Interlinking Drought with Water-Food-Energy Nexus: Application of an Integrated Approach towards Sustainable Resource Management

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ABSTRACT

Under the current changing environment, water, food and energy resources are under immense stress. For sustainable and effective planning, development and management of these interrelated resources, the implementation of a holistic and integrated approach has become crucial. This study supports the evaluation of extreme event of climate change (drought) and its effect within the Water-Food-Energy (WFE) nexus framework at farm level. The integrated approach utilized in this study quantitatively describe the dynamics of WFE nexus with respect to different severity levels of drought. Different rain-fed and irrigated crops are used and compared to analyze the multiple implications of drought on different dimensions of the nexus and on WFE nexus by assessing the drought induced WFE nexus index (DI-WFENI). The application area for the implementation of this approach is the northern part of Cyprus (NC). The analysis indicated that there is a gradual increase in the occurrence and magnitude of drought in different regions of NC. During moderate, severe, and extreme drought, the estimated reduction in the yield of rain-fed crops was 31, 39 and 44%, while increase in irrigation water requirement (IWR) of irrigated crops was 5, 9 and 14%, respectively. Relatedly, the temporal rise and fall of groundwater levels, quantified using hydrological indices are closely related to the positive and negative values of meteorological drought indices. In different locations of aquifer depending upon heterogeneous climate, soil and hydrogeological characteristics and pattern of utilization, the groundwater trend varied from one location to another. The increase in the energy requirement of irrigated crops is computed as 10, 15, and 22 % for moderate, severe and extreme severity levels, respectively. As a result of the reduction in yield of rain-fed crops and increase in the IWR and energy requirement of irrigated

crops, the mean reduction in farmers profitability during moderate, severe and extreme drought is calculated as 233, 296 and 352 $ per hectare. The computation of drought-induced WFE nexus index (DI-WFENI) revealed that the computed mean score of DI-WFENI for moderate, severe and extreme drought is approximately 0.85, 0.84 and 0.82, respectively. Based on the sensitivity analysis it is found that DI-WFENI is highly influenced by yield, IWR and crop price.

Keywords Cyprus; Climate change; Drought, Water-Food-Energy nexus; Rain-fed agriculture; Irrigated agriculture

ÖZ

Sürekli değişimlere maruz kalan çevremizde su, gıda ve enerji kaynakları aşırı stres altındadır. Bu birbiriyle bağlantılı kaynakların sürdürülebilir ve etkili bir şekilde planlanması, geliştirilmesi ve yönetimi için bütünsel ve bütüncül bir yaklaşımın uygulanması çok önemli hale gelmiştir. Bu çalışma, aşırı iklim değişikliği olayının (kuraklık) su-gıda-enerji (WFE) bağıntısı çerçevesindeki etkilerinin tarımsal düzeydeki değerlendirmesini içermektedir. Bu çalışmada kullanılan entegre yaklaşım, su-gıda-enerji bağlantısının dinamiklerini, kuraklığın farklı şiddet dereceleri ile ilişkilendirerek nicel olarak tanımlamaktadır. Farklı sulama yöntemleriyle (sulu tarım ve yağmura dayalı tarım) elde edilen ürünlerin farklı kuraklık şiddetleri ve su-gıda-enerji bağıntısı ile ilişkisi irdelenerek yeni bir indeks geliştirilmiş (DI-WFENI) ve bu kuraklığın neden olduğu farklı boyutların çoklu etkilerinin analizi gerçekleştirilmiştir. Geliştirilen indeksin uygulanması için çalışma alanı olarak Kıbrıs'ın kuzey kısmı seçilmiştir. Gerçekleştirilen kuraklık analizleri çalışma alanının farklı bölgelerinde kuraklığın oluşumunda ve büyüklüğünde kademeli bir artış olduğunu göstermiştir. Orta, şiddetli ve aşırı kuraklık sırasında, yağmurla beslenen mahsullerin verimindeki tahmini azalma 31, 39 ve 44% iken, sulanan mahsullerin sulama suyu ihtiyacının (IWR) orta, şiddetli, ve aşırı kuraklık sırasında 5, 9 ve 14% arttığı gözlemlenmiştir. Buna bağlı olarak, hidrolojik indeksler kullanılarak ölçülen yeraltı suyu seviyelerinin zamansal yükselmesi ve düşüşü, meteorolojik kuraklık endekslerinin pozitif ve negatif değerleri ile yakından ilişkili olduğu yapılan analizlerle ortaya konmuştur. Heterojen iklime, toprağa ve hidrojeolojik özelliklere ve yeraltı suyu kullanım modeline bağlı olarak oluşan eğilim, akiferin farklı yerlerinde farklılıklar göstermiştir. Sulanan bitkilerin enerji ihtiyacındaki artışı, sırasıyla orta, şiddetli ve aşırı şiddetli kuraklık seviyeleri için 10, 15 ve 22% olarak bulunmuştur. Yağmurla beslenen ürünlerin verimindeki düşüş, sulama suyu ihtiyacının artması ve sulanan ekinlerin enerji ihtiyacının bir sonucu olarak, orta, şiddetli ve aşırı kuraklık döneminde çiftçilerin karlılığında ortalama azalma hektar başına 233, 296 ve 352 USD olarak hesaplanmıştır. Kuraklığa bağlı su-gıda-enerji bağıntı indeksinin (DI-WFENI) hesaplanması, orta, şiddetli ve aşırı kuraklık için ortalama DI-WFENI skorunun sırasıyla 0.85, 0.84 ve 0.82 olarak ortaya koymuştur. Duyarlılık analizi, DI-WFENI'nin verim, sulama suyu ihtiyacı, ve ürün fiyatından büyük ölçüde etkilendiğini ortaya çıkarmıştır.

Anahtar Kelimeler: Kıbrıs; İklim değişikliği; Kuraklık, Su-Gıda-Enerji bağıntısı; Yağmurla beslenme tarım; Sulu tarım.

DEDICATED TO MY PARENTS, MY WIFE, MY SON (MUQEET PAYAB), MY DAUGHTER (RAHWA PAYAB) AND TO THE ENTIRE PAYAB FAMILY.

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LIST OF ABREVIATIONS

NCF	Net Cash Flow
RDI	Reconnaissance Drought Index
SPI	Standardized Precipitation Index
SGI	Standardized Groundwater Index
SGWLA	Standardized Groundwater Level Anomaly
WFE	Water-Food-Energy
DI-WFENI	Drought-Induced Water-Food-Energy Nexus Index

Chapter 1

INTRODUCTION

1.1 Overview

Water, food and energy are interconnected and interlinked to each other in numerous ways and are vital and crucial for survival and sustainability of human population and health of ecosystem. However, population growth, increase in anthropogenic activities and climate change and variability is adversely affecting the quality and quantity of these scarce and diminishing resources around the globe (IRENA, 2015; FAO, 2014; ADB, 2013). Climate change and variability in particular, increases the frequency, duration and severity of extreme events such as drought (Dabanli et al. 2017; Zarch et al. 2015; IPCC 2014). Hence, studying and monitoring the effect of drought on water security, food security and energy security at this point of time through an integrated approach is urgently needed than any time before for strategic and sustainable planning and management of these resources at space and time.

Drought is a dynamic and multi-dimensional recurrent phenomenon and is considered a natural feature of climate (Tigkas et al. 2012; Wilhite 2003). Drought with varying frequency, severity and duration that has widespread consequences than any other natural hazard occurs in all climatic regimes affecting wide areas (Paulo et al. 2012). Due to its inherently complex nature, it is hard to determine and predict the onset, termination, severity, and spatial extent of drought events (Tsakiris et al. 2013). Being a least understandable phenomenon, generally depending upon its impact it is defined in many ways, with no unique and universally acceptable definition to adequately describe it (Mishra and Singh 2010; Niemeyer 2008). Generally, drought is categorized into meteorological drought, agriculture drought, hydrological drought and socio-economic drought. Figure 1 demonstrates the interconnection between different types of drought and the produced impact.

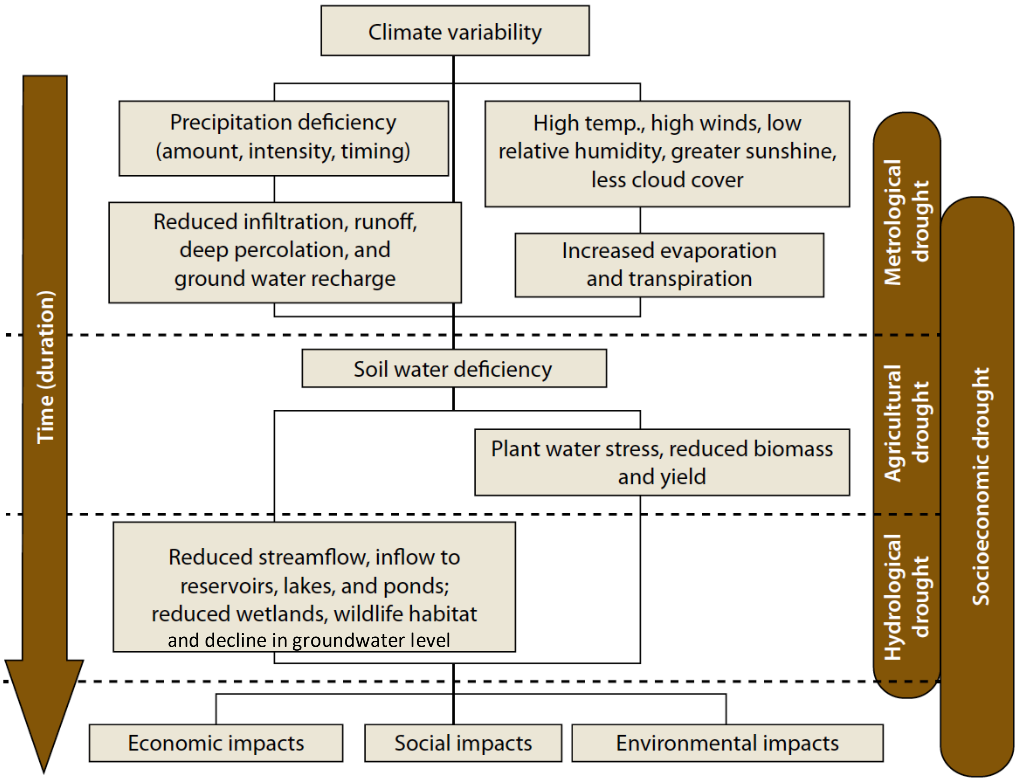


Figure 1.1: Relationship between different types of drought (adapted from Venton, 2012)

In the last few decades many regions of the world have suffered from frequent occurrence of drought events. Climate change has turned Europe and in particular the Mediterranean region into a global hotspot with more longer, frequent and severe occurrence of drought (Spinoni et al. 2015; IPCC 2014). In fact, the eastern part of the Mediterranean is considered to be the most vulnerable basin to global change in climate and water scarcity due to increased temperature, reduced precipitation (rainfall) and consequently rise in evapotranspiration (García-Ruiz et al. 2011).

Drought has affected globally large geographical areas, however, the anticipated adverse consequences of the impact of drought in arid and semi-arid climatic zones is much more profound (Vangelis et al. 2013), affecting many sectors of the society negatively. Drought in particular affects water, agriculture and energy sectors. Meanwhile, social and environmental impacts of drought are also significant, but it is difficult to quantify the impacts and assign a monetary value to them. The impacts of drought are non-structural in nature as compared to other natural hazards such as floods which makes it to be extremely disastrous in nature, causing losses of billions of dollars (Wilhite, 2010). Drought has caused a total amount of €100 billion to Europe in the last three decades (Vangelis et al. 2013). The 2001-2002 droughts in Canada reduced the Gross Domestic Product (GDP) of the country by $5.8 billion with an estimated loss of 41,000 jobs and an estimated $3.6 billion reduction in agriculture production (AGR, 2013). In Spain, the 2005 drought caused losses of more than €1.6 billion in crop and livestock production (Oiles, 2005). In Australia, Horridge et al. (2005) estimated that the 2002–2003 droughts reduced Australian GDP by 1.6 per cent with agriculture being the worst hit sector. During the 2002 drought in India, food grain production reduced by 29 million tons (UNISDR, 2011).

Recently many studies have been conducted in different countries of the world that focuses on drought monitoring, assessment and analyzing and evaluating the impact of drought on water, agriculture and energy sector. Dabanlı et al. (2017) utilized Standardized Precipitation Index to analyze drought condition in Turkey. Kopsiaftis et al. (2017) assessed the impact to drought on a coastal aquifer in Greece employing Reconnaissance Drought Index and hydrological model. Wang et al. (2014) studied the temporal-spatial characteristics of severe drought events and their impact on agricultural crops. Horridge et al (2005) modelled the impact of 2002-2003 droughts on Australia. Keshavarza et al. (2013) conducted qualitative research on social impact of drought in rural areas of Iran.

While numerous studies such as the ones mentioned in the previous paragraph, have been conducted on drought and its impact on different sectors, few studies have really focused and considered an approach that is holistic and integrated in nature such as the Water-Food-Energy (WFE) nexus approach. Knowing the fact that over the coming decades the demand for food, water and energy will increase between 30% to 50% (Kaddoura and El-Khatib, 2017; IRENA 2015) and climate change will cause an increase in the frequent and severity of drought (Liu, 2016; Yillia, 2016; IPCC, 2014) these resources will be under immense stress (Martinez-Hernandez et al. 2017). Therefore, under the current changing environment the conventional 'silo' approach of dealing with water, food and energy independently without considering the synergies and trade-offs between them, is becoming less efficient and justify the need to intensify the adoption of WFE nexus approach (Cai et al. 2018; Menegaki and Tiwari, 2018; Martinez-Hernandez et al. 2017; Daher and Mohtar, 2015; Olsson, 2013).

The concept of WFE nexus is presented for the first time in a conference in 2011 (Hoff, 2011). Since then, the concept has gained an increased popularity and its development and implementation is rapidly expanding among scientists, researchers and practitioners (Olsson, 2013). An agreed standard and unified definition for this integrated approach is yet to be identified (Liu et al. 2016; Smajgl et al. 2016; Daher and Mohtar, 2015) but the interrelations, interdependencies, interconnections, interlinkages, the synergies and tradeoffs between water, food and energy is generally termed as the Water-Food-Energy nexus (Martinez-Hernandez et al. 2017; FAO, 2014; ADB, 2013; Hoff, 2011). Under the varying demand and climatic conditions, the nexus perspective at space and time is to maximize benefits, balance and manage trade-offs, minimize risks, internalize impacts, enhance efficiency, capture synergies, reduce social, economic and environmental externalities and explore new opportunities (Albrecht et al. 2018; Yillia, 2016; Olsson, 2013).

There exist complex but visible interconnections between water, food and energy (Figure 2). Water is required in the production of energy (hydroelectric power generation, thermoelectric power generation, nuclear power generation). Energy is essential in the extraction, production, treating, and distribution of water (surface and groundwater pumping, desalination, wastewater treatment). Food is essential in the production of energy (bioenergy/biofuel). Energy is essential in different activities of food production. In food production, on farm and off farm activities are heavily dependent upon water (Martinez-Hernandez et al. 2017; Yillia, 2016).

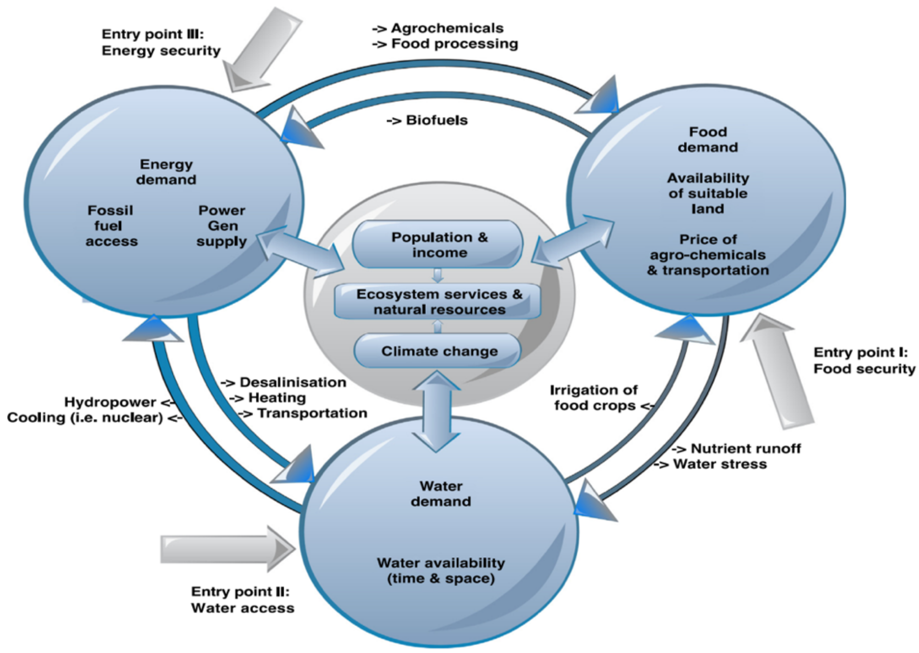


Figure 1.2: Interrelationship between water, food and energy (adapted from Smajgl, 2016)

Nexus approach requires a balanced look into the system by considering the interplay of all dimensions (Smajgl et al. 2016). Though balanced quantification of nexus dimensions and elements is complex in nature, it depends on establishing an efficient model with the linkages between the elements are clearly defined based on specific problem boundaries and scales (Yillia, 2016). Currently, several studies have been conducted by modeling the interrelationship between water, food and energy using the nexus framework. El-Gafy et al. (2017a) used maximization technique to compare the nexus and non-nexus approach for optimal cropping pattern. El-Gafy (2017) using indicators analyzed the agriculture production system within the WFE nexus framework. De-Vito et al. (2017) considering the WFE nexus approach and employing indices evaluated the practices of irrigation water use. Zhang et al. (2017) used the concept of WFE nexus to develop an effective management system to combat agriculture drought. Zhang and Vesselinov (2017) developed an integrated optimization model to quantitively evaluate the synergies and trade-offs between nexus dimension. However, while the nexus approach is promising and is promoted globally, the progress to systematically evaluate the different elements of the nexus and linking them with other natural processes, still remains slow and fragmented (Albrecht et al. 2018; Liu et al. 2017; Liu, 2016; Daher and Mohtar, 2015).

1.2 Objective of Research

The primary aim of this study is to fill the gap and support the operationalization of WFE nexus by linking and combining drought to WFE nexus and quantify the impact of drought on nexus and its respective dimensions through an integrated and holistic approach for sustainable and efficient utilization of these scarce resources. The specific objectives of the study and the research questions to be answered with respect to each objective are listed below:

Objective 1

To analyze the spatial and temporal characteristics and variability of drought events using meteorological drought indices.

Research Questions

1- Is there any change in temperature and precipitation trend?

2- How does drought propagate from one timescale into another?

3- What are the critical rainfall values at different timescale based on different severity levels of drought?

Objective 2*:*

To assess and quantify the negative spatial influence of drought on rain-fed and irrigated agriculture with respect to drought severity levels?

Research Questions

1- How does drought affect the yield and production of rain-fed crops?

2- What is the increase in irrigation water requirement of irrigated crops during drought events?

3- What are the possible adaptation and mitigation measures necessary for the minimization of the negative effect of drought?

Objective 3*:*

To investigate the response of groundwater level to temporal and spatial effect of drought by employing meteorological and hydrological drought indices?

Research Questions

1- Is there any change in groundwater level trend?

2- Does the response of groundwater level to drought at different locations of the aquifer is the same?

3- Does the temporal severity between meteorological and groundwater drought resemble each other?
4- What is the potential magnitude of groundwater level reduction during the drought?

***Objective 4*:**

To analyze and quantify impact of drought under various severity levels on WFE nexus using indicators and indices.

Research Questions

1- What is the value of economic impact of drought on famers return?
2- Is there any change in consumption of energy for irrigation?
3- How to integrate different dimensions of WFE nexus and quantify the effect of drought through one number?
4- What is the effect of certain key variables or drivers on WFE nexus index?

1.3 Research Design and Methodology

1.3.1 Analytical Framework

The multidisciplinary nature of WFE nexus system requires use of integrated models and tools to realistically model and better understand the spatio-temporal behavior of nexus dimensions, their synergies, trade-offs, interdependences and interconnections under varying conditions and external and internal forces (Daher et al. 2017; McCarl et al. 2017b; Bazilian et al. 2011). Existing models, tools and theoretical methods can be employed to model and assess the WFE interconnection, synergies and tradeoffs at different scales (Miralles-Wilhelm, 2016; Daher and Mohtar, 2015). Methods such as mathematical modelling, stochastic and optimization techniques and Cost Benefit Analysis can be utilized for evaluating different aspects of nexus (Albrecht et al. 2018; Cai et al. 2018).

The methodological framework to carry out this study is shown in Figure 1.3. The drought linked WFE nexus model is kept simple to avoid excessive complexity without losing the original essence of the nexus concept as the nexus itself is a complex system. The model is made up of three main sections namely, the spatio-temporal input data section, the simulation model section and the spatio-temporal output section.

