rainfall, whereas Eramayur reported the highest total rainfall. Figure 12 shows the average rainfall for 6 years calculated station-wise. From the analysis, it is evident that Kanjirapuzha station received the highest average rainfall, indicating station recorded the lowest average rainfall, making it the driest location when compared to other stations its importance as significant rainfall zone in the study area. In contrast, the Walayar is a dry area with less rainfall.

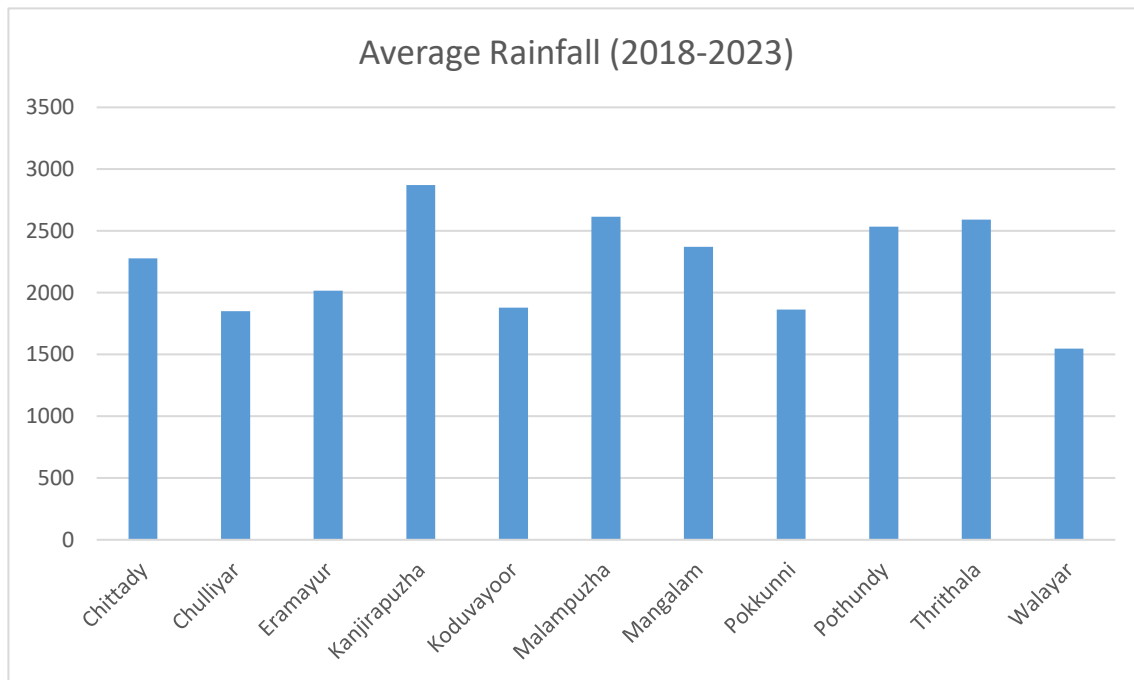


Figure 12. Average rainfall for 6 years in 11 stations within the study area

4.2 Rainfall concentration patterns derived from Precipitation Concentration Index

4.2.1 Precipitation Concentration Index (Annual)

The temporal rainfall distribution expressed in terms of PCI represents a considerable variation across the district at annual and seasonal scales. The station data shows that the average Precipitation Concentration Index of 11 Stations falls between 17 and 20. PCI value of less than 10 indicates more or less uniform and greater than 20 suggests substantial variability in rainfall patterns (Dhanya and Jayarajan, 2024). According to the PCI classification, the Walayar region shows PCI that means high irregularities and other regions do show irregular precipitation from their concentration index values. This could be correlated to the seasonality of rainfall in Kerala. However, values beyond 20 represent a high concentration or irregularity of rainfall, for example in Walayar. Considering average values at the annual level, 2019 shows

maximum rainfall concentration followed by 2018 and 2023. 2018 and 2019 were the years when Kerala experienced flood situations (Dhanya and Jayarajan, 2024) and deficient rainfall in 2023 (IMD, 2023). Table 5 shows the PCI values for 11 stations over a six-year period.

Place/ Year	2018	2019	2020	2021	2022	2023
Chittady	21.2	20.9	18.9	15.5	20.6	19.0
Chulliyar	19.3	20.3	15.5	14.4	17.5	19.0
Eramayur	19.5	25.4	18.4	14.2	18.3	19.0
Kanjirapuzha	19.9	20.9	18.8	12.8	15.3	23.6
Koduvayoor	19.0	23.3	18.4	15.8	19.7	22.2
Malampuzha	22.3	21.2	20.7	14.1	16.7	16.1
Mangalam	20.2	21.5	19.6	16.8	17.9	20.2
Pokkunni	20.8	22.3	16.3	16.0	19.2	20.4
Pothundy	21.9	20.4	17.2	15.3	18.3	21.1
Thrithala	20.6	21.9	19.5	13.4	15.7	19.0
Walayar	20.5	22.1	21.1	14.9	21.8	23.6

Table5. Precipitation Concentration Index values for 6 years in 11 stations in the study area.

4.2.2. Seasonal Precipitation Concentration Index

Considering the seasonal values it can be interpreted that all stations are nearly uniformly to highly irregular from PCI values.

The pre-monsoon values are more than 10 and around 15 with slight exceptions indicating uniform to slight concentration (Table 6). The post-monsoon values in general range from 11 to 20 in the stations indicating uniform to considerable variation of rainfall over the years. 2018 exhibited more rainfall concentration on a temporal scale, with high values ranging from 15 to 24 which can be correlated to the Mini-cloudburst event happened (Table 8). While the winter rainfall is very scarce and mostly absent in all stations (Table 9). But monsoon rainfall is uniform, with values below 10 (Table 7). However, in 2023 all stations recorded PCI ranging from 14 to 22, indicating rainfall concentration, which can again display the rainfall departure in the State (IMD, 2023).

Place/ Year	2018	2019	2020	2021	2022	2023	PCI Pre-monsoon
Chittady	12.7	13.2	9.5	17.3	13.6	12.7	13.2
Chulliyar	13.7	12.8	10.5	10.8	14.3	12.7	12.5
Eramayur	14.2	15.5	19.8	12.6	12.2	15.4	14.9
Kanjirapuzha	14.2	12.9	14.9	12.0	13.2	11.2	13.1
Koduvayoor	12.3	13.8	17.4	14.4	16.6	9.4	14.0
Malampuzha	18.2	13.4	8.4	9.4	10.3	10.8	11.8
Mangalam	14.1	11.2	11.1	16.2	16.7	15.0	14.1
Pokkunni	11.6	25.0	18.0	9.6	15.7	11.8	15.3
Pothundy	9.5	13.0	12.6	14.8	16.7	9.4	12.6
Thrithala	21.1	12.5	10.1	15.8	14.7	18.0	15.4
Walayar	13.1	23.7	14.2	12.2	8.5	11.2	13.8

Table 6. Precipitation Concentration Index values for Pre-monsoon season in the study area regions

Place/ Year	2018	2019	2020	2021	2022	2023	PCI Monsoon(Average)
Chittady	10.9	10.5	8.9	9.7	12.1	14.6	11.1
Chulliyar	10.8	12.2	9.9	10.1	12.0	14.6	11.6
Eramayur	10.2	12.4	9.3	9.6	11.4	13.3	11.0
Kanjirapuzha	9.9	10.8	8.5	8.3	9.3	22.1	11.5
Koduvayoor	10.5	11.9	9.4	9.0	11.3	14.3	11.1
Malampuzha	10.7	10.6	9.4	8.9	9.7	11.5	10.1
Mangalam	10.6	10.9	10.0	10.9	11.5	14.8	11.5
Pokkunni	10.3	11.6	8.8	10.1	11.5	15.6	11.3
Pothundy	11.5	11.2	9.1	10.3	11.8	15.1	11.5
Thrithala	10.5	10.2	8.4	8.6	9.1	11.1	9.6
Walayar	10.5	10.6	11.7	10.3	10.9	22.1	12.7

Table 7. Precipitation Concentration Index values for Monsoon season in the study area

Place/ Year	2018	2019	2020	2021	2022	2023	PCI Post Monsoon
Chittady	16.0	17.0	10.6	13.5	8.6	11.6	12.9
Chulliyar	19.9	14.5	10.1	12.8	9.5	11.6	13.1
Eramayur	20.9	14.3	13.1	13.1	11.1	11.1	13.9
Kanjirapuzha	24.1	17.0	17.8	12.1	15.4	8.7	15.8
Koduvayoor	18.1	19.5	11.8	14.3	11.4	11.7	14.5
Malampuzha	21.7	13.8	10.5	13.4	14.4	8.9	13.8
Mangalam	20.1	15.3	13.9	15.5	8.5	12.2	14.2
Pokkunni	14.0	14.7	13.0	15.0	10.2	11.2	13.0
Pothundy	20.3	17.0	12.6	14.0	9.3	11.1	14.0
Thrithala	20.8	19.5	24.1	13.4	8.8	12.0	16.4
Walayar	11.8	15.8	8.4	11.5	9.6	8.7	11.0

Table 8. Precipitation Concentration Index values for Post-monsoon season in the study area

Place	2018	2019	2020	2021	2022	2023	PCI Winter
Chittady	17	0	0	17	17	0	8.5
Chulliyar	17	0	0	15.1	17	0	8.2
Eramayur	17	0	0	17	0	0	5.7
Kanjirapuzha	17	17	0	17	0	0	8.5
Koduvayoor	17	0	0	17	0	0	5.7
Malampuzha	17	0	0	17	0	17	8.5
Mangalam	17	0	0	9.4	0	0	4.4
Pokkunni	17	0	0	10.6	0	0	4.6
Pothundy	17	0	0	17	0	0	5.7
Thrithala	17	0	17	13.2	0	17	10.7
Walayar	17	0	0	16.0	17	0	8.3

Table 9. Precipitation Concentration Index values for Winter season in the study area

4.2.3. GIS-based Precipitation Concentration Index patterns

The interpolated Average PCI values from the Figure 11 illustrates that areas with in Chittur and Malampuzha blocks showing high precipitation concentrations implying strong precipitation irregularities. While areas within Alathur, Kollengode, and Kuzhalmannam