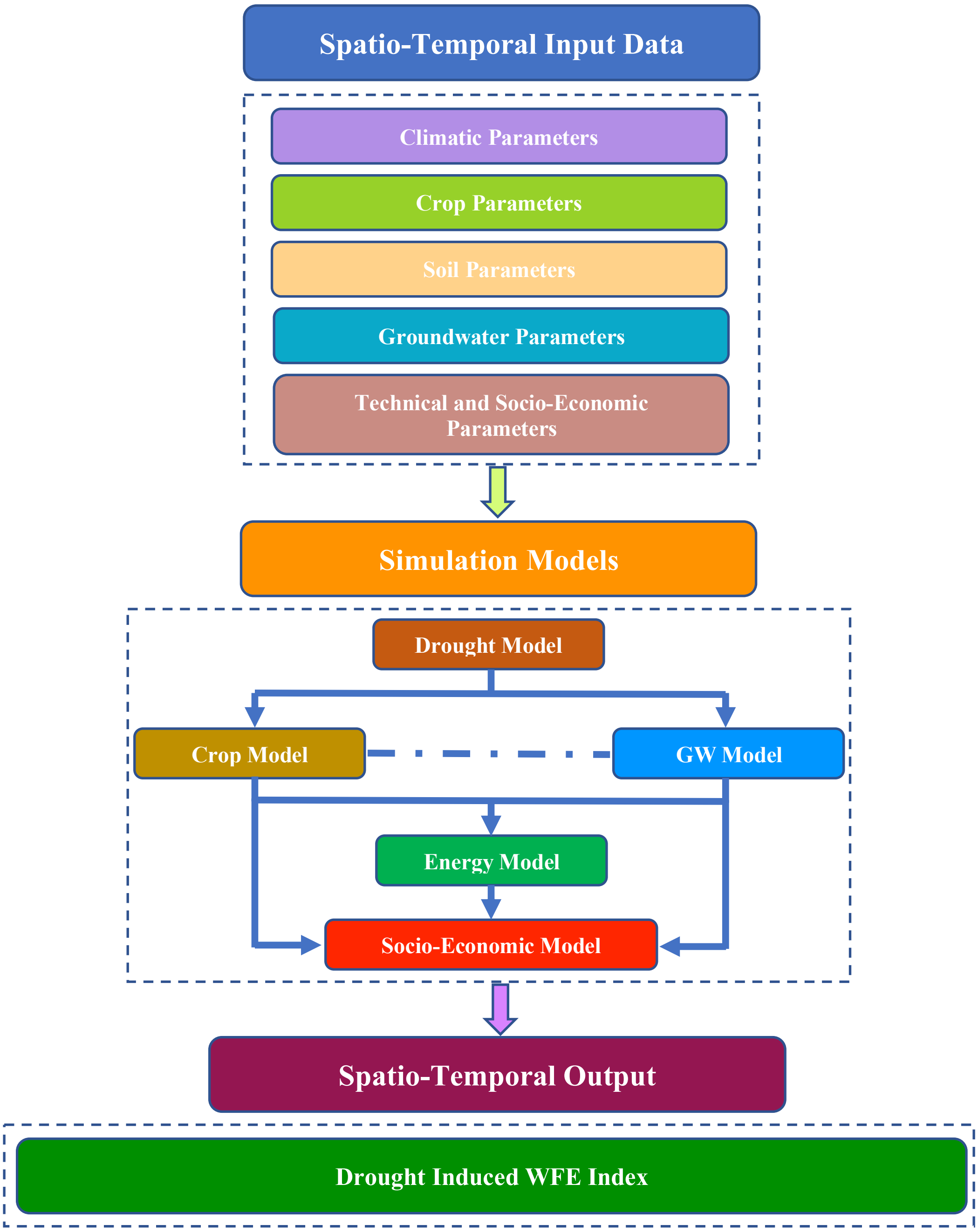


Figure 1.3: Drought linked WFE nexus methodological framework.

The spatio-temporal input data section includes all the data and parameters required for the analysis. In WFE nexus approach due to its inherently interdisciplinary and transdisciplinary nature of the system, active participation of all stakeholders and intensive and extensive utilization of data is crucial. In fact, cooperation, coordination and collaboration of all stakeholders across the scales and sectors at each stage of the study is at the core of nexus platform and is key for its successful implementation (Yillia, 2016). Data is essential part of nexus system modelling and analysis. Data utilization is dependent upon complexity and spatio-temporal scale and scope of WFE model as well as availability, accessibility, quality and compatibility of data across scale and dimensions (Daher et al. 2017; McCarl et al. 2017a). In this study, a variety of multidisciplinary datasets including climatic data, crop data, soil data, energy data, groundwater data and financial and technical data are used. The data is obtained and adopted from various sources including statistical reports, other studies and from the field survey.

The simulation model section is the core where all calculations and analysis are performed. The simulation model section is made up of several sub-models or components and are linked to each other in a modular form. Based on the existing approaches, holistic and modular methods are used to integrate or combine the sub-models to interact with each other. The holistic model tightly combines the sub-models and performs the analysis in a consistently single model. In the modular or compartmental approach there exists a lose connection in the sub-models and each component of the model operates independently without being connected all in one model (Harou et al. 2009). Similarly, models are generally categorized into deterministic, probabilistic and stochastic models (Harou et al. 2009). Though in this study the model is a deterministic model and can run sensitivity analysis, it can also be turned into a probabilistic model and run Monte-Carlo simulation. Based on the aim of the study the model is designed to compare results under dry and wet conditions. As such, the model includes a base case representing the without drought condition and alternative drought conditions based on drought intensity or categories. However, the alternative condition is also applicable to other key and sensitive parameters of the model beside different drought intensities that can be used to create various scenarios and compare it with the base case.

In the simulation model, the output of one model is the input to another model. Drought model is used to perform drought modelling essentially for the purpose of drought characterization, monitoring and management. For this purpose, drought indices which are quantitative measures to characterize drought levels are employed. To assess and understand the impact of drought on agriculture, crop model is used to perform crop modelling. Different analytical methods can be used to model and analyze crops under varying conditions. As such, a process-based crop growth model is employed to determine the crop water requirement of irrigated agriculture and to assess the changes in crop yield of rainfed crops due to water stress under drought conditions. The groundwater model by employing meteorological and hydrological indices is used to investigate and quantify the temporal-spatial response of aquifer to drought and the propagation of drought to groundwater by analyzing the historical groundwater data series. The energy model is utilized to determine the amount of direct and indirect energy consumption in the process of crop production during wet year and under drought conditions. It includes the energy to pump water for irrigation from groundwater sources using either fuel or electricity, energy consumed by machinery and human. Lastly, among the sub-models the socio-economic model is the most important model of the WFE nexus modelling approach presented in this paper. The output from the rest of the models are all input along with other technical and financial parameters to analyze the impact of drought on the WFE nexus and its elements. The impact on WFE nexus is quantified and assessed through the utilization of universally accepted indicators. These indicators are used to derive WFE nexus sub-indices and at last a unified and general drought induced WFE nexus index (DI-WFENI) is developed. In socio-economic model, sensitivity test is also performed on different key variables that inherits uncertainty and riskiness and can have a significant impact on the outcome of the study.

The spatio-temporal output section of the model provides the output of the sub-models and the overall output of the WFE nexus model developed in this study. Among others, the main output includes values related with DI-WFENI.

1.3.2 Scope and Spatial Scale

The model discussed above is applied on the northern part of Cyprus. The island is geographically located within semi-arid climatic condition. Similar to other Mediterranean countries, northern part of Cyprus is also faced by the limited and highly variable rainfall and high temperatures. As a result of this inter-annual decrease in precipitation and because of climate change, drought occurrence in the last four decades has increased both in magnitude and frequency. As a result, seriously affecting the water sector and the agriculture sector which is highly dependent upon groundwater resources.

In WFE nexus approach, identifying the scope and spatial scale of the model is also critical in the development of such integrated model. The scope and spatial scale of the model is dependent upon the need and problem in hand and question to be answered (Daher et al. 2017; Mohtar and Lawford, 2016). The models generally include the spatial domain (farm, local, national, regional, global) and the temporal domain which is the time horizon of the model (seconds, hours, daily, annual and decadal) (Cai et al. 2018). As such, the scope of this study is on all five regions or zones of the northern part of Cyprus. Based on administrative boundaries the regions are Lefkosa, Girne, G. Magusa, Guzeyurt and Iskele. Similar to administrative boundaries, the agricultural zones also have the same boundaries and names. The spatial scale of the model is at farm level. The focus of the study is on farm level as at local and national level the model would have become extremely complex. Similarly, at these levels key macro-economic parameters such as detailed export and import data and costs are not readily available. The temporal scale is static and is tied to annual time-step. However, the analysis and calculation in the model is done in such a way that makes it possible for the temporal scale to be dynamic and extend it to any desired number of years in the form of a time series.

1.4 Achievements

The achievements based on the objectives of the study is shown in Figure 1.4. The figure contains all the output of the study relative to the 5 targeted regions of the study area. For instance, if the annual rainfall in Lefkosa is less than 145 mm, this is identified as extreme drought and the corresponding severity value will be approximately -2.58. For this severity level, the average yield reduction of rain-fed crops will be approximately 55%. The corresponding loss in the profit to this reduction is approximately $618 per hectare. The table can be used in such a way for the irrigated agriculture as well. Meanwhile, in the same figure the positive trend shows increasing trend while negative trend demonstrates negative trend. In terms of groundwater, since only one aquifer is used in the analysis, so it is assumed that the finding for this aquifer is applicable to other aquifers. Overall, the findings of the study are summarized as:

1- An integrated model is developed by linking drought to WFE nexus and its impact of it is assessed from the perspective of various dimensions of nexus and nexus itself.
2- The study revealed variation in the spatio-temporal characteristics of drought in the study area.
3- From the perspective of drought impact on agriculture, it is found that drought severely reduced the yield of rain-fed agriculture and increased the irrigation water requirement of irrigated crops. Several adaptation measures are proposed for future in depth investigation.
4- The response of aquifer to drought is positive with reduced groundwater level observed in different locations, though the reduction varies from location to location within the aquifer.
5- A drought induced index (DI-WFENI) linked to various severity levels of drought by keeping into consideration the different dimensions of the WFE nexus and their respective key drivers, is derived. The DI-WFENI index analyze the interlinkage and the trade-offs among the nexus system components quantitively. The result demonstrated that DI-WFENI is highly sensitive to yield of crop, variation in irrigation water requirement which in turn affect the energy consumption for irrigation, and the market price of crops.

Regions					Lefkosa	G.Magusa	Girne	Guzelyurt	Iskele
Drought			Trend	Rainfall (mm/year)	0.75	0.88	1.99	1.06	-1.58
				Temperature (^{0}C/year)	0.01	0.01	0.03	-0.01	0.04
			Severity	Moderate	-1.14	-1.35	-1.22	-1.19	-1.16
				Severe	-1.67	-1.57	-1.69	-1.75	-1.81
				Extreme	-2.58	-2.13	-2.24	-2.12	-2.11
			Critical Rainfall Range (mm)	Moderate	178-210	175-215	269-324	170-205	285-335
				Severe	145-178	140-175	221-269	135-170	240-285
				Extreme	<145	<140	<221	<135	<240
			Timescale Drought Propagation (%)	M3→M6	41	58	46	31	47
				M3→M12	36	54	38	47	54
				M6→M12	39	54	37	47	47
WFE Nexus	Impact on Agriculture	Rain-fed	Yield Reduction(%)	Moderate	39	36	18	38	22
				Severe	52	41	29	43	28
				Extreme	55	48	37	47	35
		Irrigated	Increase in IWR (%)	Moderate	8	3	8	4	3
				Severe	11	6	13	7	7
				Extreme	16	10	20	11	11
	Impact on Groundwater		Trend	m/year			-0.11		
			Reduction in GWL (m)	Moderate			3		
				Severe			4		
				Extreme			5		
	Impact on WFE Nexus	Rain-fed	Profit Reduction ($/ha)	Moderate	463	335	332	489	352
				Severe	550	416	414	584	435
				Extreme	618	465	462	657	486
			Drought Induced WFE Nexus Index	Moderate	0.45	0.44	0.45	0.46	0.44
				Severe	0.39	0.39	0.40	0.41	0.39
				Extreme	0.38	0.38	0.38	0.39	0.37
		Irrigated	Increase in Energy (%)	Moderate	15	7	13	8	7
				Severe	20	11	19	13	12
				Extreme	27	16	28	18	18
			Profit Reduction ($/ha)	Moderate	98	25	97	87	56
				Severe	126	41	143	143	103
				Extreme	171	61	227	213	164
			Drought Induced WFE Nexus Index	Moderate	0.96	0.99	0.97	0.98	0.99
				Severe	0.95	0.98	0.96	0.97	0.98
				Extreme	0.93	0.97	0.94	0.96	0.97

Figure 1.4: Achievements with respect to the objectives and questions of the study (GWL and IWR represents groundwater level and irrigation water requirement, respectively. M3, M6 and M12 shows the 3-months, 6-months and 12-months timescales, respectively).

1.5 Overview of Thesis

This section presents the overview of the organization and contents of the thesis. Finding of Chapter 2, 3, 4, and 5 of this study have been published or are under review and consideration in peer-reviewed journals, as of the date this thesis is completed. As such, keeping into consideration the conceptual framework steps and the objective of each model, each of these chapters start with an overview of the subject, followed by methodology, result and discussions and chapter conclusion.

Chapter 1 is the introduction and focuses on the background of the subject, objectives, conceptual framework and achievements of this study.

Chapter 2 characterizes historical drought using drought indices. Discussion is mainly based on the frequency, severity and duration of drought under different timescale essential for drought monitoring. Furthermore, new concepts such as duration-based drought, drought propagation and critical rainfall ranges are introduced and explained.

Chapter 3 quantifies and assess the impact of drought on various rainfed and irrigated crops using process-based crop simulation model with respect to different severity levels of drought. For rain-fed crops the reduction in yield is estimated while for irrigated crops the increase in irrigation water requirement is computed.

Chapter 4 focuses on understanding the spatio-temporal effect of drought on groundwater resources by employing meteorological and groundwater drought indices.

Chapter 5 introduces an integrated modeling framework, termed as socio-economic sub-model that connects the different dimensions of the WFE nexus under one platform. Based on the proposed model, several indicators are used as a tool to quantify the effect of drought on WFE nexus. Utilizing these indicators, sub-indices and drought induced WFE index is developed and presented. This index can be used as a tool for assisting decision makers in formulating and designing efficient strategies under extreme events of climate change for sustainable utilization of resources.

Chapter 6 highlights the major findings of this study. Limitations and the areas of future research are identified and recommended.

Chapter 2

SPATIAL-TEMPORAL DROUGHT CHARACTERIZATION

2.1 Introduction

Drought is a normal and recurrent natural feature of climate with varying frequency, severity and duration. It is both a hazard and a disaster with a nature that is extremely hard to predict its timing and severity (Paulo et al. 2012). Drought can occur in both high and low rainfall areas when precipitation amount is ‘substantially below’ what is usually experienced for that place and time. Moreover, drought is also related to the timing of rainfall and/or the amount or effectiveness of the rainstorms. Climatic factors such as high temperature, high wind and low relative humidity are also responsible for significantly aggravating the drought severity (Wilhite 2003).

Droughts are generally classified as meteorological, agricultural, hydrological or socio-economic. Meteorological drought occurs due to seasonal or annual lack of precipitation compared to long-term average. Hydrological drought initiates when meteorological drought is extended and shortages of surface and subsurface water resources (evidenced by stream flow, reservoir and lake levels, and groundwater levels) are observed. Agricultural drought develops when soil moisture deficiency is detected, leading to reduced crop yield. Lastly, socioeconomic drought emerges when continued drought of severe intensity causes the disruption and failure of water supply system to meet the socioeconomic demand (Mishra and Singh 2010; Niemeyer 2008; Wilhite 2003).

Many sectors of the society are affected by the drought impact. Drought primarily affects agriculture, since it can give rise to agricultural yield losses and water shortages (Anjum et al. 2010). It also damages the economy (Salami et al. 2009), forest ecosystem (Luce et al. 2016) and tourism (Köberl et al. 2016). It is difficult to quantify the impacts of drought and assign a defined value to quantify them. In order to do so, drought indices are designed aiming to provide decision makers with a comprehensive picture regarding the required drought parameters, to include factors such as intensity, duration, severity, and spatial and temporal extent which are essential for drought preparedness, mitigation and risk management as well as for planning and management of scarce resources in the face of climate change (Dabanli et al. 2017; Morid et al. 2006). Though numerous indices have been developed and are currently in use (Palmer Drought Severity Index, Crop Moisture Index, National Rainfall Index, Effective Drought Index, etc.), each has its own strengths and weaknesses as none of these indices are based on their respective nature, which are superior to the rest in all circumstances (Mishra and Singh, 2010; Niemeyer, 2008). As such, many researchers consider that utilizing multiple indices is advantageous for more accurate drought related information (Mishra and Singh, 2010; Keyantash and Dracup, 2002). Moreover, combining different indices is beneficial to inspect and compare their sensitivity, accuracy, correlation, dependability and effectiveness among each other with respect to drought characteristics and parameters (Banimahd and Khalili, 2013; Dogan et al. 2012; Keyantash and Dracup, 2002).

The Standardized Precipitation Index (SPI) and the Reconnaissance Drought Index (RDI) are among the widely used drought indices around the world and in the Mediterranean basin particularly for drought characterization and monitoring (Buttafuoco and Caloiero 2014; Capra et al. 2013; Tigkas et al. 2013; Paulo et al. 2012;

Vergni and Todisco 2011; Livada and Assimakopoulos 2007; Sönmez et al. 2005). SPI is based on precipitation alone and can be used to determine the precipitation deficit for different timescales. SPI allows short-term monitoring (1, 3, 6, 9 monthss) of water supplies since it is suitable for agricultural application such as soil moisture. With respect to long-term (12 and 48 monthss) water resources, these are relevant for hydrological applications such as groundwater balance, stream flow, lake and reservoir storage (Gocic and Trajkovic 2013; Dogan et al. 2012; Mishra and Singh 2010; Abebe and Foerch 2008; Bonaccorso et al. 2003). On the other hand, RDI utilizes both precipitation and temperature as inputs in its formulation. It is based on the cumulative ratio of precipitation and potential evapotranspiration (PET) and can be considered as an extension of the SPI. The RDI considers the balance between the input (precipitation) and the output (potential evapotranspiration). Similar to SPI it can be calculated for any timescale and can be used to determine the effects of climate change and variability (Tsakiris and Vangelis 2005). Due to the intrinsic probabilistic nature, both SPI and RDI are the ideal candidates for carrying out drought risk analysis (Cancelliere et al. 2007; Guttman 1999). Although both SPI and RDI present advantages, they have their own limitations as well. Firstly, the length of precipitation records and choice of probability distribution significantly affects the SPI and RDI values. Secondly, when the index is applied on short term records with low precipitation, they produce misleading results (Mishra and Singh 2010; Niemeyer 2008).

Since severe consequences of drought events have given rise to water shortage problems and agricultural yield losses recently, focus on analyses of drought events in several parts of the Mediterranean Basin has increased. There is also high confidence that many semi-arid areas, as found in the Mediterranean basin, will suffer a decrease in water resources due to climate change (IPCC, 2007). For the past 25 years drought conditions that have spread across the Mediterranean basin (France, Spain, Greece, Italy, Tunisia, Turkey, Cyprus etc.) were detected during the years 1989-1992, 1995-1998 and 2007-2009 (Buttafuoco et al. 2015; Tsiourtis 2001). According to Cook et al. (2016) recent Mediterranean droughts have highlighted that natural climate variability in the region is still poorly understood. They even added that a particular drought from 1998 to 2012 was 20 percent drier than the drought of the past 900 years. Moreover, in the case of Cyprus, 250-years of annual precipitation and drought assessment using Pine species was carried out by Griggs et al. (2014). Results show that, Cyprus experiences annual droughts once every 5 years and sustained droughts, 2-6 years in length. According to an intergovernmental panel on climate change report (IPCC, 2007) and Lehner et al. (2006), change in recurrence of 100-years droughts, based on comparisons between today's climate and water use and simulations for the 2020s and 2070s, the future return period (in years) of droughts in the northern part of Cyprus will be more frequent than elsewhere on the island. This will therefore increase the vulnerability of the region with regards to precipitation-based water demanding sectors such as agriculture and tourism.

Based on the findings of Cook et al. (2016) and Griggs et al. (2014) the northern part of Cyprus appears to be particularly prone to droughts with a significant decrease in precipitation. Therefore, this study uses SPI and RDI to analyze the spatial and temporal characteristics and variability of drought events in northern part of Cyprus at multiple time steps. The spatio-temporal variance of drought occurrences is approached from two different and important perspectives. The first one is to analyze and derive information on time scale related drought propagation. The second perspective is to estimate critical rainfall values of different time scales for moderate, severe, and extreme drought conditions. Additionally, the two indices are also compared with each other to evaluate the strength in relationship and behaviour of the drought indices within the context of northern part of Cyprus. Furthermore, to assist the drought assessment, precipitation and temperature trends for the same period are analyzed and the results validated through similar studies performed for other regions of the Mediterranean basin and taking several local environmental impacts into consideration.

2.2 Materials and Methods

2.2.1 Study Area and Database

The northern part of Cyprus is geographically located within semi-arid climatic conditions. Northern part of Cyprus is divided administratively into five main regions namely, Lefkoşa, Gazimağusa, Girne, Güzelyurt and İskele. In these regions, uniformly distributed nine meteorological stations are selected to perform the drought analyses. Monthly precipitation (rainfall) and monthly average temperature data gathered from these stations for the period of 1977-2013 are obtained from the State Meteorological Department. The criteria for the selection of these stations were topography, hydrology, climate and data availability. The locations of the stations are shown in Figure 2.1. The selected stations have a good geographical distribution along the northern part of Cyprus and each of them represents the meteorological conditions of the region they are located. Table 2.1 shows geographical characteristics and related climate information of the nine stations. Based on Aridity Index, the stations are located in humid, sub-humid and semi-arid climate conditions. In these stations rainfall which is the only source of precipitation varies between 286 and 546 mm per year.