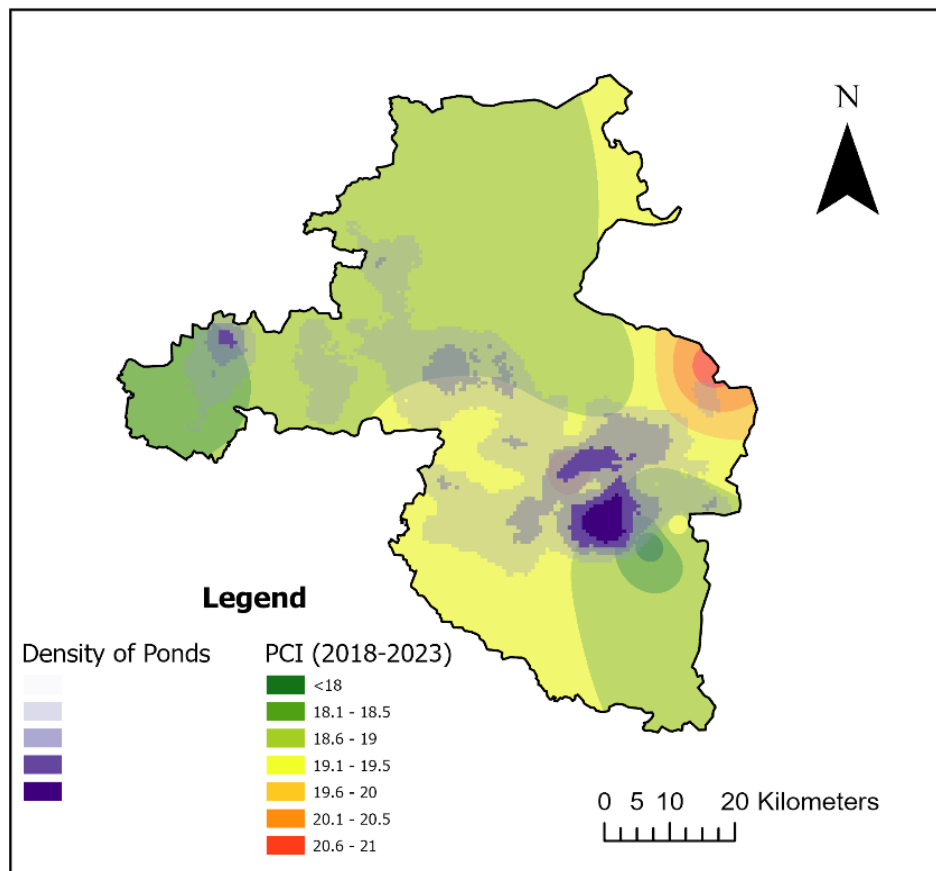
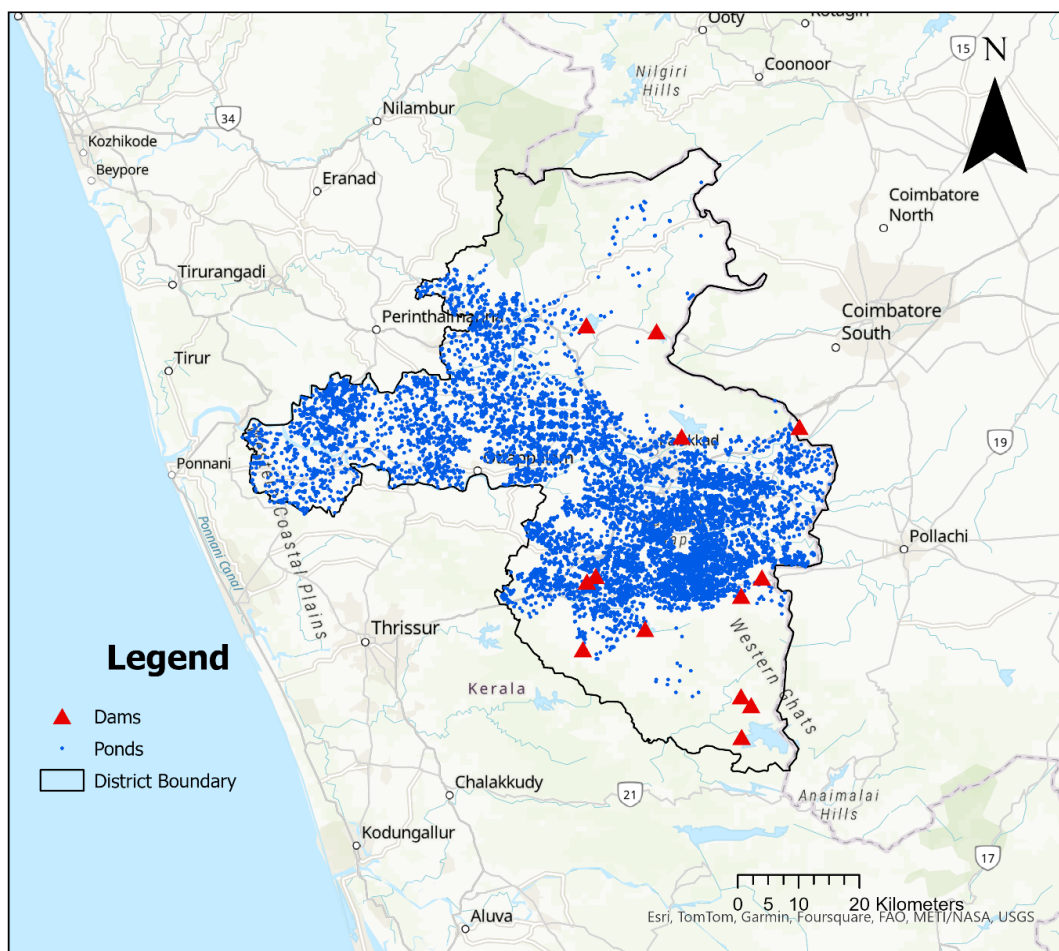