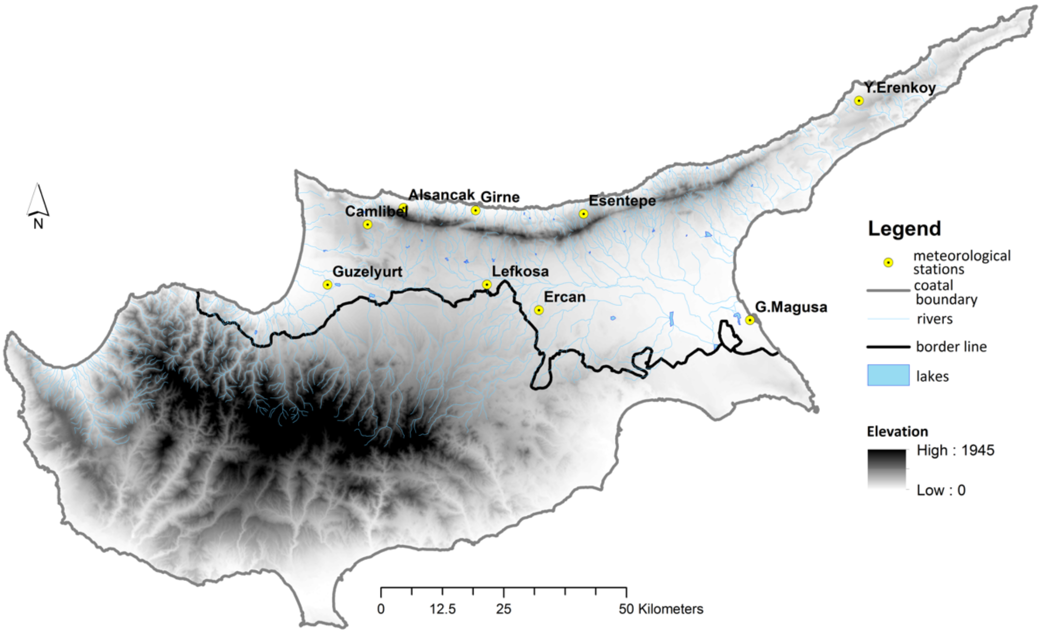


Figure 2.1: Geographical location of nine stations at northern part of Cyprus.

Table 2.1: General characteristics and information related to the climate of nine stations based on 1977-2013 data (PPT=Precipitation and PET=Potential Evapotranspiration).

Station number	Station Name	Station Latitude	Station Longitude	Elevation above sea level (m)	Mean PPT (mm year^{-1})	Mean PET (mm year^{-1})	Climatic Condition
Station 1	**Camlibel**	35°.18N	33°.04E	275.0	452	1040	Sub-humid
Station 2	**Alsancak**	35°.20N	33°.10E	62.0	546	1061	Humid
Station 3	**Girne**	35°.19N	33°.19E	14.0	464	1067	Sub-humid
Station 4	**Esentepe**	35°.29N	33°.35E	217.0	446	1051	Sub-humid
Station 5	**Guzelyurt**	35°.11N	32°.59E	48.4	286	1044	Semi-arid
Station 6	**Lefkosa**	35°.11N	33°.21E	31.0	301	1066	Semi-arid
Station 7	**Ercan**	35°.09N	33°.29E	115.2	311	1065	Semi-arid
Station 8	**G.Magusa**	35°.07N	33°.56E	2.0	334	1062	Semi-arid
Station 9	**Y.Erenkoy**	35°.32N	34°.11E	112.0	462	1057	Sub-humid

The proximity of northern part of Cyprus is 35°N and 33°E in the eastern Mediterranean region with a total catchment area of approximately 3,300 km^2. The long and narrow Kyrenia Range (maximum height 1,024 m) extending from west to east and lying parallel to Mediterranean Sea along the northern part of Cyprus, plays an important role in the occurrence of meteorological anomalies in the area.

The short autumn and spring seasons in October, April and May are typical characteristics of Cyprus climate (Price et al. 1999) generating long and dry with almost no cloud cover high temperatures during summers and cool and wet winters with frequent rainfall as low as 162.2 mm in 1995 and as high as 646.8 mm in 1934.

Starting with the first quarter of the century, available meteorological data indicates a general decrease in rainfall and incorporates an increase in the number of consecutive dry years extending to two or three, and sometimes up to four consecutive years. The average regional temperature distribution for Lefkosa, G. Magusa, Girne, Guzelyurt and Iskele is estimated as 19.3^{0}C, 19.8^{0}C, 19.9^{0}C, 18.8^{0}C and 19.2^{0}C, respectively. Similarly, in these regions the variation in relative humidity is 63, 70, 69.3, 69 and 68.4%, respectively (Elkiran, 2010).

In the northern part of Cyprus precipitation in the form of rainfall is the only source that replenishes the water sources. The average annual rainfall is about 518 mm with more than 60% of rainfall taking place during winter. However, statistical analysis of monthly average rainfall data for the years of 1900-2014 over the northern part of Cyprus reveals that on average, there is a decreasing trend. Figure 2.2 (a) depicts the average annual and 10-year moving average precipitation from the beginning of the 1900s for the island and the comparison of it with the average annual precipitation between 1977 and 2013 for the stations considered in this study. The 10-year moving average was 536.7 mm before it reduced to 385.2 mm within the last 10 years. Meanwhile, there is not a strong relationship between the 100 years average precipitation from 1977 to 2013 with the average of each station during this period (Figure 2.2 (b)). The correlation coefficient varies between 0.26 and 0.45 with maximum correlation of coefficient obtained for Alsancak station.

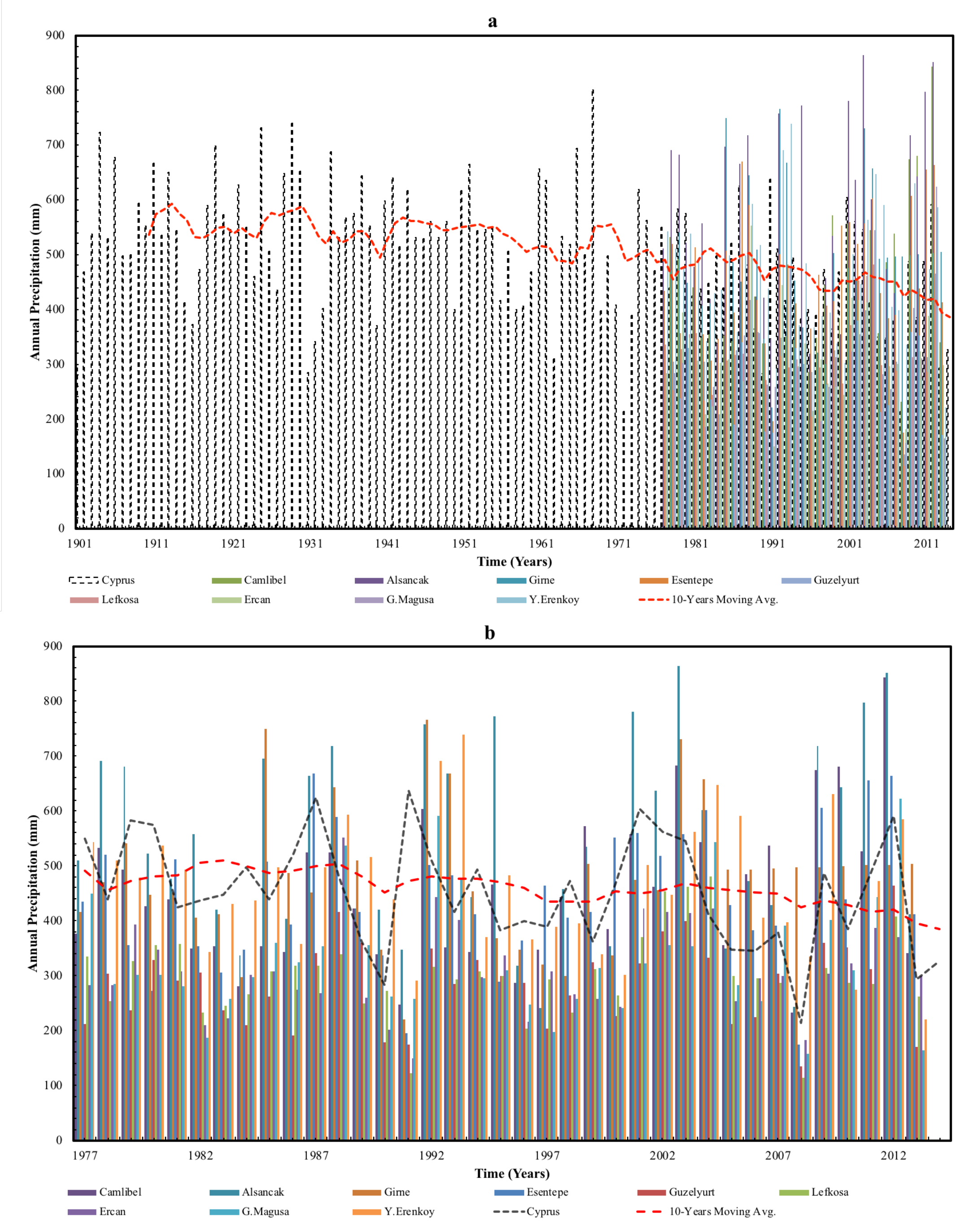


Figure 2.2: a) Decreasing trend of yearly precipitation of northern part of Cyprus. The trend shows 10 years moving average of 114 years of annual average precipitation and **b)** comparison of 100 years average precipitation from 1977 to 2013 with the average of each station during this period.

Similar to other Eastern Mediterranean countries, the northern part of Cyprus suffers from decreasing trends of precipitation in which existing water supplies continue to decline, while the demand for those supplies continues to grow (Jamal and Türker, 2015; Türker et al. 2013; Ergil, 2000). Prolonged absence of the replenishment of water resources is linked with climate changes and its consequences such as decreasing rates of precipitation levels and enhanced water demand rates due the inefficiencies identified in the agricultural sector.

Several studies related to climatological variables of the northern part of Cyprus are conducted based on hydro-climatological variations and trends, intensity curves and annual and seasonal trend patterns of climate change (Seyhun and Akıntug 2013; Sharifi, 2006; Akıntug and Baykan 2000). The outcomes of all previous studies and observations indicate that the main requirement for northern part of Cyprus is sustainable, holistic management of water demand to match, or preferably conserve, existing supplies for the survival of water resources. However, before holistic management, an understanding, monitoring and evaluating period should be made in order to identify the drought conditions in time and space. Classifying drought levels through means of indices, is fundamental to a wide range of environmental concerns with respect to the availability of water.

2.2.2 Methods of Analysis

Initially, statistical analysis was performed to investigate the quality, independence, randomness, homogeneity of the data and to detect the significant trends of the time series. Spearman's independence test, Spearman's randomness test and double mass curve analysis were useful for the independence, randomness and the homogeneity analysis (Spearman, 1904; Kohler, 1949). Non-parametric Mann-Kendall test was used to detect annual and seasonal trends of the meteorological time series data (Kendall, 1948). The magnitude of trends related to rainfall and temperature was determined by the linear regression method. The drought analyses were performed by Standardized Precipitation Index (SPI) and the Reconnaissance Drought Index (RDI).

Mann-Kendall Trend Test

In recent years, much research has been conducted to detect possible climate trends in order to better understand the variation in climate averages. Since extreme conditions such as drought, is directly linked to climate changes, it is important to analyze and evaluate the existence of possible trends in climatic variables such as temperature and precipitation. Therefore, the non-parametric Mann-Kendall trend test, at a significance level of 5% was used (Kendall, 1975; Mann, 1945). The trend slope was identified accordingly using linear regression method. The null hypothesis (H_o) of the test was to accept that there was no trend in precipitation over time, whereas the alternate hypothesis (H_1) was that there has been either increasing or decreasing trends in precipitation over the time. The Mann-Kendall statistic, S can be calculated as

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign(x_j - x_k) \tag{2.1}$$

where, n is the sample size, x_j and x_k are the data values in the time series j and k, respectively with the condition of $j > k$. The term $sign(x_j\text{-}x_k)$ is a sign function which can be computed as

$$sign(x_j - x_k) = \begin{cases} 1 & if \quad x_j - x_k > 0 \\ 0 & if \quad x_j - x_k = 0 \\ -1 & if \quad x_j - x_k < 0 \end{cases} \tag{2.2}$$

S is an indicator of an increasing or decreasing trend. When *S* is positive it indicates increasing trend, whereas negative value shows decreasing trend. However, it is necessary to calculate the probability associated with *S* and the sample size, *n*, to statistically quantify the significance of the trend. The procedure to calculate this probability is defined by the standardized test statistics, *Z* which is defined as follows.

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} & if \quad S < 0 \end{cases} \tag{2.3}$$

in which the variance of *S*, is given by

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p (t_p - 1)(2t_p + 5) \right] \tag{2.4}$$

where, t_p is the number of ties for p^{th} value, and q is the number of tied values. Positive Z values indicate an upward trend in the hydrologic time series and negative Z values indicate a negative trend.

Computation of Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI) expresses the actual rainfall as a standardized departure from the rainfall probability distribution function. This index has gained importance in recent years as a potential drought indicator since it permits comparisons across time and space (Kumar et al. 2009). The Standardized Precipitation Index (SPI) is developed by McKee et al. (1993) as a tool to monitor and analyze droughts. SPI is calculated by fitting long term precipitation to a probability distribution and afterwards it is normalized. Thorn (1966) found that the gamma distribution fits well to the climatological precipitation time series. The gamma distribution is defined by its probability distribution function (PDF) (Gocic and Trajkovic, 2013; Edwards and McKee, 1996):

$$g(x) = \frac{1}{\beta^{\alpha}.\Gamma(\alpha)} x^{\alpha-1}.e^{-\frac{x}{\beta}}, \qquad x > 0 \tag{2.5}$$

where α and β are the shape and scale parameters, x the precipitation quantity and $\Gamma(\alpha)$ the gamma function, defined by the following equation:

$$\Gamma(\alpha) = \int_0^\infty y^{\alpha-1}.e^{-y}dy \qquad (2.6)$$

The α and β parameters of the gamma probability distribution function are estimated for each station, for each timescale of interest (3-months, 6-months, 12-months, etc.) and for each months of the year.

There are several techniques which can be used to determine the parameters such as the graphical method, the least square method, the method of moments, the maximum likelihood method, the method of probability-weighted moments, and the method of L-moments. In this study the maximum likelihood approach is used as it is one of the most efficient and widely used approach to optimally estimate α and β (Thom, 1958). The sampling variance of the parameters produced by this method is the smallest as well as the variance of quantiles. Under this method, the α and β parameters are determined as:

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \qquad (2.7)$$

$$A = ln(\bar{x}) - \frac{\sum_{i=1}^{n} ln(x_i)}{n} \qquad (2.8)$$

$$\beta = \frac{\bar{x}}{\alpha} \qquad (2.9)$$

where *n* is the number of precipitation observations, $\bar{x}$ is the mean precipitation over the timescale of interest. The resulting parameters are then used to find the cumulative probability of an observed precipitation event for the given months and time scale for the station under consideration. The cumulative probability is given by:

$$G(x) = \int_0^x g(x)dx = \frac{1}{\beta^\alpha.\Gamma(\alpha)}\int_0^x x^{\alpha-1}.e^{-\frac{x}{\beta}}dx \qquad (2.10)$$

From equation (2.10), by letting *x/β* be equal to *t*, this equation then reduces to the incomplete gamma function:

$$G(x) = \frac{1}{\Gamma(\alpha)} \int_0^x t^{\alpha-1}.e^{-t}dt \quad (2.11)$$

Since the gamma function is undefined when x=0 and it is normal for precipitation distribution to contain zero values, the cumulative probability distribution function becomes:

$$H(x) = q + (1 - q)G(x) \quad (2.12)$$

where q shows the probability of precipitation with zero value. If m represents the number of zeros in precipitation time series and n be the total number of observations then:

$$q = \frac{m}{n} \quad (2.13)$$

The cumulative probability, $H(x)$, is then transformed to the standard normal random variable Z with mean zero and variance of one, which is the value of the SPI. SPI values can be easily obtained using the following equations (Gocic and Trajkovic, 2013; Edwards and McKee, 1997):

$$Z = SPI = -\left(t - \frac{c_0+c_1t+c_2t^2}{1+d_1t+d_2t^2+d_3t^3})\right), \quad 0.0 < H(x) \leq 0.5 \quad (2.14)$$

$$Z = SPI = +\left(t - \frac{c_0+c_1t+c_2t^2}{1+d_1t+d_2t^2+d_3t^3})\right), \quad 0.5 < H(x) \leq 1.0 \quad (2.15)$$

where,

$$t = \sqrt{ln\left(\frac{1}{(H(x))^2}\right)}, \quad 0.0 < H(x) \leq 0.5 \quad (2.16)$$

$$t = \sqrt{ln\left(\frac{1}{(1-H(x))^2}\right)}, \quad 0.0 < H(x) \leq 1.0 \quad (2.17)$$

The coefficients c_0, c_1, c_2, d_1, d_2, and d_3 are all constants and previously assigned as, c_0 = 2.515517, c_1= 0.802853, c_2 = 0.010328, d_1 = 1.432788, d_2 = 0.189269, and d_3 = 0.001308.

Computation of Reconnaissance Drought Index (RDI)

The Reconnaissance Drought Index (RDI) is calculated using precipitation and potential evapotranspiration (PET) (Tsakiris et al. 2005). RDI is calculated in three forms, the initial value (α_k), the normalized form (RDI_n) and the standardized form (RDI_{st}).

The initial value α_k of RDI is calculated for the i-th year in a time basis of k (monthss) as follows:

$$\alpha_k{}^{(i)} = \frac{\sum_{j=1}^{k} P_{ij}}{\sum_{j=1}^{k} PET_{ij}}, \;\; i = 1(1)\, N \, and \, j = 1(1) \qquad (2.18)$$

in which P_{ij} and PET_{ij} are the precipitation and potential evapotranspiration of the *j-th* months of *i-th* year respectively, and *N* is the total number of the years. The normalized form (RDI_n) is computed using the following equation:

$$RDI_n{}^{(i)} = \frac{\alpha_k^{(i)}}{\bar{\alpha}_k^{i}}, \;\; i = 1(1)\, N \, and \, j = 1(1)k \qquad (2.19)$$

where, $\bar{\alpha}_k^{i}$ is the arithmetic mean of $\alpha_k^{(i)}$. The work carried out by Tikgas (2008) and Tsakiris et al. (2008) has shown that the values of $\alpha_k^{(i)}$ follow both lognormal and gamma distribution satisfactorily. As such in order to calculate the standardized form of RDI (RDI_{st}), gamma distribution is used in a similar way as that of SPI. The steps taken to obtain the standardized form of RDI (RDI_{st}) are similar to that of SPI as explained in previous section from equation (2.5) through equation (2.17). After standardizing the probability distribution function for both SPI and RDI_{st}, the drought severity values are classified as shown in Table 2.2 (McKee et al. 1993; Tsakiris and Vangelis, 2005). In order to quantify the magnitude of droughts in the northern part of Cyprus, in this study, drought is analyzed and assessed by computing 3, 6 and 12-months timescales for both SPI and RDI (SPI_3, RDI_3; SPI_6, RDI_6 and SPI_{12}, RDI_{12})

values. Note that the subscripts indicate the timescales.

Table 2.2: Drought classification of SPI and RDI.

Wet category		**Dry category**	
SPI & RDI values	**Category**	**SPI & RDI values**	**Category**
2.00 +	Extremely Wet	- 0.99 to 0.00	Normal Drought
1.50 to 1.99	Very Wet	- 1.00 to - 1.49	Moderate Drought
1.00 to 1.49	Moderately Wet	- 1.50 to - 1.99	Severe Drought
0.00 to 0.99	Normal Wet	- 2.00 and less	Extreme Drought

In order to proceed with RDI analysis, the knowledge of potential evapotranspiration is necessary. There are different approaches that are in use to estimate the potential evapotranspiration (PET). The calculation methods for these approaches are generally divided into three main categories: hydrologic or water balance methods, analytical methods based on climate variables and empirical estimates (Vangellis et.al, 2013). The empirical methods such as Hargreaves, Thornthwaite and Blaney-Criddle methods are popular and are widely used around the world because of their simplicity and where data are scarce. Therefore, in this study Thornthwaite approach to calculate the PET for the analysis of RDI is selected. Though, the Thornthwaite method is over simplified as it uses only mean temperature in the calculation, it is revealed that the choice of PET calculation method does not influence the result of drought estimation particularly in coastal semiarid (Mediterranean) climatic conditions. (Vangellis et.al, 2013).

2.3 Results and Discussions

2.3.1 Summary of Statistical Parameters

The analyses on the annual precipitation of nine selected stations located at different regions during the period 1977-2013 show that the minimum precipitation was observed at Lefkosa as 114.74 mm and the maximum was 864.60 mm detected in

Alsancak. The mean annual precipitation ranged from 285.95 mm to 546.23 mm. The annual precipitation variation across all regions during the observed period was reasonably similar. The highest rate of the coefficient of variation was 33.51%, detected at G.Magusa and the lowest was 25.22%, detected at Lefkosa. The coefficient of skewness indicated smaller values between the observed data. Camlibel, Girne, Ercan and G.Magusa have shown that they are moderately skewed as the coefficient of skewness for these regions were between +1/2 and +1. The rest of the regions were approximately skewed with the coefficient of skewness between -1/2 and +1/2. The mean annual temperature varied from 18.59 ^{o}C to 20.25 ^{o}C. The minimum average temperature was 16.46 ^{o}C and the maximum was 22.09 ^{o}C, being detected at Camlibel and Alsancak, respectively. In terms of the coefficient of variation, Y.Erenkoy showed the highest rate of 5.10% and Ercan the lowest rate of 3.13%. The coefficient of skewness results indicated that Camlibel, Alsancak, Esentepe, Guzelyurt and G.Magusa were moderately skewed while the rest of the regions were approximately skewed.

The station-based minimum (min), maximum (max) and mean annual monthly distribution of precipitation is shown in Figure 2.3. The annual monthly temporal fluctuation is given in Appendix A. As can be shown from the figure, the shape of the distribution is concave upward as the maximum amount of precipitation falls between the months of November and February. Generally, the highest rainfall occurs during the month of December. The maximum December rainfall was 467.5 mm in Alsancak. In January the maximum observed rainfall was 377.1 mm in Y.Erenkoy.

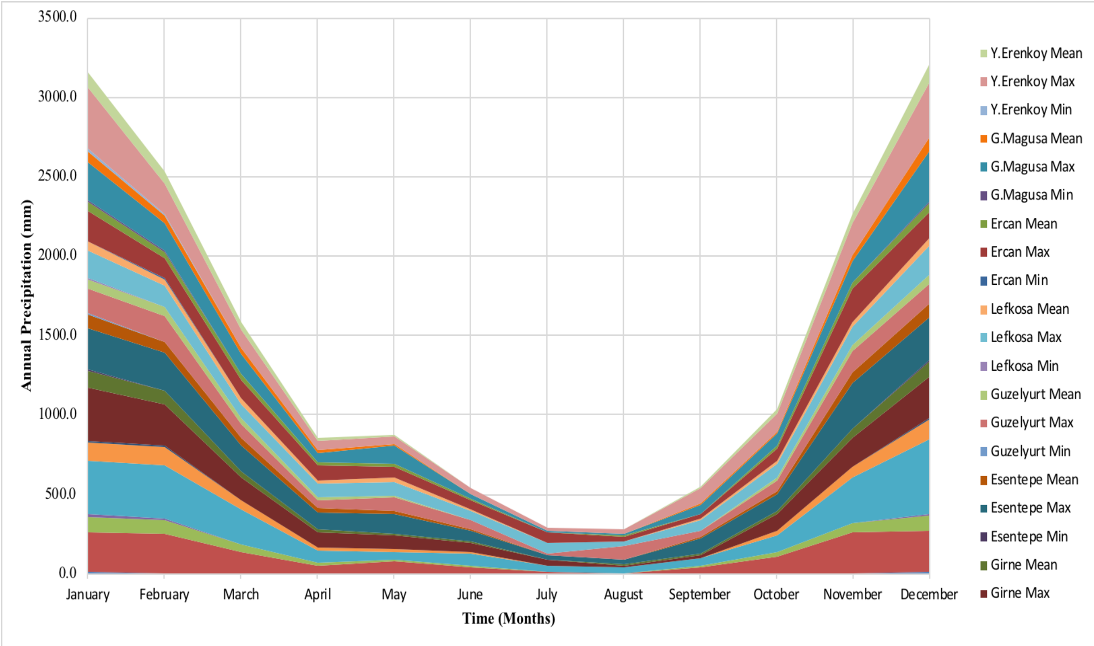


Figure 2.3: The minimum (min), maximum (max) and mean annual monthly distribution of precipitation.

2.3.2 Trend Analysis

Table 2.3 shows the annual and seasonal precipitation trends obtained by statistical tests at nine regions during the period 1977-2013. Based on the achieved results, only Camlibel (Z^*=1.74) and Esentepe (Z^*=1.66) followed an increasing trend for precipitation while the rest of the regions in their annual value, revealed no significant increasing or decreasing trends. The Mann-Kendal test results were close to null. On seasonal basis, during spring Girne and Y. Erenkoy showed a significantly negative trend with slope -0.99 mm per year and -1.04 mm per year, respectively. During fall, only Camlibel showed a significant positive trend with a positive slope of 2.18 mm per year, whereas during the winter season no trend was detected. However, during the summer season, a significant increasing trend was observed in all regions with the highest slope of 1.77 mm per year at Ercan. The Mann-Kendal trend test indicates that the annual and seasonal trends in precipitation do not follow significant changes. Even though the situation remains quite stationary the occurrences of high rainfall rates that are recorded over a short period of time has changed the consequences of precipitation and extraordinary river floods are experienced (Şahin et al. 2013).

Table 2.3: Results of statistical test for annual and seasonal precipitation based on nine stations located at different regions during the period 1977-2013.

Regions	Annual		Spring		Summer		Fall		Winter	
	Z*	b** (mm/year)	Z	b (mm/year)	Z	b (mm/year)	Z	b (mm/year)	Z	b (mm/year)
Camlibel	1.74	4.66	0.07	0.05	6.59	0.72	2.60	2.18	1.10	3.34
Alsancak	0.41	1.31	-0.83	-0.54	6.77	1.23	0.91	1.29	-0.42	0.78
Girne	-0.07	-0.19	-1.73	-0.99	7.93	1.49	0.61	0.75	-0.48	0.32
Esentepe	1.66	2.18	-1.05	-0.51	7.70	1.41	0.94	1.06	0.69	1.58
Guzelyurt	0.80	1.06	1.47	0.51	7.22	1.01	0.61	0.24	0.72	1.31
Lefkosa	-0.14	0.65	-0.61	-0.18	8.13	1.59	0.46	0.21	0.15	0.19
Ercan	0.59	0.85	-0.29	-0.10	8.44	1.77	0.83	0.34	0.56	0.31
G.Magusa	0.38	0.88	0.23	0.23	7.54	0.49	1.13	0.34	0.50	1.04
Y.Erenkoy	-0.95	-1.58	-1.76	-1.04	6.77	0.75	-0.69	-0.25	0.18	0.46

*Z: Mann-Kendall test.
** b: Slope of linear regression.

The temperature trend analysis shown in Table 2.4 revealed that Alsancak, Girne, Guzelyurt, G.Magusa, and Y.Erenkoy demonstrated an increasingly significant trend with slope 0.04, 0.06, -0.01, 0.01 and 0.04 ^{o}C per year, respectively. On a seasonal basis, a significant trend was detected in Alsancak, Girne and Y.Erenkoy during the spring season. Alsancak, Girne, Esentepe and Y.Erenkoy revealed a significant trend during fall, whereas, Girne and Y.Erenkoy followed a significantly positive trend during winter. However, during the summer season with the exception of Camlibel and Esentepe, the remaining stations demonstrated a significant increasing trend with the highest slope of 0.07 ^{o}C per year occurring in Alsancak. The reason for occurrences of high rainfall over a short period of time, whilst experiencing increasing trends in temperature around the Mediterranean basin is defined by Rigo and Llasat (2004). According to their study, intersection between the tip of a warm-wet flow and a thermal-humidity boundary is the most likely place for attaining or releasing the convective instability and for the development of large convective clouds that produce high rainfall within a short period of time.

Table 2.4: Results of statistical test for annual and seasonal average temperature over based on nine stations located at different regions during the period 1977-2013.

Regions	**Annual**		**Spring**		**Summer**		**Fall**		**Winter**	
	Z*	**b** ** (^{0}C/year)	**Z**	**b** (^{0}C/year)	**Z**	**b** (^{0}C/Year)	**Z**	**b** (^{0}C/year)	**Z**	**b** (^{0}C/year)
Camlibel	0.61	0.00	0.59	0.00	0.80	0.01	-0.42	0.00	-0.11	-0.01
Alsancak	3.31	0.04	1.91	-0.54	3.50	0.07	3.47	0.05	0.65	0.02
Girne	4.09	0.06	2.77	0.05	3.73	0.06	3.95	0.08	2.94	0.06
Esentepe	1.37	0.02	0.56	0.01	1.42	0.02	1.76	0.03	0.15	0.01
Guzelyurt	1.70	-0.01	0.20	-0.01	2.82	0.01	0.57	0.00	-0.89	-0.02
Lefkosa	1.01	0.01	0.25	0.00	2.67	0.02	1.01	0.02	-0.53	-0.01
Ercan	1.02	0.00	0.01	-0.01	2.14	0.02	0.35	0.01	-1.17	-0.01
G.Magusa	2.24	0.01	-0.35	-0.01	2.00	0.01	1.19	0.02	0.22	0.01
Y.Erenkoy	3.06	0.04	2.18	0.06	2.54	0.05	2.81	0.05	2.03	0.04

*Z: Mann-Kendall test.
** b: Slope of linear regression

2.3.3 Comparison of Indices

The short (3-months timescales, RDI_3 and SPI_3), medium (6-months timescales, RDI_6 and SPI_6) and long-term drought (12-months timescales, RDI_{12} and SPI_{12}) between RDI and SPI are analyzed and compared with respect to correlation coefficient and Root Mean Square Error (RMSE) for each station within the study area. The assessment is essential to understand the sensitivity and robustness of these indices to different timescale and the choice of a drought index. The obtained results depicted in Table 2.5 indicate that difference between RDI and SPI in terms of detecting occurrence of drought at different timescale is statistically insignificant. Overall, the correlation coefficient for all the stations and timescales is approximately 1.0, signifying the fact that both of these indices are well suited and adapted at different timescale to the climatic condition in the study area. However, the strength in the similarity between RDI and SPI reduces as the time scale increases. This can be possibly due to lower variation in precipitation during the short and medium term while higher variation during the long term which include the summer months. It can be also referred to the fact that during long term the effect of PET which depends on temperature prevail itself as during the summer months the weather gets more drier. As can be observed, the correlation coefficient had a decrease while RMSE had an increase with an increase in timescale. The highest correlation coefficient and lowest RMSE between RDI_3 and SPI_3 were 1.000 and 0.023, respectively. In terms of RDI_6 and SPI_6, the highest correlation coefficient was 0.999 with a RMSE of 0.052. On the other hand, the highest correlation coefficient between RDI_{12} and SPI_{12} is detected as 0.998 with a corresponding RMSE of 0.065.

The difference between RDI and SPI at different timescale can also be spotted among the stations located in different climatic conditions. Though the difference in short and medium term is insignificant, it becomes more visible at long term. The correlation coefficient between RDI and SPI at long term in Lefkosa and Ercan which have much drier climate than the rest of the stations located in different regions of northern part of Cyprus, is 0.996 and 0.995, respectively. Similarly, the corresponding RMSE for these two stations is 0.093 and 0.102, respectively.

Table 2.5: Correlation coefficient and RMSE between RDI and SPI at different time scales.

Stations	Time Scale					
	3-Months		6-Months		12-Months	
	Correlation Coefficient	RMSE	Correlation Coefficient	RMSE	Correlation Coefficient	RMSE
Camlibel	0.999	0.033	0.998	0.070	0.997	0.077
Alsancak	1.000	0.030	0.998	0.069	0.997	0.074
Girne	0.999	0.033	0.998	0.063	0.997	0.076
Esentepe	0.999	0.037	0.999	0.052	0.997	0.077
Guzelyurt	0.999	0.038	0.998	0.058	0.997	0.081
Lefkosa	0.999	0.038	0.998	0.057	0.996	0.093
Ercan	0.999	0.037	0.999	0.048	0.995	0.102
G.Magusa	1.000	0.023	0.999	0.052	0.998	0.065
Y.Erenkoy	0.999	0.036	0.998	0.060	0.997	0.071

The comparison between RDI and SPI at different timescale is also performed by grouping the occurrence of different severity level of drought in the time series based on their drought categories. Figure 2.4 shows the mean rate of occurrence of drought in different timescales for moderate, severe and extreme drought. Both RDI and SPI at different timescales detected the occurrence of these drought classes at different rate. However, the difference in rate between RDI and SPI for the same category and timescale is statistically insignificant. The rate of occurrence of moderate drought for any timescale detected by RDI (RDI_3=8.95%, RDI_6=8.02% and RDI_{12}=8.33%) was slightly higher than SPI (SPI_3=8.02%, SPI_6=7.41% and SPI_{12}=6.48%). On the other hand, though both RDI and SPI showed the same rate of occurrence (5.56%) in 12-months timescales, rate of occurrence of RDI in 3 and 6-months timescales (RDI_3 and RDI_6=5.56%) was lower than SPI (SPI_3=5.86% and SPI_6=6.81%). The rate of occurrence of extreme drought for RDI at any timescale (RDI_3=2.47%, RDI_6=4.01% and RDI_{12}=2.78%) was also slightly lower as compared to SPI (SPI_3=2.78%,

SPI_6=4.03% and SPI_{12}=3.70%). As can be noticed, the rate of occurrence detected by SPI for sever and extreme drought increased from short term to medium term and decreased at long term. RDI revealed, the same pattern for extreme drought, however, for severe drought the rate always remained the same. On the other hand, the pattern for moderate drought was different and both RDI and SPI behaved similarly. The rate decreased while moving from short term to medium term and increased in the long term.

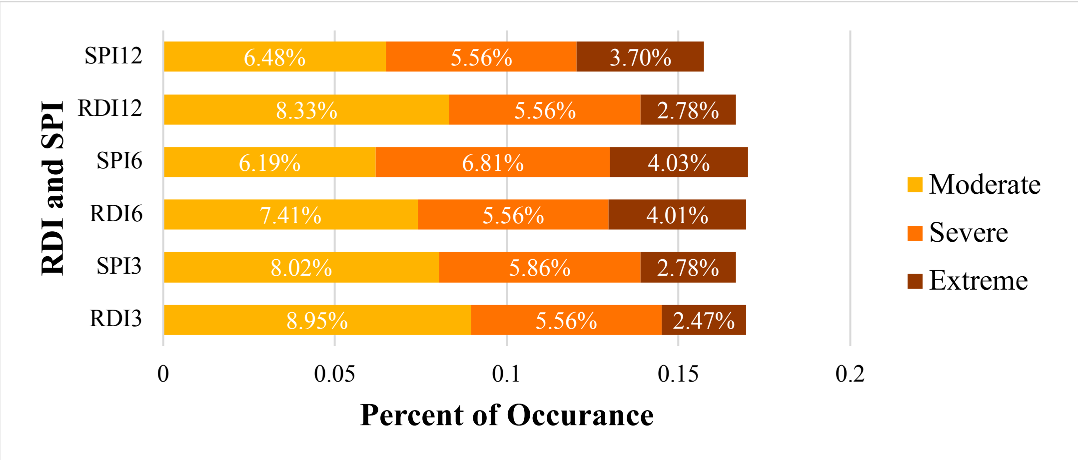


Figure 2.4: Mean rate of occurrence of different categories of drought at different timescale.

In the study area, all the stations confirmed to be affected by frequent occurrence of drought. However, the rate of occurrence of drought detected by both RDI and SPI depending upon spatial heterogeneity of hydro-meteorological and climatological characteristics of each location, changes from one station to another. In short term, Guzelyurt (Figure 2.5) suffered the highest rate of occurrence of moderate drought provided by both RDI and SPI (RDI_3=19.44% and SPI_3=16.67%). For severe drought the highest rate is detected in Ercan and Y.Erenkoy (RDI_3 and SPI_3=11.11%) while for extreme drought the highest rate is perceived in Lefkosa and Esentepe (RDI_3 and SPI_3=5.56%). In medium term, for moderate drought RDI and SPI showed the highest rate in Y.Erenkoy (RDI_6=13.89%) and Camlibel (SPI_6=11.11%), respectively. In terms of severe drought both RDI and SPI demonstrated same rate (8.33%). The stations affected by this rate for RDI are Alsancak, Guzelyurt and G.Magusa while for SPI the stations are Alsancak, Girne, Guzelyurt, G.Magusa and Y.Erenkoy. Meanwhile, both RDI and SPI confirmed the occurrence of same rate of extreme drought (5.56%) in Girne, Esentepe and Ercan and Lefkosa though in Lefkosa the rate was slightly higher for SPI (SPI_6=5.71%). In long term, the observed (actual) highest rate shown by RDI for moderate (11.11%), severe (8.33%) and extreme (5.71%) drought was in Camlibel, Ercan, and Y.Erenkoy; Esentepe; Girne, G.Magusa and Y.Erenkoy, respectively. The highest rate detected by SPI for moderate drought (11.11%) was in Camlibel, Guzelyurt and Y.Erenkoy. For severe drought G.Magusa and Y.Erenkoy showed the highest rate (11.11%) while Alsancak, Girne, Esentepe and Ercan revealed the highest rate (5.56%) for extreme drought.

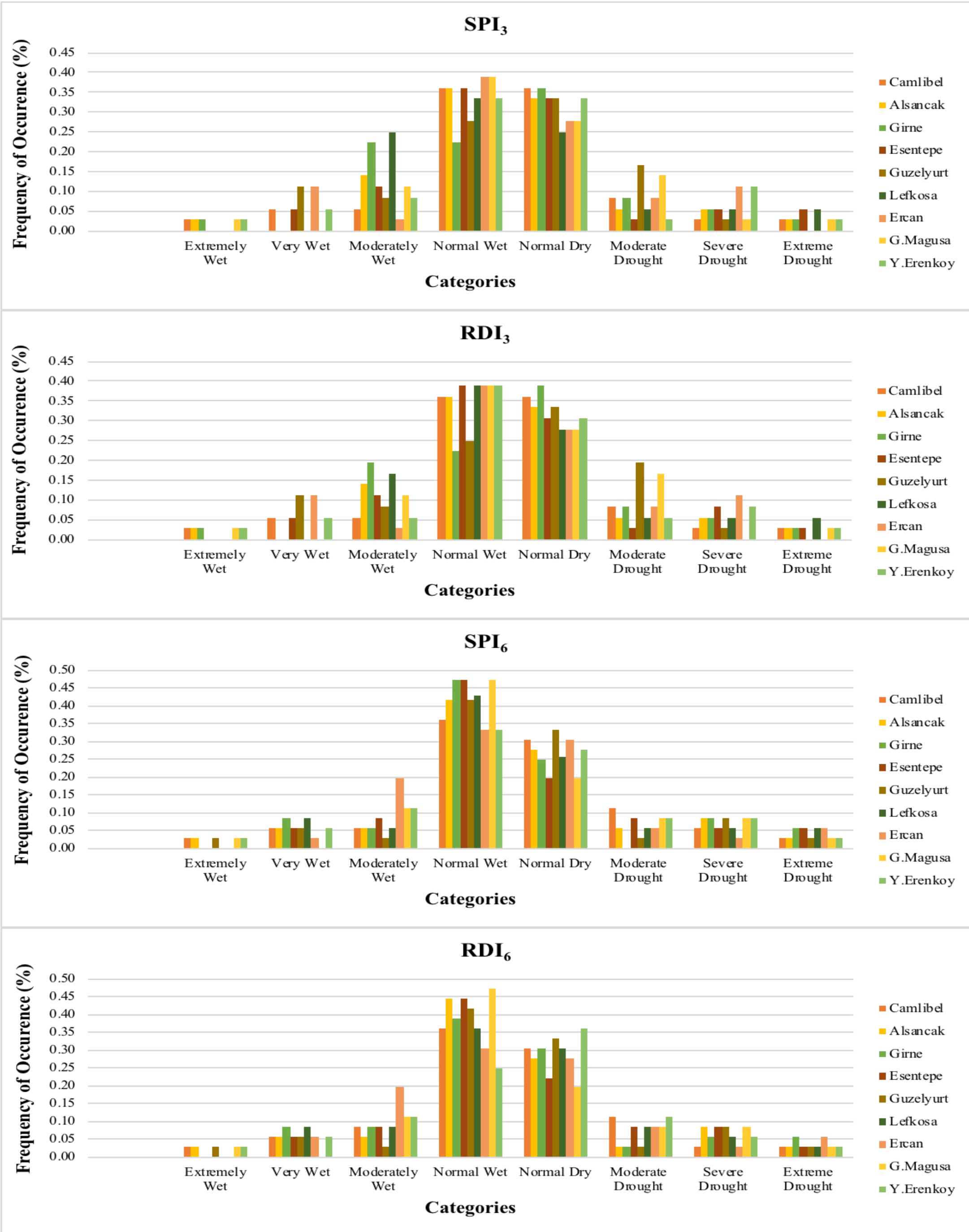
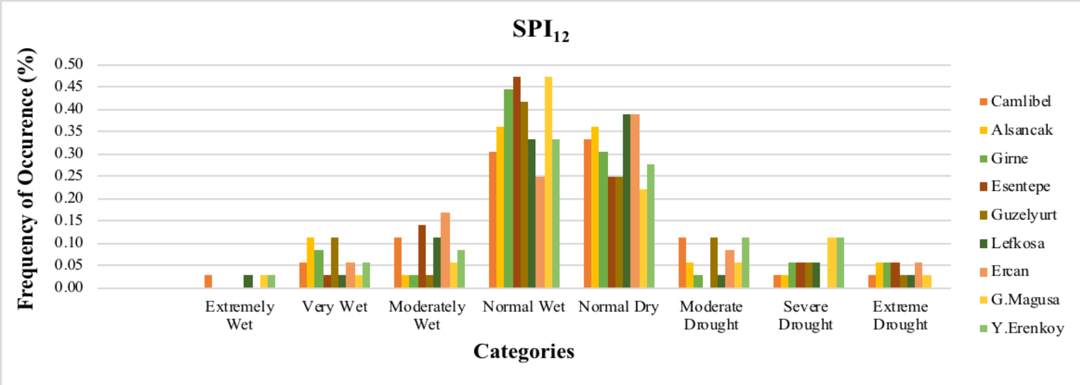


Figure 2.5: Frequency of occurrence of drought at different timescales and locations.