Figure 13. *Precipitation Concentration Index Average for 6 years of Palakkad and pond density*

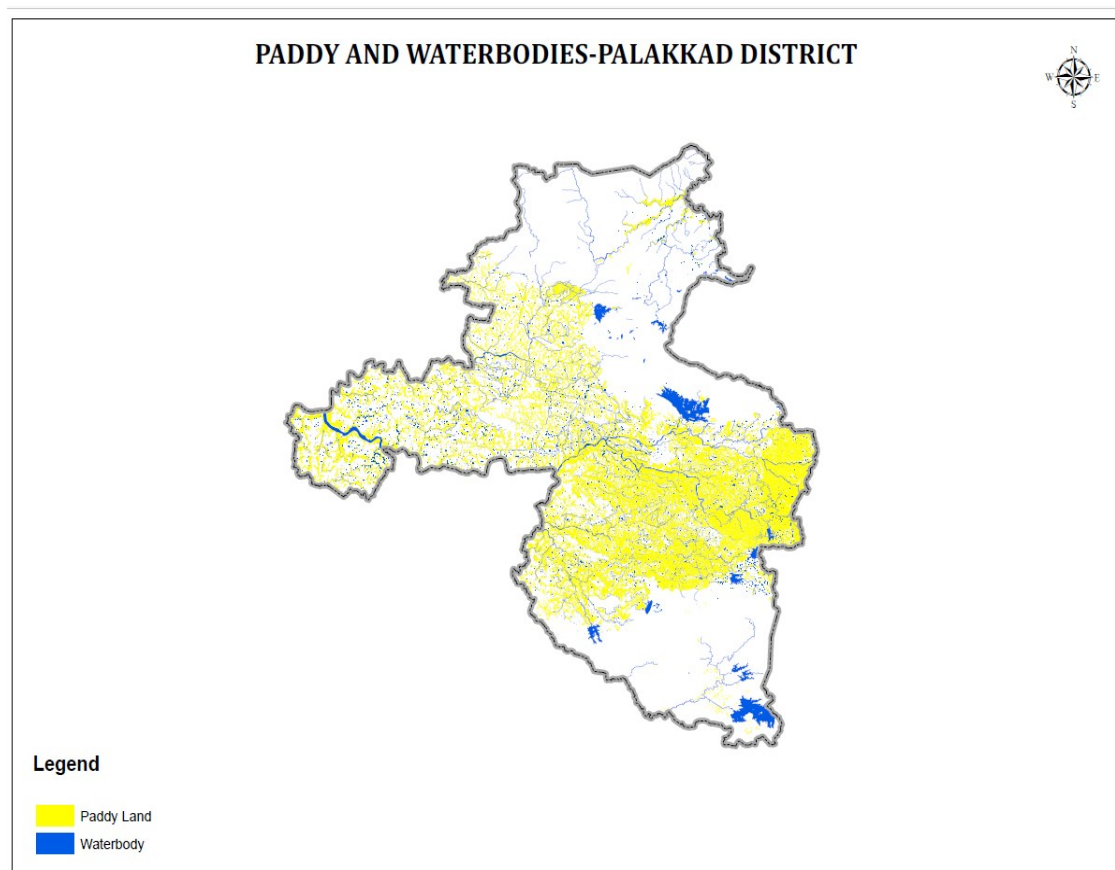
Blocks show values ranging from 19 to 19.5 denoting irregular precipitation concentration. The PCI annual values range from 18-21 show moderate to strong irregularity in rainfall. The annual PCI for all stations was calculated and Walayar station showed high irregularity in multiple years. The lowest value observed was 15 and the maximum value was 23 in Walayar in 2023. Results indicate that the eastern side of the region is experience high rainfall variability. A

similar result from previous study also indicated the region to be comparatively drier than the western side which is similar from the long-term average PCI and the value range was 40 in July, June and October in Bharathapuzha Basin (Dhanya and Jayarajan, 2024).

Figure 12 illustrates the distribution of paddy fields and water bodies, especially reservoirs in Palakkad. The results show that the paddy production is more intensive in the eastern part of the Palakkad. While Figure 13 shows the different types of ponds in Palakkad and reservoirs. This representation is based on consolidated data collected over multiple years. This would give a comprehensive view of region's water resource infrastructure.



(a)



(b)

Figure 14. (a) Map created from the consolidated spreadsheet of Ponds and Reservoir (Dams) in Palakkad **(b)** Map created from the consolidated spreadsheet of Ponds and Reservoir (Dams) in Palakkad.

4.3. Spatial and Temporal Analysis of Standardized Precipitation Index Values in Palakkad

The standardized precipitation for 6 years shows values ranging from -2 to 2. Table 10 shows that the Walayar station has negative value in multiple years indicating the region to be moderately dry to extremely dry. Kanjirapuzha, Malampuzha, and Thrithala are relatively wetter considering 6 years of data. In 2018, -2.13 SPI value was observed in Walayar station marking it as the driest area while Malampuzha station recorded a 1.31 wetter region. -1.39 in Walayar again in 2019 making it the station drier and Kanjirapuzha, the wet region. -1.34 (Koduvayur) and 2.08 (Kanjirapuzha) are the values for the year 2020. -1.57 in Walayar and 1.33 in Thrithala

in the year 2021. Again Kanjirapuzha showed 2.38 in 2022 and -1.03 Eramayur. In 2023 Walayar and Kanjirapuzha showed -1.6 and Thrithala showed 1.51.