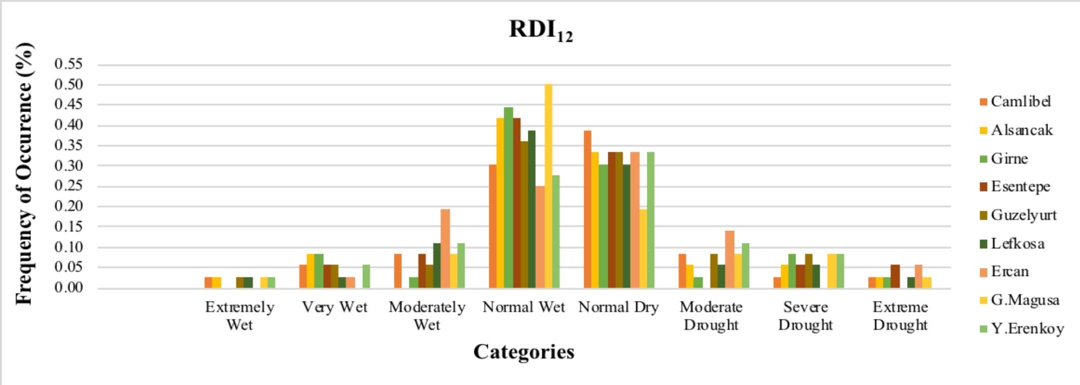


Figure 2.5 (continued): Frequency of occurrence of drought at different timescales and locations.

2.3.4 Drought Characteristics

Frequent occurrence of droughts in the northern part of Cyprus has caused adverse impacts on agriculture, water resources, the economy, social life and the environment. During the period of 1977-2013 on 12-months timescales considering only the result of SPI index (SPI_{12}, October-September), the northern part of Cyprus practically suffered from three major long duration drought events. This is illustrated in Figure 2.6 which depicts SPI_3 (October-December), SPI_6 (October-March) and SPI_{12} (October-September) at nine regions for the observed period 1977-2013. The 12-months' timescale drought events were between 1981-1985, 1995-1999 and 2005-2009. The drought spells recorded were between 8 and 11 spells and the duration of drought events or episodes were normally between 1 and 2 years. However, drought episodes occurring between 3 and 5 years, were also recorded in almost all the regions.

In terms of drought category and severity values, the analysis of SPI_{12} revealed that most of the regions provided evidence on three common years of severe to extreme drought occurrence in the northern part of Cyprus. Based on a 12-months' timescale, extreme drought took place between the years 2007-2008. During that period, the average severity value of more than 5 regions over nine regions was -2.22. The corresponding average precipitation for this severity level was found to be 170 mm per year. Severe drought took place between the years 1996-1997 and 1994-1995 with average severity values of -1.69 and -1.89, respectively. The average precipitation for these two periods was found to be 220 mm and 185 mm per year, respectively. Based on drought category, the considered region suffered moderate, severe and extreme droughts with average severity values of -1.20, -1.71 and -2.29, respectively. The corresponding average annual precipitation for these severity values were 245 mm, 205 mm and 165 mm, respectively. The temporal analysis of drought also revealed that not only the frequency of drought events has increased but also their severity has intensified. Considering the 12-months timescales drought provided by SPI, in 1980's, the highest severity detected was -2.29, in 1990's the severity was -2.31 while in the last decade the highest severity was -2.76. These findings indicate that all regions in the northern part of Cyprus suffered from meteorological drought which were usually followed by agriculture and hydrological drought. The year 2007-2008 that suffered the most extreme drought event, production of agricultural crops seriously reduced and the water storage at the dams declined significantly. In the southern part of Cyprus the water storage declined to 6.8% of the total capacity (Michaelides and Pashiardis, 2008). In this year, to cope with the water crisis the government imported water from Greece. Similarly, in the northern part of Cyprus, the 2007-2008 drought event beside having affected the water resources, it seriously reduced the production of agricultural crops particularly the rain-fed crops. This caused a twofold increase in the prices of wheat, barley and olive and the authorities had to increase its share of import to fulfil the consumers demand (ASP, 2008).

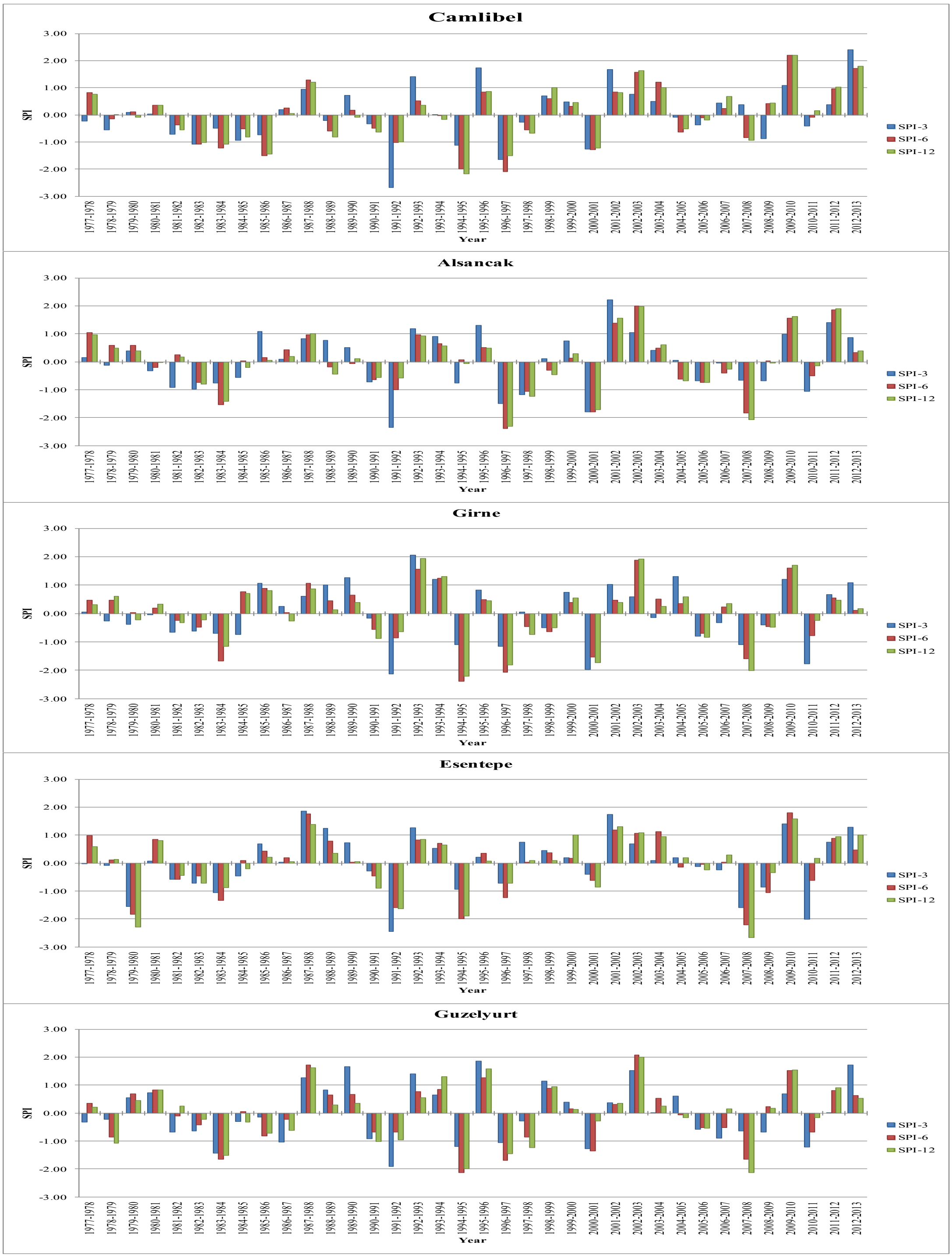


Figure 2.6: Standard Precipitation Index temporal values plotted for the timescales of 3, 6, and 12-monthss. The time duration of data is for the observed period of 1977-2013.

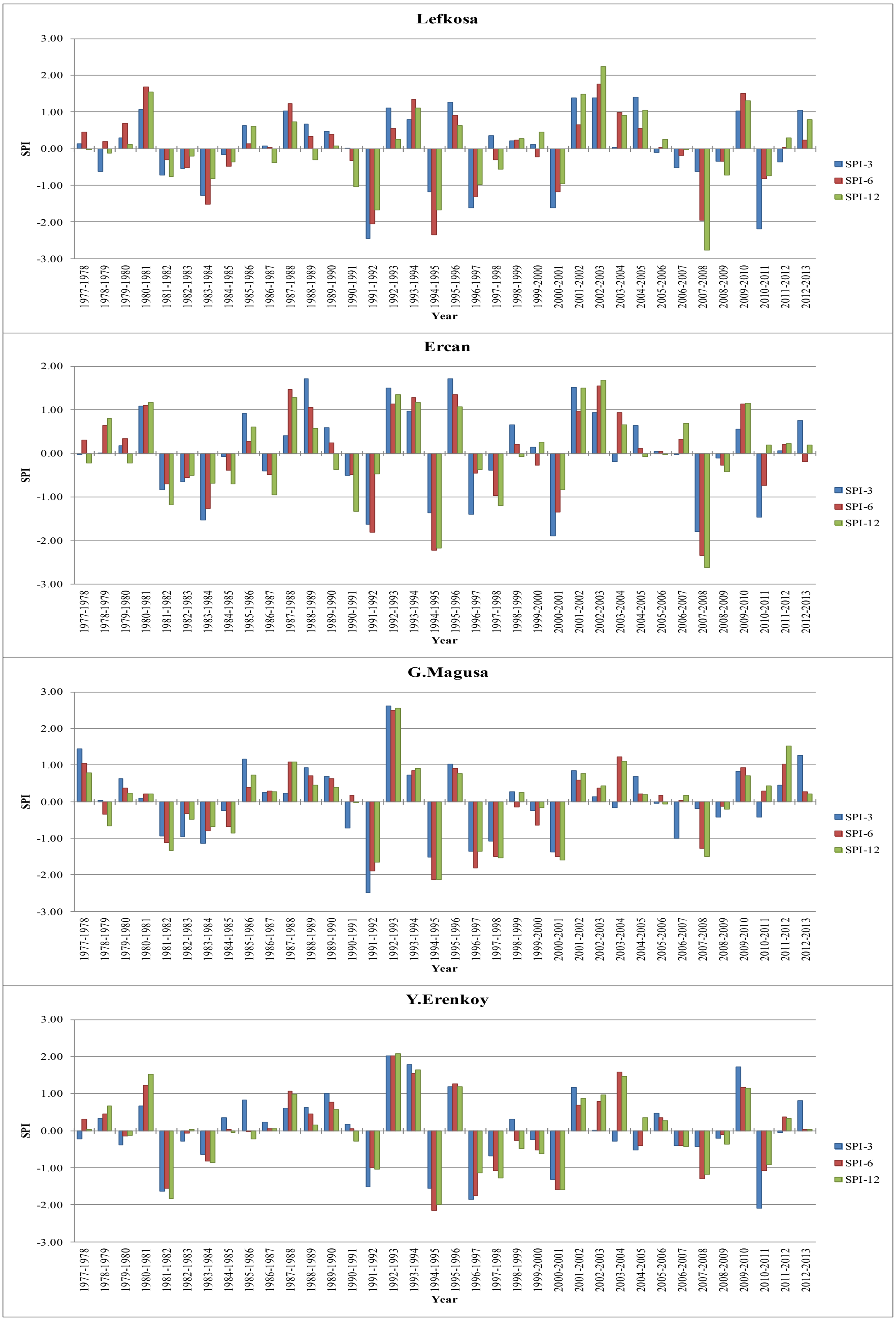


Figure 2.6 (continued): Standard Precipitation Index temporal values plotted for 3, 6, and 12-months timescales. The time duration of data is for the observed period of 1977-2013.

The occurrence and details of moderate to extreme drought events based on SPI_{12} (October-September) for all nine regions and the number of drought years during the observed period at these regions are presented in Table 2.6. According to the result, the total drought years for moderate to extreme droughts were between 4 and 8 years for the observed period. The most extreme drought took place over the years of 1994-1995, 1996-1997 and 2007-2008. Similarly, the duration of consecutive moderate, severe and extreme drought years for the observed period 1977-2013 for all regions based on SPI method are also given in Table 2.6. The two years consecutive drought took place between the years 1982-1984, 1990-1992, 1996-1998 and 2007-2009. The result also shows that the northern part of Cyprus did not experience consecutive, severe or extreme drought events at any region for the last 36 years. Considering all the regions, it is clear that only Y.Erenkoy has not experienced extreme droughts within the period of analysis. The regions situated in the western part of the studied area (Camlibel, Alsancak and Guzelyurt) are extremely influenced by the droughts.

Table 2.6: Drought occurrence and details over a 12-months' timescale for moderate to extreme drought events (October-September) between 1977-2013 in all nine stations (Mod=Moderate, Sev=Severe, Ext=Extreme and PPT=Precipitation).

Regions	**Drought Events**				**The Most Extreme Drought**			**Consecutive 2 Years Drought**	**Drought Years for 2 Years Drought**	
	Mod.	**Sev.**	**Ext.**	**Total**	**Year**	**SPI**	**Annual PPT. (mm)**			
Camlibel	4	1	1	6	1994-95	-2.12	207	1	1982-83	1983-84
Alsancak	2	1	2	5	1996-97	-2.48	202	1	1996-97	1997-98
Girne	1	1	3	5	1994-95	-2.18	195	0	-	-
Esentepe	2	2	2	6	2007-08	-2.59	133	1	2007-08	2008-09
Guzelyurt	5	2	1	8	2007-08	-2.28	132	2	1990-91	1991-92
									1996-97	1997-98
Lefkosa	2	2	1	5	2007-08	-2.86	99	1	1990-91	1991-92
Ercan	2	0	2	4	2007-08	-3.11	87	0	-	-
G.Magusa	3	3	1	7	1994-95	-2.11	131	1	1996-97	1997-98
Y.Erenkoy	3	3	0	6	-	-	-	0	-	-

2.3.5 Time Series Comparison of SPI Values

The analysis showed that each of the three different timescales have fairly strong relationship in characterizing drought events. The correlation coefficient between SPI_3 and SPI_6 was 0.88 while between SPI_3 and SPI_{12} was 0.77. Positively, an extremely high correlation was observed between SPI_6 and SPI_{12} which was equal to 0.95.

Similar to drought events given by SPI_{12}, SPI_3 and SPI_6 indicated major long duration drought events between 1981-1985, 1995-1999 and 2005-2009 are shown in Figure 2.6. However, in terms of drought spell and duration of drought episodes, a slight difference was detected among these time scales. As compared to SPI_{12} drought spell, the drought spell recorded by SPI_3 and SPI_6 were between 7 to 10 and 6 to 9, respectively. Even though the duration of drought episodes for all these timescales were between 1 and 2 years with few recorded events between 3 and 5 years, SPI-3 also showed 6 and 7 year's drought episodes. The agricultural sector of the northern part of Cyprus is vulnerable to such prolonged 3-months' timescale droughts since the majority of crops are planted in October and require effective rainfall up to January in order to grow to maturity.

2.3.6 Validation of the Results

The findings of the SPI and RDI analysis for the northern part of Cyprus can be validated through the drought occurrences detected by other researchers within other regions of the Mediterranean (Buttafuoco et al. 2015; Tsiourtis 2001). Consecutive two years droughts in Lefkosa and Guzelyurt match droughts experienced in Spain, Tunisia, Greece and Southern Italy in the period 1990-1992. The most extreme droughts experienced at Camlibel, Girne and G.Magusa were also experienced in Sardinia during the drought period 1994-1995. The Mediterranean basin suffered from the detrimental impacts of water scarcity and drought in the period 2007-2008. As a consequence of drought in Turkey, a number of lakes and wetlands dried up, extreme salt water intrusion was observed in Greece and in most of the European coastal aquifers (Buttafuoco et al. 2015; Tsiourtis 2001). In Cyprus and Catalonia only 20% of reservoir capacities were full supporting the findings of SPI analyses performed for drought periods in 2007-2008.

2.3.7 Timescale Related Drought Propagation Occurrence

Besides different characteristics of drought events such as severity level or duration, another important and helpful characteristic in drought assessment, as well as monitoring, is the understanding of how and by what level or percent drought propagates and develops from one timescale to another. This can be obtained by looking at common years of drought events in different time scales followed by setting one timescale as a reference timescale. The other timescales are then compared with respect to this reference timescale. As such by setting SPI_3 as a reference time scale, the analysis shown in Table 2.7 revealed that on average 79% of drought events of this reference scale developed into SPI_6's 6-months drought and 78% developed into SPI_{12}'s 12-months drought events. Similarly, by setting SPI_6 as a reference time scale, approximately 90% of drought events developed into SPI_{12}'s 12-months drought event. Moreover, based on this approach and taking the severity level of drought into consideration, as shown in Table 2.7, 45% (out of 79%) and 41% (out of 78%) of 3-months drought events developed into moderate to extreme drought events over 6 and 12-months timescales, respectively. Whereas, 40% (out of 90%) of a 6-months drought event developed into a 12-months moderate to extreme drought event.

Table 2.7: Drought propagation occurrence from one timescale into another.

Regions	Normal to Extreme Drought Propagation Occurrence			Moderate to Extreme Drought Propagation Occurrence		
	$SPI_3 \rightarrow SPI_6$	$SPI_3 \rightarrow SPI_{12}$	$SPI_6 \rightarrow SPI_{12}$	$SPI_3 \rightarrow SPI_6$	$SPI_3 \rightarrow SPI_{12}$	$SPI_6 \rightarrow SPI_{12}$
Camlibel	89%	78%	89%	44%	50%	44%
Alsancak	71%	88%	94%	50%	33%	33%
Girne	68%	74%	100%	38%	36%	36%
Esentepe	82%	76%	86%	50%	31%	33%
Guzelyurt	84%	79%	88%	31%	47%	47%
Lefkosa	80%	80%	87%	50%	25%	31%
Ercan	82%	82%	81%	36%	36%	38%
G.Magusa	71%	76%	93%	58%	54%	54%
Y.Erenkoy	83%	72%	88%	47%	54%	47%
Average	79%	78%	90%	45%	41%	40%

Drought propagation analysis also revealed three other important facts as well. Firstly, development of a 3-months drought into a 6-months drought showed that the percent development was higher (89% for Camlibel) compared to the development of a 3-months drought into a 12-months drought (78% for Camlibel). This was due to the fact that few years of 3-months' timescale droughts that had developed fully into 6-months' timescale droughts did not propagate and developed into 12-months' timescale droughts. This was only possible when the average 12-months precipitation of those specific few years were above the minimum threshold (to make the drought event possible) compared to 3-months and 6-months timescales where the average precipitation was below the minimum threshold. Secondly, the percent development of 3-months timescales droughts into 6-monthss was lower (71% for Alsancak) as compared to 3-months timescales droughts into 12-monthss (88% for Alsancak). This shows that few specific years of 3-months droughts developed into 12-monthss but these few specific years of 3-months droughts did not develop into 6-monthss. In this case, the average 6-months' timescale precipitation of those few specific years were above the minimum threshold compared to 3-months and 12-months timescales.

Lastly, the percent development of 3-months timescales droughts into 6-monthss (80% for Lefkosa) was equal to the percent development of 3-months timescales into 12-monthss (80% for Lefkosa). In this case, all drought years of 3-monthss fully propagated into 6 and 12-months timescales droughts revealing that the average precipitation level for all these timescales were below the minimum threshold resulting in the emergence of drought event.

2.3.8 Estimation of Critical Rainfall Range

For decision making purposes and monitoring of drought, it is also advantageous to know the range of critical rainfall values associated to each drought category. As such, an attempt was made to estimate these values for moderate, severe, and extreme drought conditions for 3, 6 and 12-months timescales. The range of these critical rainfall values were based on upper and lower limits of drought categories. The range for each drought category was estimated by putting the drought severity values of any specific year along with their observed rainfall values together and then linearly interpolating these values to obtain the lower and upper boundaries of the range similar to original SPI severity limits. Initially, the increased rate of rainfall between 3 and 6-months timescales, 3 and 12-months timescales and 6 and 12-months's was calculated as shown in Table 2.8. It was revealed that on average the rate of increase of rainfall from 3-months (October-December) to 6-months (October-March) was 154%, from 3-months (October-December) to 12-months (October-September) was 217% and from 6-months (October-March) to 12-months (October-September) was 25%. Meanwhile, Alsancak showed the highest rate of increase (194%) for 3 and 6months timescales, Lefkosa showed the highest rate of increase (271%) for 3 and 12-months timescales and Ercan showed the highest rate of increase (49%) for 6 and 12-monthss.

Table 2.8: Rate of increase of rainfall from one timescale into another under drought conditions.

Regions	$SPI_3 \rightarrow SPI_6$	$SPI_3 \rightarrow SPI_{12}$	$SPI_6 \rightarrow SPI_{12}$
		(%)	
Camlibel	150	180	12
Alsancak	194	249	19
Girne	168	232	24
Esentepe	137	195	24
Guzelyurt	159	211	20
Lefkosa	169	271	38
Ercan	144	264	49
G.Magusa	137	182	19
Y.Erenkoy	128	166	17
Average	154	217	25

The regional critical rainfall values for moderate to extreme drought conditions are shown in Table 2.9. It was found out that on 6 and 12-months timescales for moderate, severe, and extreme drought conditions Alsancak showed the highest critical rainfall range while Guzelyurt revealed the lowest. On the other hand, for 3-months timescales, Camlibel provided the highest critical rainfall range, whereas, Lekosa and Ercan showed the lowest range.

Another important finding, revealed in Table 2.9 was that the 6-months timescales moderate drought category critical rainfall range was almost equal to the range of the 12-months timescales severe drought category. Meanwhile, the upper boundary of the 6-months timescales severe drought category critical rainfall range was approximately equivalent to that of the lower boundary of 12-months's.