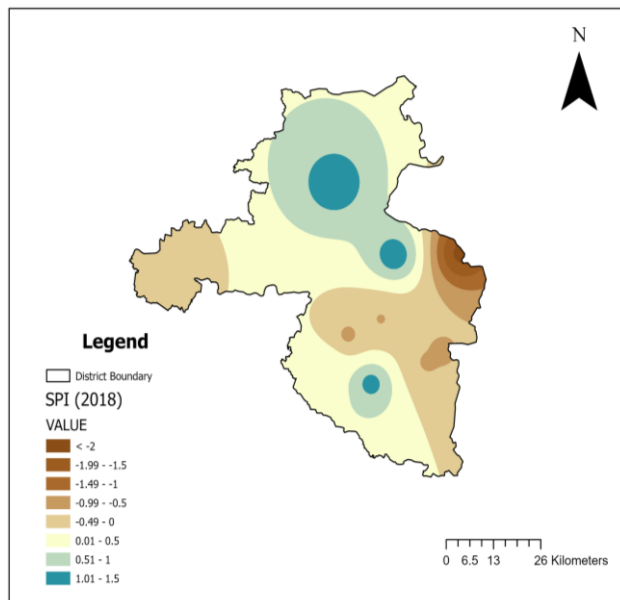
Place/ Year	2018	2019	2020	2021	2022	2023
Chittady	0.36	0.42	0.35	0.08	-0.59	0.04
Chulliar	-0.54	-1.31	-0.93	-0.97	-0.67	0.04
Eramayur	-0.59	-0.43	-0.69	0.04	-1.03	0.12
Kanjirapuzha	1.29	1.66	2.08	1.83	2.38	-1.6
Koduvayoor	-0.52	-0.98	-1.34	-1.15	-0.7	0.76
Malampuzha	1.31	1.03	0.8	0.07	1.27	0.55
Mangalam	0.45	0.05	-0.28	0.79	0.26	0.62
Pokkunni	-0.56	-0.73	-0.57	-0.71	-0.72	-1.27
Pothundy	1.2	0.48	0.85	0.26	0.5	0.84
Thrithala	-0.29	1.2	0.76	1.33	0.03	1.51
Walayar	-2.13	-1.39	-1.04	-1.57	-0.74	-1.6

Table 10. Standardized Precipitation Index average of 11 stations in Palakkad for 6 years

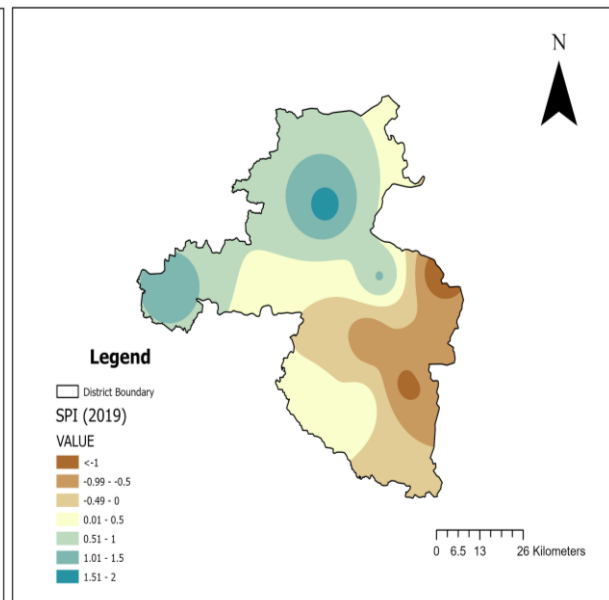
4.3.1. GIS-based SPI patterns

In all the maps the northern part has appeared wetter with SPI values around 2 for most of the years. Mannarkad and Kongad Blocks fall in this region. The west part is also normal to moderately wet. The East to Southeast part of the district was observed to be moderately dry to extremely dry over the years implying arid characteristics.

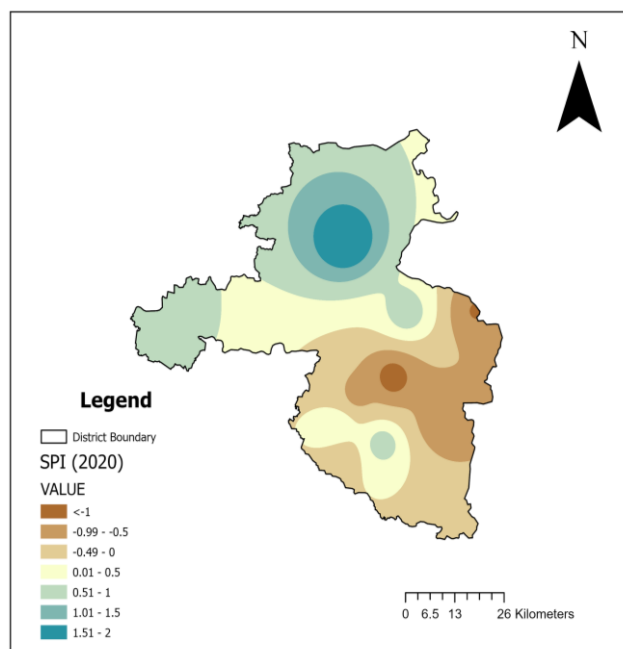
In all the maps the northern part has appeared wetter with SPI values around 2 for most of the years. Mannarkad and Kongad Blocks fall in this region. The west part is also normal to moderately wet. The East to Southeast part of the district was observed to be moderately dry to extremely dry over the years implying arid characteristics. The geographical position and climatic features of the region as mentioned above characterise the dry situation. The eastern part of the Palakkad is known for its geographic and climatic features and it also holds a unique position in the irrigation map of Kerala.