Table 2.9: Critical rainfall ranges for moderate to extreme drought conditions at considered stations. (a) SPI_3, (b) SPI_6 and (c) SPI_{12}.

a)

Regions	Drought Category		
	Moderate Drought	Severe Drought	Extreme Drought
	Precipitation Range (mm)	Precipitation Range (mm)	Precipitation Range (mm)
Camlibel	80-100	60-80	<60
Alsancak	75-100	50-75	<50
Girne	60-80	30-60	<30
Esentepe	55-80	40-55	<40
Guzelyurt	45-60	35-45	<35
Lefkosa	40-55	25-40	<25
Ercan	40-55	25-40	<25
G.Magusa	45-65	30-45	<30
Y.Erenkoy	85-100	60-85	<60

b)

Regions	Drought Category		
	Moderate Drought	Severe Drought	Extreme Drought
	Precipitation Range (mm)	Precipitation Range (mm)	Precipitation Range (mm)
Camlibel	230-280	185-230	<185
Alsancak	260-325	210-260	<210
Girne	215-260	170-215	<170
Esentepe	180-230	140-180	<140
Guzelyurt	135-165	110-135	<110
Lefkosa	120-150	95-120	<95
Ercan	115-145	85-115	<85
G.Magusa	140-180	110-140	<110
Y.Erenkoy	230-280	185-230	<185

c)

Regions	Drought Category		
	Moderate Drought	Severe Drought	Extreme Drought
	Rainfall Range (mm)	Rainfall Range (mm)	Rainfall Range (mm)
Camlibel	260-320	225-260	<225
Alsancak	310-370	255-310	<255
Girne	265-315	215-265	<215
Esentepe	240-290	190-240	<190
Guzelyurt	170-205	135-170	<135
Lefkosa	175-205	145-175	<145
Ercan	180-215	145-180	<145
G.Magusa	175-215	140-175	<140
Y.Erenkoy	285-335	240-285	<240

2.3.9 Influence of Precipitation and Potential Evapotranspiration on Drought Indices

Sustained low precipitation rates and high PET rates either individually or combinedly may lead to drought. A temperature rise is anticipated to cause an increase in PET which will lead possibly to longer and more severe and frequent droughts. Within this context, to better understand the degree of influence of either P or PET on drought, the effect of various drought indices to variations in P and PET is evaluated by estimating the correlation between the drought indices at 12-month timescale with cumulative 12-month P and PET timeseries. Figure 2.7 and 2.8 demonstrates the correlation coefficients between timeseries records of drought indices at 12-month timescale and mean P and PET, respectively. As can be noticed from Figure 2.7 the correlations between the drought indices and P show extremely high positive relationship in all the stations considered in this study. However, the relationship between the drought indices and PET (Figure 2.8) is extremely weak, either positively or negatively with no clear pattern. These results indicate that the drought at various station of the study area is governed by either the reduction or high inter-annual variability of the precipitation. According to Spinoni et al. (2015), though PET can be the important cause of drought in areas with insignificant precipitation trends, the inter-annual variability in precipitation is considered to be more influential than the annual trend. Due to inter-annual variability, extreme rainfall may balance the overall reduction in precipitation of prolong dry periods of drought that will result in overall precipitation increase. However, the inter-annual variability may also increase the frequency and severity of drought events.

Sensitivity analysis is also performed on drought indices that uses PET in their calculations to check the effect of PET on the outcome of drought severity values. It is implemented only on RDI and for the test a range between -20 % and +20 % with an increment of 5 % is considered for the PET. It is observed that by varying the PET, the magnitude of PET (mean value of PET) changed, however, no effect is detected on the severity values of RDI. This is because the response of RDI is dependent upon the variations in the standard deviation of P and PET, while no change can be detected when the magnitude of P and PET is changed (Vicente-Serrano et al. 2015).

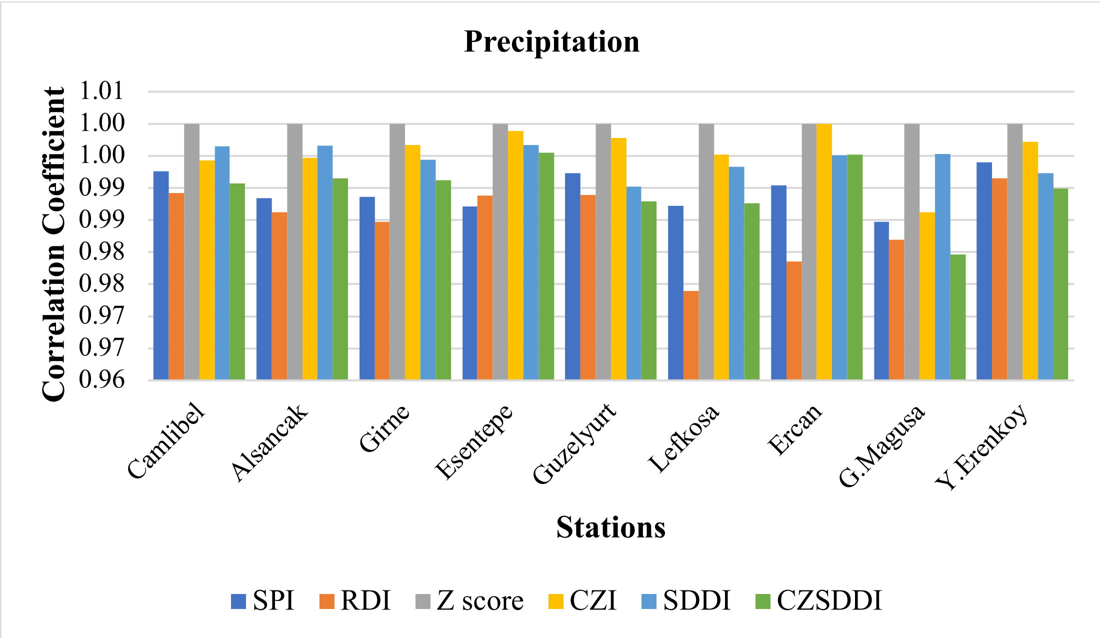


Figure 2.7: Correlation between timeseries record of precipitation and drought indices at various stations.

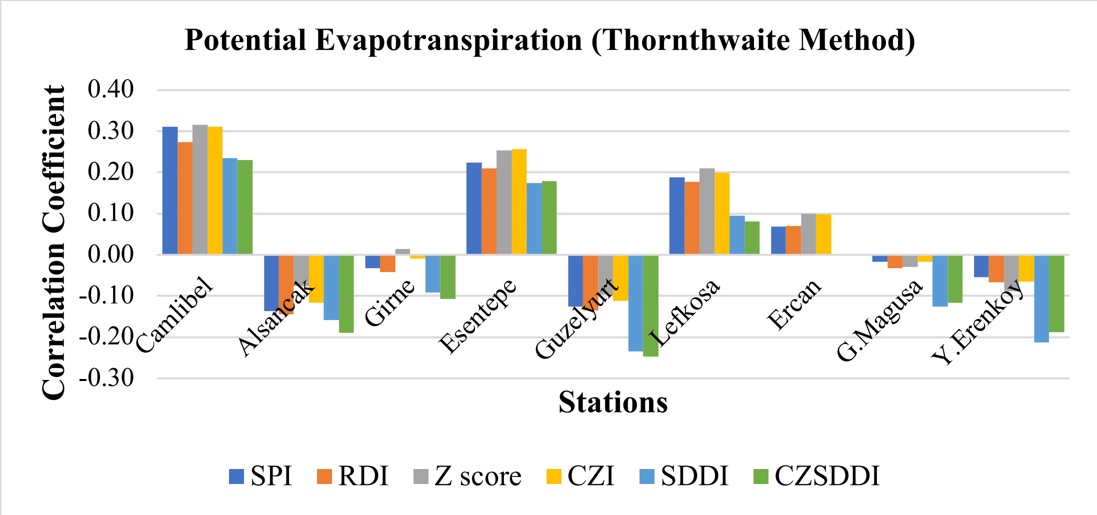


Figure 2.8: Correlation between timeseries record of potential evapotranspiration and drought indices at various stations.

2.4 Chapter Conclusions

The trend analysis of precipitation and temperature time series for the northern part of Cyprus revealed that in most of the regions no significant precipitation trend was detected. However, strong increasing trends in the annual temperature were detected in most of the areas observed. On the other hand, on a seasonal basis for both precipitation and temperature time series, significant increasing trends in almost all regions were observed in summer, while no significant trends were observed during other seasons in the majority of the regions.

The study demonstrated that for operational monitoring and characterization of drought both RDI and SPI is equally responsive in detecting the emerging drought conditions. In general, the difference between RDI and SPI is statistically insignificant at different timescales and locations as the correlation coefficient was close to 1.0. Similarly, the performance assessment of drought based on drought class in terms of rate of occurrence and severity also perceived insignificant difference between the two indices at different timescales.

The analysis results revealed that SPI_3, SPI_6 and SPI_{12} have a fairly strong relationship in showing drought events. All these timescales indicated that the northern part of Cyprus suffered from three major long durations of drought between 1981-1985, 1995-1999 and 2005-2009. According to the results of 12-months SPI, for the observed period, most of the regions revealed that the northern part of Cyprus experienced extreme drought in 2007-2008 and severe drought had taken place in 1996-1997 and 1994-1995.

The calculation of time scale related drought propagation occurrence revealed that on average 79% and 78% of drought events for 3-months timescales drought, developed into SPI_6's 6-months drought and SPI_{12}'s into 12-months drought events, respectively. Similarly, for 6-months timescales droughts, approximately 90% of drought events developed into SPI_{12}'s 12-months drought events.

The estimation of the range of critical rainfall values associated with lower and upper limit of moderate, severe, and extreme drought severity values, showed that with respect to moderate to extreme drought conditions for 6 and 12-months timescales, Alsancak has the highest rainfall range whereas Guzelyurt presented the lowest range. On the other hand, for 3-months timescales, Camlibel provided the highest rainfall range, while Lekosa and Ercan showed the lowest range.

The findings of this study are validated through other drought analysis performed within the Mediterranean basin by other researchers. The outcomes can be used for drought monitoring and management purposes. It can be used for efficient planning and use of water resources during drought events. As more than 75% of water in the northern part of Cyprus is utilized by the agriculture sector, this study will be helpful in preparing agriculture production water utilization contingency plans. Moreover, for any future projects, the results of this study can be utilized in estimating the impact and modelling of water resources under severe and extreme drought conditions.

Chapter 3

IMPACT OF DROUGHT ON AGRICULTURE

3.1 Introduction

Exposure, sensitivity and vulnerability of agriculture sector to climate change and its extreme event such as drought is both a risk and a challenge to food security and availability around the globe. The effect of drought on agriculture is both on rainfed and irrigated agriculture in terms of reduced yield of crops and increased water demand for irrigation (Tigkas and Tsakiris, 2015; Hayes et al. 2011). Under rain-fed agriculture 60-70% of the worlds staple food and 55% of the gross value of food is produced (Garcia-Tejero et al. 2011). Irrigated agriculture is a major consumer of global fresh water resources; however, it plays an important role in agriculture production in sustaining the global food security and availability (Schaldach et al. 2012). Currently, about 67% of the global water withdrawal and 87% of the consumptive water use is utilized for irrigation (Döll, 2002). Irrigated agriculture in the Mediterranean regions is huge consumer of water with 60% total abstraction. However, limited availability of water, high climate variability and recurrent drought in the Mediterranean region similar to other part of the world is making both the rain-fed and irrigated agriculture to be exposed to immense variability and high vulnerability (Tigkas and Tsakiris, 2015; Hayes et al. 2011, Iglesias et al. 2009; Wriedt et al. 2009b).

Drought is a normal characteristic of climate and is mainly due to reduction in mean precipitation for a sustained period of time. Other climatic factors such as temperature, wind and relative humidity also play an important role in the occurrence of drought

(Wilhite 1996). Though other climatic factors also affect agriculture production, their influence is significantly low as compared to precipitation since crops are generally more sensitive to rainfall variability (Boken, 2005; Kang et al. 2009). Consequences of agricultural drought can have direct and indirect effects that can lead to reduced production, damaging the economic growth, lower the income of farmers and agribusiness resulting in an unemployment, forced migration and other socio-political upheavals (Wilhite et al. 2007). Thus, most of the recent studies focus on the impact of drought on the agricultural sector (Hayes et al. 2011).

The impact of drought on agriculture and crop production mainly depends upon its frequency, severity, duration, timing, spatial extent and drought preparedness (Bodner et al. 2015). Thus, to assess, estimate, quantify and predict the potential impact of drought in agriculture, models and tools that can be used are generally divided into two categories. Firstly, approaches that deals with crop productivity and secondly methods that measures the economic performance of the agriculture sector (Iglesias et al. 2011). Based on crop productivity approach, generally empirical models and crop simulation models can be used. Empirical models are mainly based on statistical approaches that use historical data to link crop yield to climatic variables whereas, crop growth simulation models or process-based models such as CROPWAT, uses the knowledge of physiological processes of crop growth and development (Motha 2010; Roudier et al. 2011). The process-based models can be very useful in estimating agricultural production, crop yield and crop water requirement. Such models can also be used for the potential impact assessment of agriculture drought by calculating the water deficiency and drought reduced crop yields (Paredes et al. 2014). Quiroga & Iglesias (2009) used statistical models to determine the effect of temperature and precipitation variability on yield of different crops in Spain. Hlavinka et al. (2009)

analysed the impact of seasonal agriculture drought on yield of different type of crops in Czech Republic using statistical methods. Tunalioglu & Durdu (2012) used different indices and curvilinear regression based on crop yield models to assess and project olive yield response to climate change. Al-Bakri et al. (2010) used crop simulation model DSSAT to assess the impact of climate change scenarios on yield of wheat and barley in Jordan. Yanga et al. (2017) used STICS and AquaCrop two process-based models to assess maize yield response to climate change scenarios. Tigkas and Tsakiris, 2015 used AquaCrop and the Reconnaissance Drought Index (RDI) to determine the effect of drought on yield of wheat.

The literature review showed that different models and tools based on crop productivity are used in issues related to the impact of drought on agriculture, but they were rarely used for ranking the impact of drought on crop productivity based on different drought severity levels or drought categories. And since severity of drought is an important characteristic of drought that influences agriculture crop production therefore, in this research, we focused on quantifying the effect of different categories of drought on productivity of varying rain-fed crops and irrigation water requirement of seasonal and perennial irrigated crops. The assessment and simulation are performed using process-based crop simulation model. The severity levels considered for this purpose are moderate, severe and extreme and are obtained for different years using Reconnaissance Drought Index (RDI). The proposed model is used to assess the impact of drought on rain-fed and irrigated crops in the northern part of Cyprus.

3.2 Materials and Methods

3.2.1 Study Area and Database

Cyprus is geographically located within the semi-arid climatic condition of the eastern Mediterranean region. Throughout the history, economic development of

Cyprus was predominantly dependent on agriculture. In northern part of Cyprus which has a total land area of 329,842 hectare, 56.7 % of the area is utilized for agriculture, 19.5 % is the forest land, 5 % is used for grazing, 10.7 % constitutes the urban land and 8.2 % is an unused land. The cultivated land covers approximately 65.35 % of the total agriculture area. In this, rain-fed agriculture is occupying 92.1 % of the area while irrigated agriculture makes 7.9 %. The major rain-fed crops comprise of wheat and barley with a percent area coverage of 77.3 % (out of 92.1 %). The major irrigated crop is citrus fruit constituting 55.2 % of the total irrigated area followed by potato with a share of 9.3 %. Currently, the irrigated land is under modern irrigation system after the great effort made by the authorities in 1998 to modernize the irrigation system from furrow irrigation to efficient irrigation systems. Approximately 94% of irrigated land is under trickle irrigation system, 5% is under high sprinkler system and 1% under low sprinkler system.

Agriculture is an important sector of the economy of the northern part of Cyprus. Although through the years its share to Gross Domestic Product (GDP) has fallen, still it has remained an important sector of the economy. In 2013, the share of agriculture sector in GDP was approximately 5.3 %. Its share in total value of export (processed and unprocessed agriculture products) is estimated as 68 %. Though the employment in agriculture has dropped down drastically in the last two decades mainly because of other profitable activities, the share of agriculture employment to total employment in the country is approximately 5 %. To carry out the farm activities, currently part time hired labour are extensively used by the farmers (ASP, 2013).

Agriculture in the northern part of Cyprus, similar to other Mediterranean countries, is faced by the limited and highly variable rainfall and high temperatures. As a result of inter-annual decrease in precipitation, drought occurrence in the last four decades has increased both in magnitude and frequency and because of climate change; it's expected that occurrence of drought episodes will increase, consequently, seriously affecting the agriculture and water sector (Payab and Türker 2017).

Northern part of Cyprus similar to administrative divisions, is divided into five main agricultural zones namely, Lefkoşa, Gazimağusa, Girne, Güzelyurt and İskele. In these zones, uniformly distributed nine meteorological stations are selected to perform the drought analyses and the crop modelling. The locations of the meteorological stations are shown in Figure 3.1. The effect of drought is investigated on rain-fed and irrigated agriculture. As such, three rain-fed crops namely, wheat, barley and olive are selected to quantify the impact of drought on yield of these crops. Meanwhile, ten irrigated crops (citrus, pomegranate, almond, fig, vines, artichoke, sweet melon, water melon, tomato and potato) based on their area coverage and economic value are selected to evaluate the increase in irrigation water requirement of these crops with respect to drought. Among these crops, six are perennial crops while four are seasonal crops.

The necessary climatological data, monthly records of precipitation, temperature, mean maximum and minimum daily temperature, mean humidity, sun hours and wind speed of each station for model simulation, are gathered for the period of 1977-2013 and are acquired from the State Meteorological Department and CLIMWAT, a climatic database (FAO, 2012). Prior to use these data for drought analysis and crop simulation purposes, statistical analysis is performed to check the independence, randomness and homogeneity.

Figure 3.1: Geographical location of nine different stations and five main agricultural zones at northern part of Cyprus.

The crop parameters of various crops (Table 3.1) such as crop coefficient values (K_c) and yield response factor (K_y) for initial, mid-season and late crop growing stages, duration of crop growing stages, planting and harvesting dates, crop development periods were obtained from FAO (1998) and Zoumides and Bruggeman (2010).

Table 3.1: Duration of crop development stages, crop coefficient (Kc) and yield response factor (Ky).

Crop	Plant Date	Initial Stage (Days)	Development Stage (Days)	Mid Stage (Days)	Late Stage (Days)	Harvest Date	K_{c_ini}	K_{c_mid}	K_{c_end}	K_y
Wheat	15/11	30	90	40	20	13/05	0.70	1.15	0.25	1.05
Barley	15/11	30	80	40	20	03/05	0.30	1.15	0.40	1.00
Olive	01/12	95	90	90	90	01/11	0.50	0.60	0.50	0.75
Citrus	01/01	60	90	125	90	31/12	0.75	0.70	0.75	1.20
Pomegranate	01/11	155	60	120	30	31/10	0.50	0.95	0.75	1.20
Almond	01/10	180	60	65	60	30/09	0.40	0.90	0.65	0.90
Fig	01/11	155	60	120	30	31/10	0.50	0.65	0.70	0.90
Vines	01/11	155	60	60	90	31/10	0.30	0.70	0.45	0.85
Artichoke	01/09	40	40	255	30	31/08	0.50	1.00	0.95	0.95
S.Melon	01/04	15	45	45	30	13/08	0.50	0.85	0.60	1.10
W.Melon	01/04	15	45	45	15	29/07	0.40	1.00	0.75	1.10
Tomatoe	01/02	15	40	50	40	25/06	0.60	1.15	0.80	1.05
Potatoe	15/01	25	30	45	30	24/05	0.50	1.15	0.75	1.10

The soil parameters include the total available soil moisture for the five agricultural productive regions of northern part of Cyprus and are obtained from the soil maps of northern part of Cyprus (Table 3.2). Based on this map, total available soil moisture of six dominant and associated soils, covering these regions is derived from the 0.5-degree Harmonized World Soil database (FAO, 2009). As a result, it was found out that majority of each agriculture zone's soil characteristic is mainly associated with total available soil moistures of 150, 130, and 100 mm. As such, in the crop model these three different soil moistures are used for each zone and each crop.

Table 3.2: Characteristics of major soil of five agricultural productive zoness and their associated total available soil moisture (SMta).

Dominant soil	Associated soils	SM_{ta} (mm)
epipetric-CALCISOLS, (CL.ptp), leptic-chromic- LUVISOLS, (LV.cr.le)	(CM.le.cr) chromic - leptic - CAMBISOLS	150
calcic-LUVISOLS, (LV.cc), chromic-vertic-LUVISOLS, (LV.vr.cr)	(CM.le.cr) chromic - leptic - CAMBISOLS	150
calcaric-fluvic-CAMBISOLS, (CM.fv.ca) vertic-CAMBISOLS, (CM.vr)	(RG.ca) calcaric - REGOSOLS, (FL.ca) calcaric - FLUVISOLS	130
vertic-CAMBISOLS, (CM.vr), calcaric-REGOSOLS, (RG.ca)	(CM.fv.ca) calcaric - fluvic - CAMBISOLS, (VR.ca) calcaric - VERTISOLS	100
gleyic - SOLONCHAKS (SC.gl)	(SN.gl) gleyic - SOLONETS	100

3.2.2 Methods of Analysis

Frequency and severity of drought affects agriculture production and crop water requirement. Different analytical methods can be used to analyze and evaluate drought events and crop production. In this study Reconnaissance Drought Index (RDI) is used to analyze and assess the drought (discussed in Chapter 2). In Chapter 2, though the discussion focused more on SPI, RDI is preferred over SPI in this Chapter as it uses potential evapotranspiration (PET) in its calculation. According to Khalili et al. (2011) for agricultural applications, under climatic variability conditions utilization of RDI could be advantageous due to availability of PET in its formulation. To determine the crop water requirement and to assess the changes in crop yield due to water stress CROPWAT 8.0, a process-based crop growth model is employed. CROPWAT 8.0 is developed by FAO (FAO, 2009) and is based on FAO irrigation and drainage paper No. 56, guidelines for computing crop water requirement (FAO, 1998), FAO irrigation and drainage paper No. 33 (FAO, 1986) that focuses on yield response to water. The main advantage of CROPWAT is that its user friendly and has been tested by many researchers in different countries to reliably and efficiently simulate crop water use and crop yield response to water stress under various scenarios of climate, crop and soil (Chowdhury et al. 2013; Stancalie et al. 2010). To examine and interpret the consequences of agricultural drought, the input data of the CROPWAT model include crop parameters, meteorological and climatic parameters and soil parameters. The main outputs are crop water requirement, irrigation water requirement (IWR), potential crop evapotranspiration, effective rainfall and estimated yield.