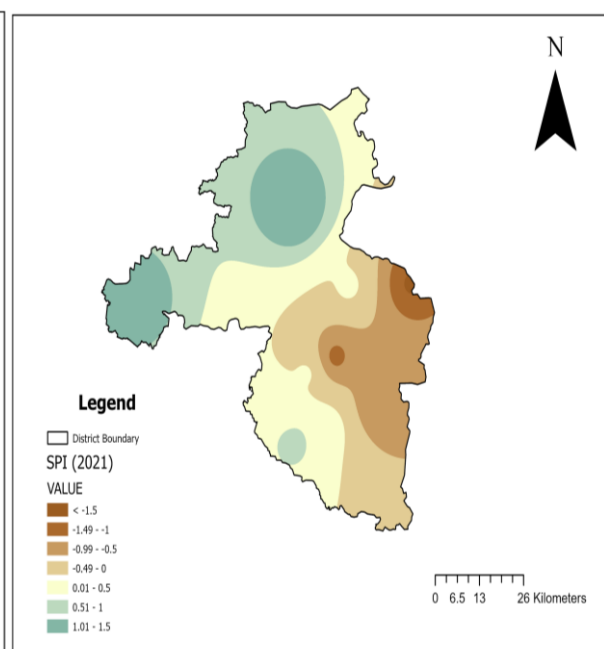
(a)



(b)



(c)



(d)

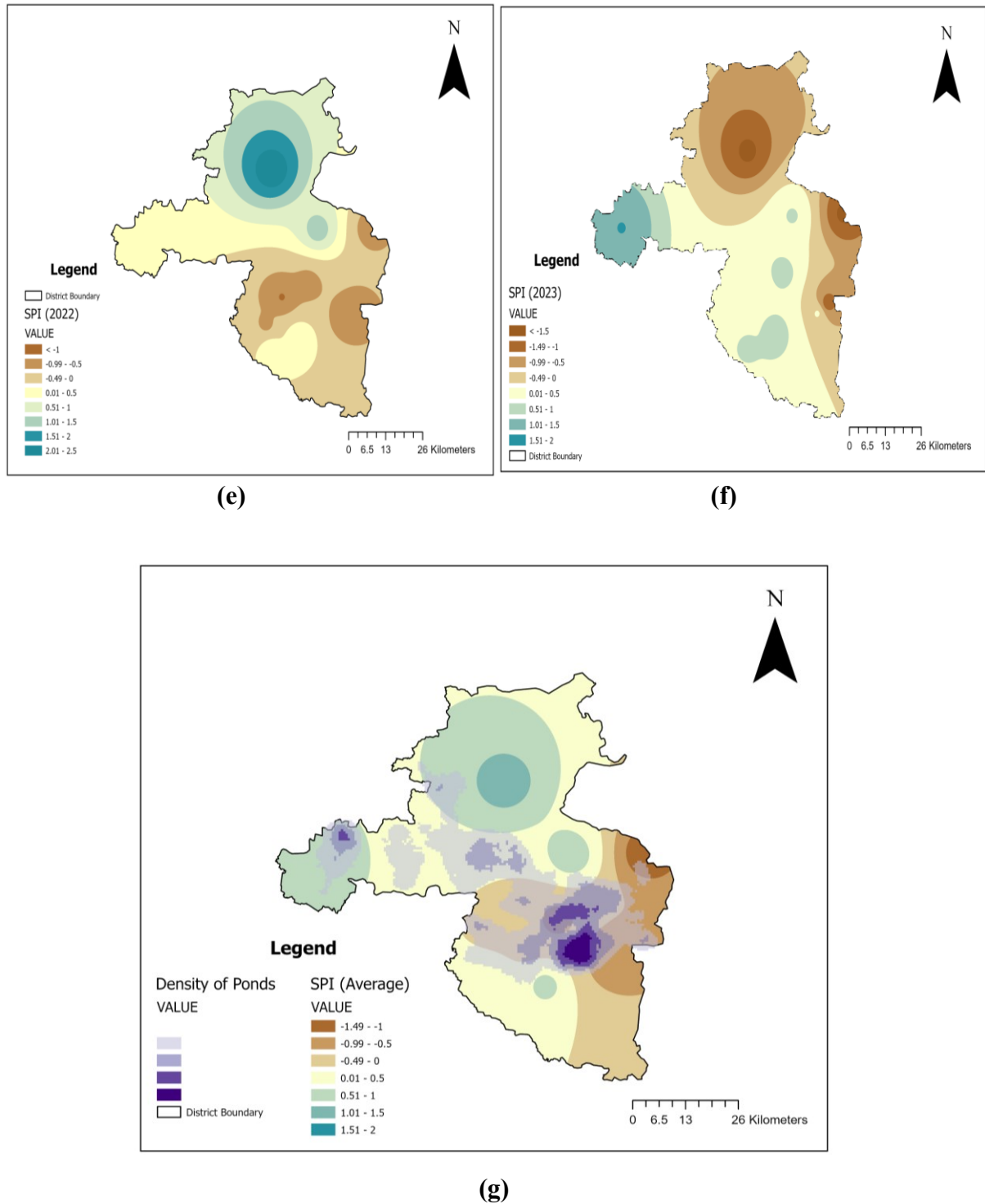


Figure 15. (a), (b), (c), (d), (e), & (f) Standardized Precipitation Index for 6 years (six maps). (g) Standardized Precipitation Index Average for 6 years and Kernel Density of Ponds data compiled (Bottom).

The Chittur block majorly covering this east region and located in the Palakkad Gap is characterized by relatively higher temperatures, lesser rainfall and high-velocity hot and dry

winds that blow in from the adjoining Coimbatore plains. Lower amounts of rainfall coupled with increased evapotranspiration rates have made the water economy crucial in the region. In addition, during summers, the district of Palakkad, particularly those portions located in the Gap, record higher temperatures than most other parts of the state. Maximum summer temperatures recorded at Palakkad have often crossed 40°C. Further, the studies of Viswambharan et al., 2022, report that the NDWI, NDMI, and NDVI analyses indicate a significant change to surface soil moisture and vegetation water content in the district and suggest that the district would face a serious threat in the near future. These findings further validate the current results, as the findings identified in that study align with the driest areas highlighted in this study's SPI analysis. Apart from the region's geographical uniqueness that contributes to its dryness, climate change could further exacerbate these conditions, threatening agricultural productivity in the coming years.

While the distribution of wet and dry regions has remained relatively consistent over the years, 2023 displayed a markedly different pattern. In this year, the Mannarkkad block, typically classified as a wetter area, experienced unusually dry conditions, highlighting a significant deviation from trends marking the unpredictable turns of weather which could affect the agricultural community

Additionally, the State Climate Action Council has designated Palakkad as a climate change hotspot. In the context of rising climate change impacts and erratic rainfall patterns, water demand in these areas is expected to increase, underscoring the necessity for additional resources and prudent water management strategies.

4.4 The Significance of Ponds in Supporting Agriculture in Dry Regions: Density Analysis

The Density analysis results show that high pond concentration is in areas in the borders Nenmara, Alathur, Kollengode, Palakkad, Malampuzha and Chittur Blocks. Chittur owing to its intensive paddy cultivation has less density of ponds. The significance of pond density becomes evident when examining the Chittur region, which demonstrates a high concentration of precipitation and elevated SPI values.

Though the canal irrigation water system by the government is extensive in the region water stress is experienced in the later part of the year which is an increasing concern among farmers who completely depend on canal irrigation. The study analyzing the role of reservoirs on regional water availability under climate change reveals that the blue water availability is in the normal range but the water availability in the normal range is not sufficient to sustain the

baseline agricultural yield in the region, underscores the need for adaptation measures in the area. Also highlights a diminishing trend in the effectiveness of the current reservoir policy (Sreeshna et al., 2023).

Furthermore, when compared with previous research indicating that global groundwater overexploitation amounts to 163 km³ annually, irrigation ponds emerge as a valuable resource for aquifer recharge, thereby reducing groundwater extraction pressures (López-Felices et al., 2020). Therefore, the construction, renovation, and utilization of irrigation ponds represent a highly sustainable approach to mitigating water scarcity challenges in agricultural regions.

In Palakkad ponds in use for irrigation are 2547, 11 reservoirs, 22 in use for water conservation schemes and 19 others water-based for irrigation. Non-functional ponds include 228 dried up , 24 affected by construction, 245 silted, 45 beyond repair , 16 salinity affected, 4 impacted by industrial development, and 382 with other issues (Water Bodies Census, 2023). This further shows the situation concerning water security and the need for ecosystem-based water management.

The influence of climate change makes it difficult to guarantee sufficient surface water for irrigation in dry years and drought periods, therefore groundwater serves as a vital supplementary source for irrigation. With the decrease in surface water availability inevitably leads to a rise in groundwater exploitation which has resulted in a range of ecological issues, including continuous decline of groundwater table and decreasing streamflow, reduced well yield and increased irrigation energy consumption as well as cost (Zhang et al., 2024).

Though the state has been perceived as a water-rich-state with 3000 mm/year annual rainfall and many freshwater bodies, the water scarcity is getting intensified. The state has been experiencing more rainfall deficit in years and acute water scarcity. The high runoff losses (40 %) and declining groundwater levels are posing issues in Kerala (Devi et al., 2022), validating the findings from the SPI and PCI values.