In order to quantitatively evaluate the impact of drought on rain-fed and irrigated crops for the drought categories under the consideration in each zone, yield reduction rate (YRR) and increase in IWR rate is calculated. In crop modelling three different total available soil moistures were used for each station and drought category. Similarly, some agriculture zones had more than one station. Prior to quantitively evaluate the impact, in order to obtain the output values based on drought categories in each zone, mean values of the crop model output are calculated. In this study, the number of cases simulated using the CROPWAT model is amounted to 1,950. These cases are function of moderate to extreme drought events in the 9 stations located in the five zones between 1977-2013, 13 rain-fed and irrigated crops and soil types with 3 soil moistures.

The YRR and increase in IWR rate is identified by the difference between the yield and IWR of reference year (a wet and non-drought year) and the yield and IWR under different categories of drought. The year 2012-13 is selected as a reference year since it was the recent normal wet year. Very wet and extreme wet years are not considered which could have otherwise caused an over estimation of the results for both YRR and increase in IWR. The YRR and increase in IWR rate is expressed by equations (3.1) and (3.2) as:

$$Yield\ reduction\ rate_{i,d,c} = -\left(\frac{Yield_{i,c,Ref} - Yield_{i,d,c}}{Yield_{i,c,Ref}}\right) * 100\% \tag{3.1}$$

$$Increase\ in\ IWR\ rate_{i,d,c} = -\left(\frac{IWR_{i,c,Ref} - IWR_{i,d,c}}{IWR_{i,c,Ref}}\right) * 100\% \tag{3.2}$$

where, yield reduction $rate_{i,d,c}$ is the percent yield reduction at zone i, drought category d and for crop c. $Yield_{i,c,Ref}$ is the reference year percent yield reduction at zone i and for crop c while, $Yield_{i,d,c}$ is the percent yield reduction at zone i, drought category d and crop c. Similarly, increase in IWR $rate_{i,d,c}$ is the percentage change of IWR at region i, drought category d and for crop c. $IWR_{i,c,Ref}$ is the reference IWR at region i and for crop c while, $IWR_{i,d,c}$ is the IWR at region i, drought category d and crop c. The negative sign is placed in equations 3.1 and 3.2 to make the rate positive demonstrating an increase in IWR and an increase in in the reduction of YRR.

3.3 Results and Discussions

3.3.1 Impact of Drought on Rain-fed Agriculture

Results from the process-based model, CROPWAT, showed yield variations of the investigated crops due to different intensities of drought. For all crops, it is observed that reduction of rainfall during drought had a negative impact on the yield of wheat, barley and olive. Variation in yield reduction on regional basis due to different severity levels of drought was not constant. This variation in fact, is influenced largely by the spatial pattern of climate and soil conditions. Though the negative influence of drought conditions was apparent in all regions, but the most vulnerable region with highest reduction in yield for both wheat and barley was Lefkosa followed by Guzleyurt and G. Magusa. The least vulnerable region was Iskele and then Girne. In terms of olive, however, all five regions showed constantly high vulnerability in terms of olive yield reduction. The variation in yield reduction in these regions is highly influenced by the spatial variation of rainfall followed by other climatic factors such as temperature. Girne with sub-humid climate normally receives the highest annual rainfall in the country whereas, Lefkosa which has a semi-arid climate is drier and receives the lowest rainfall. Overall, yield reduction in sub-humid coastal areas is lower than semi-arid inland locations of the island. Drought in the study area on average (Figure 3.2) reduced the yield of wheat by 23-52%, 17-41% for barley and 42-54% for olive, respectively.

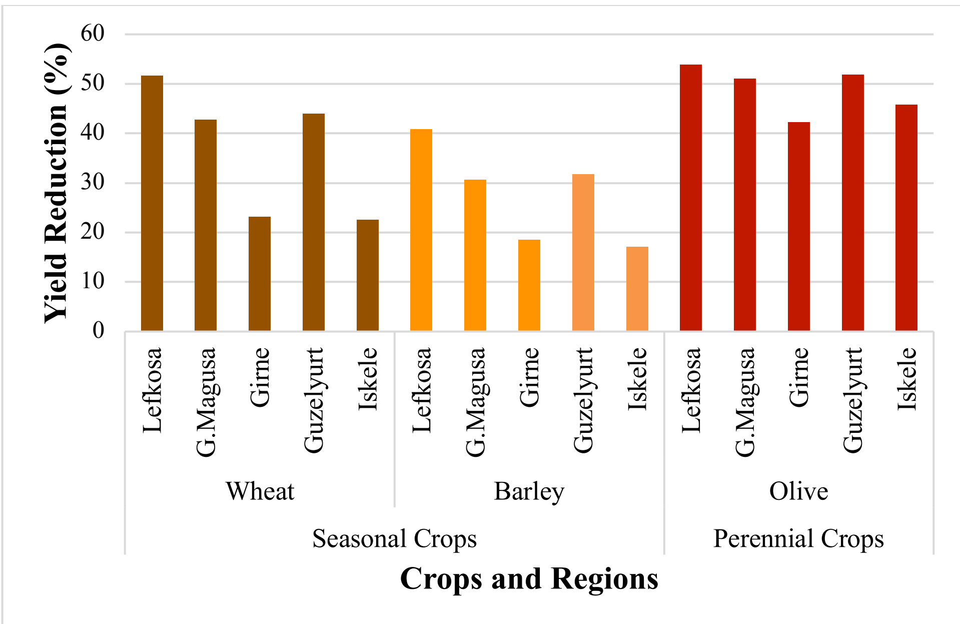


Figure 3.2: Regional mean yield reduction of rain-fed crops due to drought.

The negative impact of different severity levels of drought on yield of rain-fed crops is depicted in Figure 3.3. The values are obtained by calculating the yield reduction rate (YRR) for each zone based on drought categories as described in sub-section 3.2.2 and using Equation 3.1. In the five agricultural zones, reduction of wheat yield due to moderate drought was 10-40%, barley yield reduction varied by 9-27%, and variation in reduction of olive yield was 36-51%. Meanwhile, yield reduction during severe drought was 22-57%, 16-47% and 42-53% for wheat, barley and olive, respectively. Consequently, extreme drought reduced the yield of wheat by 29-58%, barley had a reduction of 25-49% and olive reduction was 48-58%. As can be seen, both wheat and barley are drought sensitive but barley is relatively less sensitive as compared to wheat. This is possibly due to physiological make up of barley making it more water use efficient.

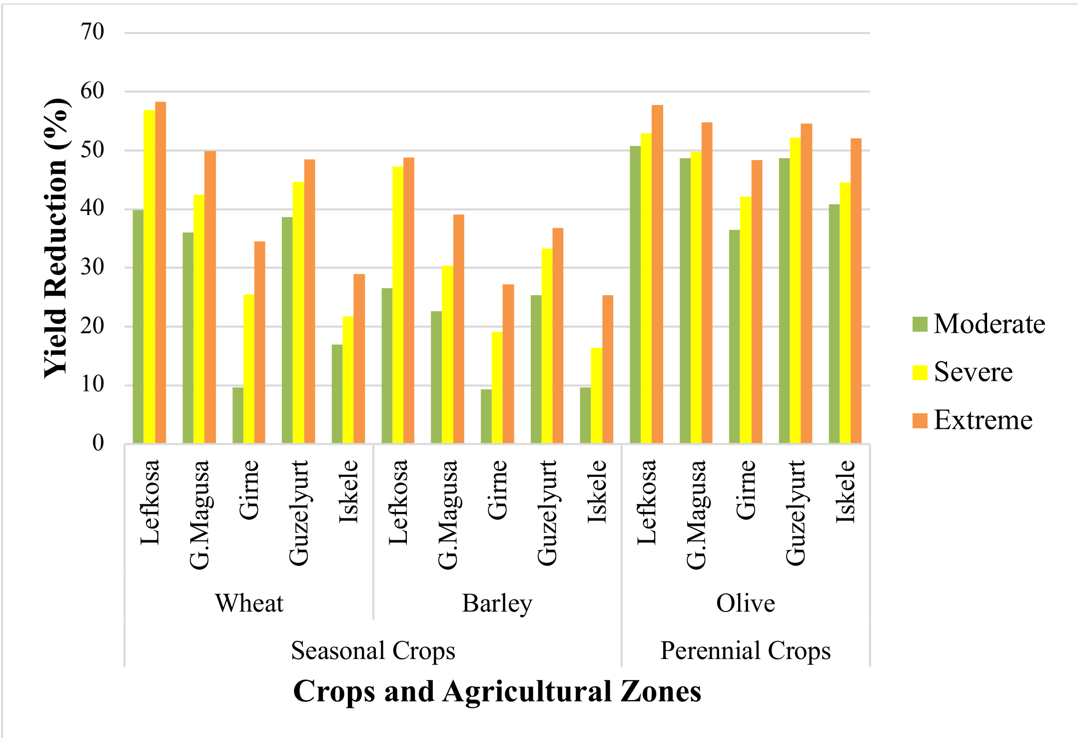


Figure 3.3: Zone based yield reduction of rain-fed crops based on drought categories.

3.3.2 Impact of Drought on Irrigated Agriculture

Drought occurrence has negative influence not only on crop yield but also on water requirement of irrigated crops. By coupled application of RDI and CROPWAT model, irrigation water requirement (IWR) and rate of increase in IWR for six perennial crops (citrus, pomegranate, fig, almond, vines and artichoke) and 4 seasonal crops (sweet melon, water melon, tomato and potato) under different severity levels of drought is estimated in this study. Generally, beside other factors the temporal and spatial demand variation for irrigation is mainly dependent upon precipitation. High irrigation is required during dry years while low irrigation is essential during wet years. Similarly, in regions where precipitation is relatively abundant, the demand for irrigation is low as compared to regions with less precipitation. In the study area, for all the crops under consideration, during the reference year of 2012-13, based on the IWR output of CROPWAT model, the mean IWR is estimated for the different zones. As such, in Girne that receives abundant rainfall the mean IWR for the year 2012-13 is estimated as 485 mm while for Lefkosa that receives less rainfall, the estimated mean IWR is approximately 615 mm. In other regions that has more or less similar precipitation trend during this wet year of 2012-13, the IWR is estimated as 595 mm. Similarly, the IWR for various drought years (moderate, severe and extreme years only) which were obtained from CROPWAT model, are aggregated and their average values are calculated with respect to agricultural zones. As such, the mean IWR in Girne and Lefkosa is calculated as 550 mm and 690 mm, respectively. In other regions, the IWR was approximately 635 mm.

The spatial variation based on the agricultural zone for the increase in IWR rate of the different crops due to drought and its different severity levels is shown in Figure 3.4. The rate of increase in IWR depending upon climatological, bioenvironmental, soil and plant physiological factor varied across different zones. The increase was highest in Girne followed by Lefkosa while in the other zones the rate of increase was approximately the same. During the moderate to extreme drought, the mean increase in IWR rate in Lefkosa, G.Magusa, Girne, Guzelyurt and Iskele is estimated as 12, 6, 14, 7, and 7%, respectively. Though Girne is receiving normally higher rainfall and the IWR is lower than any other zone, the rate of IWR is higher than any other place. It is because of the slightly higher difference between the reference year and the drought years IWR as compared to other locations. On the other hand, it can be potentially also due to the fact that the crops in Girne have adapted well to favorable high rainfall condition. Thus, they are less tolerant towards water deficiency and the dry years of drought as compared to other crops in any other location. Considering the increase in IWR with respect to severity level of drought, Girne revealed the highest increase in IWR for the three categories followed by Lefkosa while G. Magusa demonstrated the lowest increase. The difference between G. Magusa, Guzelyurt and Y. Erenkoy in fact can be considered negligible. In Girne, the increase in IWR for moderate, severe and extreme drought categories was 8, 13 and 20%, respectively. In G. Magusa for the same drought categories the rate was 10, 6 and 3%, respectively.

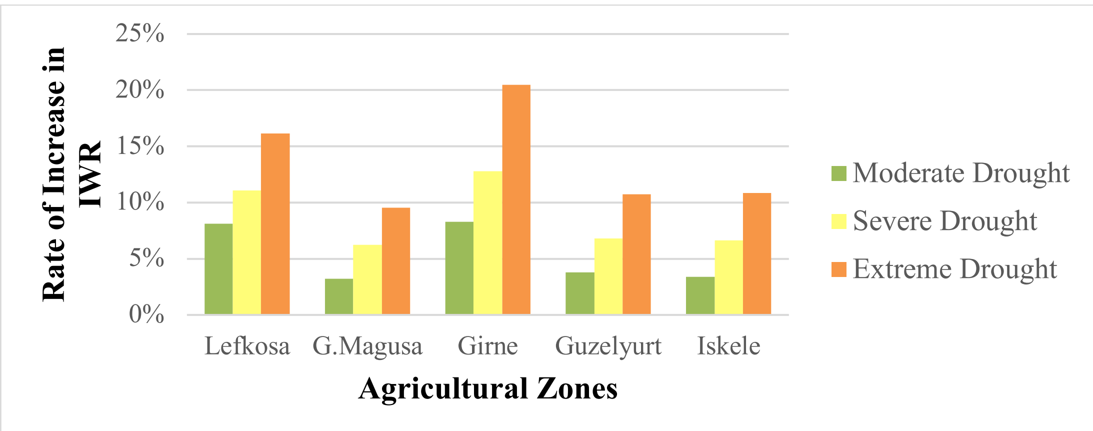


Figure 3.4: Rate of increase in IWR based on drought categories in five agriculture zones of the study area.

The variation in increase of IWR based on crop categories demonstrated that the increase for perennail crops is higher as compared to seasonal crops. The difference as can be seen in Figure 3.5 is not that high. It can be possibly due to the fact that perennail crops have roots much deeper into the soil as compared to seasonal crops as well as the water requirment at the late stages of the development is lower than the other stages of the crop development cycle. Overall, the increase in IWR of perennial crops during drought was 11% while for seasonal crops it was 8%. In terms of drought severity levels, during moderate, severe and extreme drought the increase in IWR for perennial crops was approximately 7, 10 and 15%, respectively. Meanwhile, the approximate estimated rate for seasonal crops was 3, 7 and 12%, respepetively.

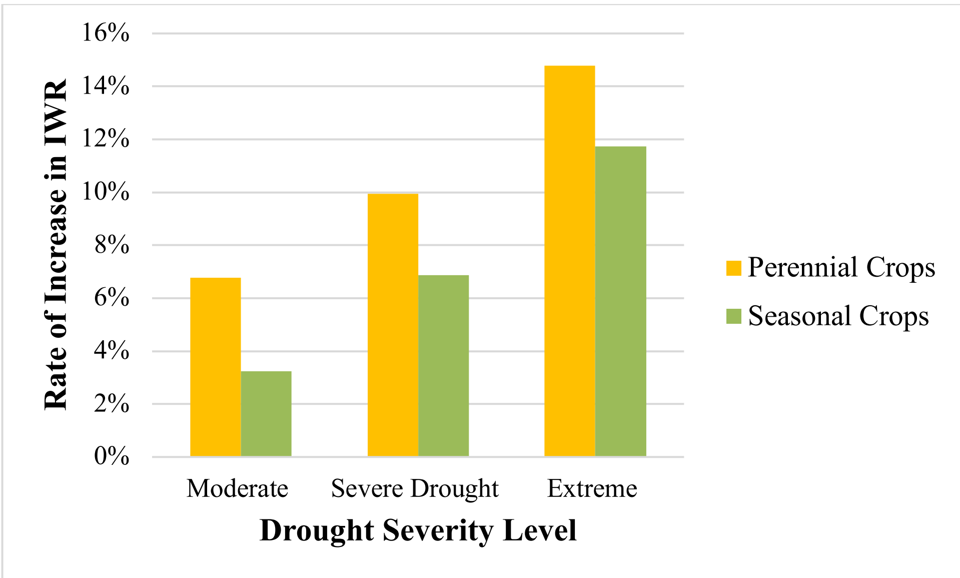


Figure 3.5: Perennial and seasonal crop's rate of increase in IWR according to Drought Severity Levels.

Variability of the increase in IWR due to drought with respect to the different crops was also not constant and was varying from crop to crop. As can be observed from Figure 3.6, among the seasonal crops, the negative effect of drought is estimated to be higher for citrus fruit while almond followed by pomegranate are the lowest affected crops. This can possibly due to physiological characteristics of almond and pomegranate making them more resistant to drought conditions, whereas, citrus is more sensitive and less resistant to dry climate. Likewise, for the seasonal crops, sweet melon is less affected while the effect on potato is comparatively higher than the rest of the crops. For citrus during moderate, severe and extreme drought events, the increase in rate of IWR is estimated as 10, 16 and 20%, respectively. For the same drought categories, the rate of increase for almond was 3, 5, 8%, respectively. Keeping into consideration the effect of climate change, frequent occurrence of drought, nutritional and economic value of almond and pomegranate the government needs to encourage the farmers to grow more almond and pomegranate. Meanwhile, the cultivated area of citrus can be reduced gradually by keeping into consideration the total demand for citrus within the market and avoid excess production as its now. Similarly, the increase in IWR rate during moderate, severe, and extreme drought calculated for sweet melon was 3, 6 and 10% whereas, for potato it was approximately 3, 9 and 15%, respectively.

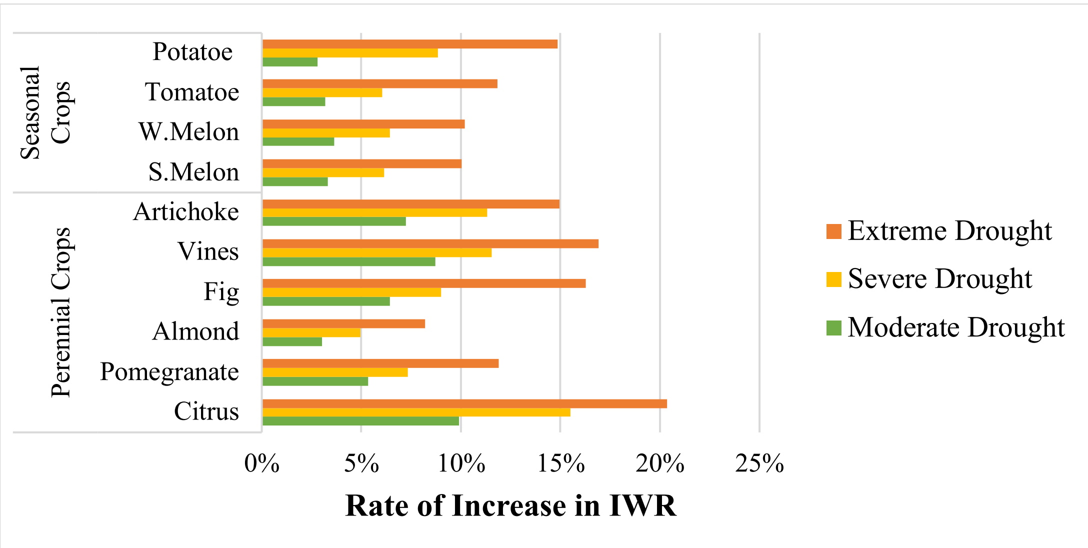


Figure 3.6: Crop based increase in IWR during moderate, severe and extreme drought.

3.3.3 Validation of the Results

Rain-fed Agriculture

To confirm and validate the findings of the impact of drought on rain-fed crops in this study, the average modelled (estimated) yield reduction during moderate, severe and extreme drought was compared with historical data (observed or actual) specifically, with those years where such drought events had taken place. For this historical timeseries yield data of wheat, barley and olive are obtained from Ministry of Agriculture and Forestry annual statistical books (ASP, 1995-2013). In order to make the comparison possible, initially the yield anomaly is calculated by subtracting the yearly yield from its long-term mean. In order to standardize the anomaly, the yield anomaly is divided by its mean. Finally, to obtain the observed (actual) yield reduction based on drought categories, the standardized yield anomaly for either moderate drought years or severe drought years or extreme drought years are aggregated and their average values are estimated. As such, the modelled (estimated) and observed (actual) yield reduction had a good agreement between each other. As shown in Figure 3.7, the modelled yield reduction of wheat for moderate, severe and extreme drought was 28, 38 and 44%, respectively. While for these events observed yield reduction was 32, 41 and 47%. Similarly, for barley modelled yield reduction was 19, 29, and 35% while observed yield reduction was 25, 33 and 40%. In the case of olive, modelled yield reduction was 45, 48 and 54% and observed yield reduction was 49, 51 and 55%. As can be noticed, in all cases modelled yield reduction was lower than observed yield reduction. This can be explained by the fact that there are other external factors as well, such as climatic factors besides precipitation and/or physical and chemical characteristics of soil that can affect yield and such factors were kept constant in modelling. Similarly, the r-squared value between the modelled and observed yield during drought for wheat, barley and olive was 0.994, 0.989 and 0.997, respectively.