In Chittur, the wells are fitted mostly with compressor pumps and farmers resort to continuous pumping for 7–18 h during early summer months and store the water in existing open wells. The average pumping time in farms with both open and borewells was 1286.8 h/ha/year which was three times greater than that of the pumping time in farms with only open wells. Furthermore, the water reserve for open wells is unconfined aquifers, while borewells depend on confined aquifers. The recharge of confined aquifers takes many years (while unconfined aquifers get recharged at faster rates) and hence resource replenishment is not in tune with

extraction rates (Devi et al., 2022). Water harvesting techniques especially on-farm ponds could be more sustainable solution. They can be the best option where rainfall intensity exceeds soil infiltration. And can provide other ecosystem services like enhanced biodiversity, improved water quality, nutrient cycling and many more (Vico et al., 2020).

Palakkad had a pond-based irrigation system which weakened over the years. From the pond density analysis, it was evident that ponds were lesser in the areas in Chittur region. Though the number of ponds is considered from the previous studies canal irrigation and existing structures appear to be insufficient to meet the water needs indicating the creation of more resources and better use. The increasing concern over the overexploitation of groundwater resource is validation this approach.

Therefore, from this study, also from the perspective of disaster risk reduction, rediscovering ponds by maintaining existing ones and creating new ones in Chittur can be the natural solution ensuring water and food security. They could supplement the existing sources like reservoirs, wells and all other structures combating current issues and better preparing for the future scenario. For this Padashekara samitis (Farmer collectives) in Palakkad could involve and maintain ponds, conduct regular desilting, monitor water quality, and implement water conservation practices with government support for long-term sustainability which will be the best step up to community resilience.

5. Future Developments and challenges

The study has many advancements and developments possible in the future. Though the current research has many insights from the analysis of a short time frame, a longer time scale could also give more robust information and more comprehensive patterns. Similarly, paddy being an important crop, incorporating crop-wise water requirements at the regional level for the design of ponds would give more tailored approach. Utilizing predictive models for future climate scenario will enable better preparation and resource management.

Strengthening the role of local farmer collectives in pond management will ensure community participation. This alignment of pond-based intervention with broader climate adaptation goals will support long-term sustainability by addressing both food and water security challenges. On the other hand, introduction of new strict policies to protect ponds can aid effective management. Incentives for individuals or groups involved in pond restoration will give the concept a higher edge. The pond system can be associated to aquaculture, Internet of Things (IoT) for better water quality and levels monitoring and solar panels for renewable energy and to reduce evaporation loss. Balancing the cost of pond restoration with the economic returns or benefits to local communities is a challenge. For effectiveness there has to be long-term evaluation mechanisms to assess the effectiveness of pond-based interventions and adapt them based on changing conditions.

The challenges could include financial constraints associated with the restoration and expansion of ponds, given their resource intensive nature particularly in rural areas. Further, administrative delays in approvals and implementation of projects can delay the adaptation of the intervention. This can even be delayed by the unpredictable turn of changes in climate such as floods and droughts can block the planned intervention.

The major hurdle would be the land-use priorities and urbanization which might limit the space available for expanding pond systems or traditional water bodies. Regular maintenance of restored ponds to prevent issues like siltation and contamination will require sustained effort. Another major problem would be community resistance from those accustomed to certain ways of thinking and closed to changes.

Water resource management is intricately linked to anticipated impacts of climate change in Palakkad. The water scarcity and stress on irrigation systems will be exacerbated with rising temperature, erratic monsoon patterns and increased frequency of weather events, as predicted in the global climate models (Sreeshna et al., 2024). Therefore adaptive strategies will be

instrumental in coping up with the conditions. This can include not just rainwater harvesting, but also improved irrigation efficiency and integrated watershed management.

6. Conclusion

This study emphasized on the critical role that sustainable water resource management can play in Palakkad region in India against the backdrop of climate variability and increasing water scarcity. Palakkad being known as the rice bowl of Kerala holds an important role in the food security and economy of the state, further defining the gravity of irrigated agriculture and water security. Through this study, by analysing the rainfall variability, drought situation and pond water management in Palakkad, the research underlines the importance of rediscovering traditional water systems like ponds, especially in areas like Chittur. Chittur has been marked as critical in groundwater extraction. Further, the SPI and PCI analysis has provided a detailed idea of the temporal and spatial patterns of rainfall and dryness in the region. The north and North West regions in general are wetter and the east and southeast parts are drier with significant rainfall concentration indicating irregularity. The current research along with previous studies shows that Chittur Block is drier, faces high rainfall concentration, dense paddy cultivation, and high-water stress, less pond density and is critical in groundwater extraction. The area has a canal irrigation system already functional. Thus pond-based intervention in its first place has to be started at Chittur. The combination of SPI, and PCI analysis with GIS mapping enabled to identify of susceptible regions for better-targeted, location-specific water management strategies.

The findings points out that the use of precipitation indices and GIS mapping can effectively capture high-risk areas and bring better-targeted interventions. Palakkad has a historical base in pond irrigation systems, though diminished, presents an opportunity to supplement other major sources like Reservoirs, thus satisfying the crop water requirement. As a first step, the deteriorated ponds due to urbanization, silt accumulation and insufficient maintenance can be revitalized and further extended. This intervention gets important as time passes by when water needs escalate and will be critical to prevent conflicts between crop production and domestic needs, ensuring sustainable access to both.

The study advocates for the integration of community-driven initiatives, supported by farmer collectives to maintain and expand pond systems. This can build community resilience and leave no one behind, overcoming the economic inequalities which leads to water poverty. In total, these steps will not only guarantee water availability and agriculture productivity but also give long-term environmental and economic stability, food security and well-being. Thus, touching all spheres of sustainability.

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