Comparing the findings of this study to other published studies in the Mediterranean region good agreement is also found. Al-Bakri et al. (2010) modelled yield of wheat and barley in Jordan under different scenarios of climate change. They found that reducing the rainfall by 10-20% the yield of wheat reduced by 10-20% and for barley the reduction was 4-8%. Gargouri et al. (2012) assessed the impact of 2001 drought in Tunisia and found that the reduction in production of olive was between 42.8 and 86% in different regions of Tunisia. Quiroga and Iglesias (2009) found that dry years of drought causes approximately 33% reduction in yield of cereals in Spain. Schilling et al. (2012) reported that the 2007 drought in Morocco reduced the production of wheat by 76%.

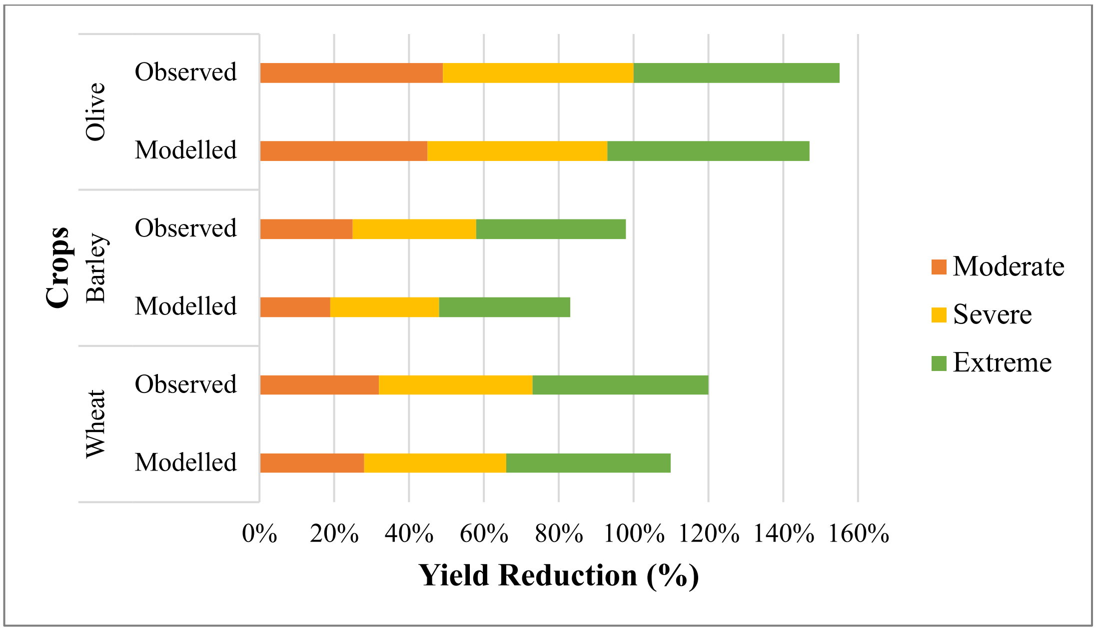


Figure 3.7: Modelled (estimated) and observed (actual) yield reduction of crops based on drought severity levels.

Irrigated Agriculture

Due to limited availability of irrigation data and groundwater withdrawal data, the validation of results is done by comparing the result of this study with other relevant studies. The rate of increase in IWR estimated in this study during dry years of drought is in line and in good agreement with the ones estimated or predicted by other authors. Although, there are some differences which can be due to specific climatic and environmental conditions and assumptions made in the analysis. In this study the mean increase in IWR rate in the northern part of Cyprus during moderate to extreme drought is computed as 10%. Döll (2002) had predicted an increase in net irrigation water requirement between 6 and 9% for Europe due to climate change by considering 1961-1990 data as the baseline. Similarly, on global basis, Döll (2002) had calculated the increase in net irrigation water requirement between 3-8%. In another similar study, Döll and Siebert (2002) have estimated an increase in net irrigation requirement of less than 10% for regions with average net irrigation requirement of above 900 mm/year. Similarly, for regions having an average net irrigation requirement between 300-600 mm/year, the increase would be between 10-30%. This suggests that evaluating the increase in IWR of irrigated crops using drought indices (RDI) and crop simulation model (CROPWAT) can be informative and productive in simulating impact of extreme events of climate change and variability such as drought on irrigated agriculture crops.

3.3.4 Sustainable Adaptation Measures

Agriculture is playing a crucial role in the economy of the northern part of Cyprus. But occurrence of extreme events of climate change such as drought and poor spatial and temporal distribution of rainfall make agriculture more susceptible and vulnerable. The direct and initial effect of drought as is evident from the findings of this study is on production of rainfed crops as well as increase in irrigation water requirement of irrigated crops. But this has a wider indirect effect on other sectors of the economy. For instance, the 2007-2008 drought event severely reduced the production of wheat, barley and olive. This caused the prices of these crops to increase by 100% (for example, the producer price of wheat in 2007 was 0.27 $/kg where it increased to 0.54 $/kg in 2008). The reduction in production not only disrupted the market price of these crops but the government had to increase its share of import to fulfil the consumers demand (additional 5,123 tons of wheat, 37,821 tons of barley, and 339 tons of olive was imported).

In northern part of Cyprus ground water is the only source of blue water (99%) and aquifers are already overexploited. At current depletion rate, the groundwater hardly meets the irrigation need of irrigated agriculture. Therefore, it is critical to look for other sustainable and effective pre-impact adaptation interventions, measures and solutions to potentially, totally or partially offset the negative impact of drought on not only rainfed agriculture but also on irrigated agriculture as well as other sectors. The adaptation measures proposed here as shown in Table 3.1 are supply and demand management measures, on farm and off farm measures, in-situ and external measures and temporal and spatial measures. Beside the proposed measures the government needs to make necessary investments in strengthening human capacities; climate, agriculture and water management research; institutional development; specific technologies (machinery, satellite imaging, drones, etc.); and media outreach. Among the viable and sustainable supply management options, external and in-situ water harvesting systems looks to be more promising and attractive both in short term and medium term. The water harvested through this approach, can be both utilized for agriculture purposes as well as to recharge the aquifers. However, all these options need to be assessed and evaluated further to determine the most cost-effective and beneficial measure.

Table 3.3: Sustainable adaptation measures.

Supply Management Measures	Demand Management Measures
▪ Reclaimed or recycled wastewater reuse ▪ Saline water use ▪ Internal and external water trading across the basins ▪ External water harvesting systems (micro-dams, sub-surface tanks and farm ponds) ▪ In-situ water harvesting systems (Bunds, micro-basins and runoff strips) ▪ Water supply using tankers ▪ Emergency wells	▪ Supplemental irrigation ▪ Deficit irrigation ▪ Use of modern and improved irrigation technologies and practices (drip and sprinkler irrigation) ▪ Irrigation scheduling optimization ▪ Crop diversification ▪ Use of improved drought resistant crop varieties ▪ Crop calendar alteration ▪ Evaporation management (mulching, conservation agriculture and tillage practices)

3.4 Chapter Conclusions

Information provided on impact of historical drought is essential for policy makers and planners to effectively formulate and develop sustainable future plans against the disastrous effect of this creeping phenomena to ensure food security and availability. In this chapter, drought monitoring index (RDI) is integrated with process-based crop simulation model (CROPWAT) to assess the impact of drought events on production of rain-fed agriculture and irrigation water requirement of irrigated crops in northern part of Cyprus.

The drought severity levels acquired from drought study for all the regions of northern part of Cyprus were used in process-based model to examine the negative effect of drought on yield of wheat, barley and olive in those years where these events had taken place. The result indicated that drought significantly reduced the yield of these rain-fed crops in different regions and as severity level increases its effect also increases. For both wheat and barley, the most vulnerable region was Lefkosa whereas, the least vulnerable region was Iskele and then Girne. In terms of olive yield reduction, however, all five regions demonstrated to be equally susceptible. The historical drought events had reduced the yield of wheat by 23-52%, 17-41% for barley and 42%-54% for olive, respectively.

The analysis revealed that the increase in IWR of perennial crops during drought was 11% while for seasonal crops it was 8%. In terms of drought severity levels, during moderate, severe and extreme drought the increase in IWR for perennial crops was approximately 7, 10 and 15%, respectively. Meanwhile, the approximate estimated rate for seasonal crops was 3, 7 and 12%, respetively. Overall, the mean increase in IWR during dry years of drought is estimated as 10% which is in line with the findings of other published studies in the region.

The findings of this study have several policy implications essential both at local and regional level for sustainable adaptation and drought risk management strategies required for the transition towards climate smart agriculture in order to reduce vulnerability, increase coping capacity, and build resilience. To this end, several measures are proposed to combat the impact of climate change, essential not only to agriculture sector but also to other sectors under the changing environment. The proposed solutions are related to managing the land, water, soil and crops sustainably. In order to implement these interventions its recommended to compare the costs of these measures with the cost of potential future drought events. Likewise, to examine the viability and sustainability of these measures multi criteria analysis, cost benefit analysis and cost effectiveness analysis can be conducted.

Chapter 4

EFFECT OF DROUGHT ON GROUNDWATER RESOURCES

4.1 Introduction

Extreme events of climate change and variability directly and indirectly affects the groundwater quantity and quality (Earman and Dettinger, 2011). Groundwater is an essential source of freshwater around the globe. It is a substantial economic and strategic resource that provides water for domestic, agricultural and industrial use. Around the globe, 40% of world groundwater resources are used to irrigate 38% of world irrigated land while half of the population of the world uses groundwater as a source of freshwater for drinking purposes (Bhanja et al. 2017; Garamhegyi et al. 2017). However, recent studies have shown that around the globe due to population growth, climate change and variability and widespread extraction, the groundwater resources are rapidly depleting than any time before (Bhanja et al. 2017; Li et al. 2015; Voss et al. 2013; Treidal et al. 2012; IPCC, 2008).

Groundwater depends upon natural recharge process which in turn among other factors, heavily relies on the distribution, amount and timing of precipitation, temperature and evapotranspiration (Garamhegyi et al. 2017). Therefore, a shift in precipitation, temperature and evapotranspiration regimes, causes a profound negative impact on the recharge rate, the depth of groundwater level and consequently the amount of the groundwater (Kløve et al. 2013). As a consequence of this direct effect on natural processes of hydrological cycle, climate change and variability indirectly affect the groundwater system through substantial change in human activities (Cui et al. 2017). The indirect effect leads to increased abstraction and utilization of groundwater resources especially in areas where economic activities like irrigated agriculture heavily depends on groundwater (Treidal et al. 2012). However, the indirect and induced response to climate change and variability will have a larger effect on the groundwater. As a result, it will likely far outweigh the direct effect of climate driver hydro-meteorological changes (Gamvroudis et al. 2017).

In arid and semi-arid regions, groundwater is a major source of water especially for irrigated agriculture. Assessing the influence of meteorological drought and the propagation of it in the form of hydrological drought through groundwater is of utmost importance in areas where irrigated agriculture dependency on groundwater is exceedingly high (Green et al. 2011). Among the different approaches such as the utilization of complex hydrogeological models, meteorological and hydrological drought indices can be utilized to assess and quantify the impact of drought on groundwater resources (Kumar et al. 2016). Khan et al. (2008) used Standard Precipitation Index (SPI) to assess the impact of rainfall reduction due to drought on watertables in Australia. They found out that SPI have good positive correlation with the shallow groundwater level fluctuation. Garamhegyi et al (2017) investigated the effect of climate on the groundwater level fluctuations of shallow aquifer. They indicated that there exists a clear relationship between the shallow groundwater level and the drought periodicity using wavelet analysis and self-calibrating Palmer Drought Severity Index (SC-PDSI) and the Aridity Index (AI). Lorenzo-Lacruz et al. (2017) assessed the response of aquifer in Mallorca island (the island is located in the western sector of the Mediterranean Sea) to precipitation variability using SPI and Standardized Groundwater Index (SGI). They demonstrated that the response of aquifer to precipitation change due to hydrogeological conditions and process within the aquifer system differs.

However, the response of groundwater to extreme events of climate change and variability have been less explored around the world whereas, most studies have addressed the impact of climate change and variability on surface water (Taylor et al. 2012, Green et al. 2011, Bates et al. 2008). Additionally, limited research has been conducted on the indirect or induced effect of climate change and variability on groundwater abstraction utilized for irrigation purposes (Treidal et al. 2012).

Understanding that frequency of extreme events of climate change and variability such as drought is increasing and groundwater resources are depleting rapidly, estimating and quantifying the effect of drought on groundwater is essential for sustainable management of this resource. Therefore, the main aim of this chapter is to investigate the temporal and spatial variability of groundwater level to drought by examining the groundwater level time series data of different observation wells through the comparison of meteorological and hydrological indices. The drought and non-drought years which were identified and discussed in chapter 2 using the SPI and RDI indices are related and compared with Standardized Groundwater Level Anomaly (SGWLA) and Standardized Groundwater Index (SGI).

4.2 Materials and Methods

4.2.1 Study Area and Database

Water resources in the island of Cyprus which is located at the Eastern part of the Mediterranean Sea are very scarce. In fact, the water scarcity problem is realized in 1960's. Currently, the scarcity situation due to population growth, economic development, and climate change and variability which has intensified the occurrence of drought during the past four decades, has got worse (Türker and Hansen, 2012).

The island of Cyprus has a semi-arid climate with mild and wet winter and hot and dry summer. Similar to the rest of the island, the rainfall in the northern part of Cyprus is the only source that replenishes the water sources. The average annual rainfall is about 518 mm with more than 60% of rainfall taking place during winter. Similarly, depending on the location, the annual potential evapotranspiration varies between 1,541 mm and 2,296 mm. It is estimated that on average about 80-85 % of total annual rainfall is lost to evaporation, leaving out only 15-20 % of the rainfall to contribute to total water budget (EU, 2011a).

The northern part of Cyprus is geographically divided into five main regions namely, Lefkosa, G.Magusa, Girne, Guzelyurt and Iskele. There are 37 streams in the island carrying a surface runoff of about 70 million m^3 annually. However, none of these rivers or streams are perennial. The nine important streams (Yeşilırmak, Kamburdere, Maden, Lefke Deresi, Çamlıdere, Çakıldere, Doğancı, Güzelyurt and Kanlidere streams) carrying more than half of the annual flow (43 million m^3) that are originating form Troodos mountains located in the southern part of Cyprus. However, the flow of these streams has almost been banned due to dams constructed in the southern part of Cyprus. The remaining 28 streams are originating from Beşparmak mountain situated in the northern part of the island. The water of these streams while directly contribute to the recharge of the aquifer, are also utilized for domestic and agricultural purposes. Some amount of water also flows into the Mediterranean Sea. It is estimated that about 38 million m^3 of the total annual water flowing in the streams, nourishes the aquifer in the western part of the island particularly the Güzelyurt/Morphou aquifer (Phillips Agboola and Egelioglu, 2012). In the northern part of Cyprus, the total water withdrawal from these streams for domestic and agriculture purposes is approximately 1.4 million m^3. There are about 41 reservoirs, dams and other hydraulic structures of various capacities, constructed mainly to prevent surface runoff to the sea, supply water for irrigation and to recharge the aquifers. The estimated annual withdrawal of water for irrigation purposes from these reservoirs is approximately 5 million m^3. Meanwhile, utilization of water from non-conventional sources such as reuse of wastewater for irrigation purposes and production through desalination plants for potable use, is extremely limited (Elkiran, 2010).

Groundwater is constituting major part of the water resources in the northern part of Cyprus. The estimated annual extraction from the aquifers is approximately 98.6 million m^3 that fulfils more than 95% of total annual water demand out of which 63.1 million m^3 is utilized for irrigation purposes. There are twenty three separate aquifers in northern part of Cyprus where the three main aquifers are Girne/Kyrenia mountain aquifer, Guzelyurt/Morphou aquifer and G.Magusa/Famagusta aquifer (Türker and Hansen, 2012).

The Güzelyurt/Morphou aquifer is currently one of the most important and the biggest aquifer in the northern part of Cyprus. It supplies water not only to the Güzelyurt area but also to the western part of the island, to the central and to east Mesaria regions. However, the aquifer is now seriously suffering from mismanagement problem, particularly due to over-pumping which has caused the salinity within the aquifer to increase each year (Türker and Hansen, 2012; Ergil, 2000).

The Güzelyurt/Morphou aquifer is situated along the west coast near Morphou Bay with a total area of about 265 km^2 and a storage capacity of 920 million m^3. The aquifer is alluvial and unconfined and rests on an impervious layer of 100–120 meters below sea level at the western part of the aquifer and has a thickness of 45 to 100 m. The aquifer is dominantly made up of gravel and sand while silt and clay layers are also observable. Meanwhile, the unconfined nature of the aquifer makes it highly vulnerable to extreme events of climate change (Ergil, 2000).

The aquifer is mainly recharged from the surface runoff carried by the streams, particularly the Güzelyurt and Dogancı streams originating from Troodos mountains and Yuvacık stream originating from Beşparmak mountains. The Lefke-Güzelyurt canal that collects water from Lefke, Çakil and Camlı streams also contribute to the recharging process. Equivalently, direct contribution of rainfall infiltration particularly through the alluvial deposits (gravel and sand) within the aquifer basin is also substantial (20-25%) (Fanta, 2015).

4.2.2 Methods of Analysis

The temporal-spatial impact of drought on groundwater is investigated and quantified by analyzing and comparing the standardized values of groundwater data series with the SPI and RDI severity values and examining the trend. The SPI and RDI severity values were obtained through SPI and RDI analysis for 3, 6, and 12-months timescales performed in chapter 2. To calculate the standardized values of the groundwater level data series, Standardized Groundwater Level Anomaly (SGWLA) and Standardized Groundwater Index (SGI) is estimated.

Evaluating the Impact of Drought on Groundwater

The analysis on the effect of drought on groundwater resources is applied on the Güzelyurt/Morphou aquifer. The groundwater table data of 160 monitoring wells from different locations of the region is obtained from the Water Works Department. The temporal coverage of water table data series of each well was of different length varying between 1977 and 2009. Out of 160 wells, 44 wells located in 12 different locations of the Güzelyurt region are selected that had more than 20 years of data and less than 10% of the records missing. Among the locations, 8 locations contained 2 or more than 2 wells (Güzelyurt = 21, Bostancı = 5, Yeşilyurt = 3, Yuvacık = 3, Sahinler, Kumköy, Aydınköy and Akçay = 2 wells each). Four locations (Gaziveren, Güneşköy, Mevlevi and Zümrütköy) comprised of one well each (Figure 4.1). The quality check of the data series is done by performing statistical analysis to inspect the independence, randomness and homogeneity of the data series. The missing records are filled by means of linear regression model using the most correlated water table series from neighbouring wells.

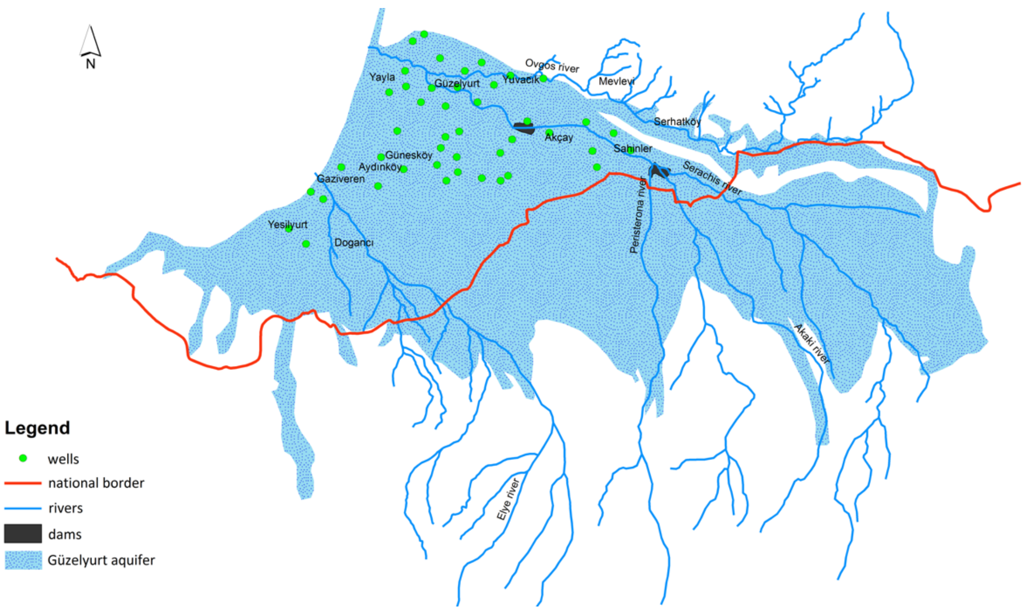


Figure 4.1: Topographic map of the Güzelyurt/Morphou aquifer and the distribution of the monitoring boreholes.

To enable comparison and correlation with the SPI and RDI and perform trend analysis based on different locations or the aquifer itself rather than each well, the groundwater level (GWL) series is transformed into a standardized anomaly or non-dimensional standardized anomaly. This removes the effect of inconsistency in the water level depth and the distortion on the trend. The first approach is the SGWLA method where initially the absolute groundwater levels are converted into groundwater level anomalies (GWLA) by following the procedure given by Bhanja et al. (2017) and Hu et al. (2016). The GWLA is obtained by the following expression:

$$GWLA_{i,j} = -\left(GWL_{i,j} - GWL_{j,mean}\right) \tag{4.1}$$

where, $GWLA_{i,j}$ is the GWLA of well i in year j, $GWL_{i,j}$ is the GWL of well i at year j and $GWL_{j,mean}$ is the mean GWL of well j. The negative sign is to understand whether ground water level is decreasing or increasing as compared to mean ground water level. Consequently, the standardized value of GWLA is calculated and expressed as:

$$SGWLA_{i,j} = \left(\frac{GWLA_{i,j}}{\sigma_{i,j}}\right) \tag{4.2}$$

where, $SGWLA_{i,j}$ is the standardized value of GWLA of well i in year j, $GWLA_{i,j}$ is the GWLA of well i in year j and $\sigma_{i,j}$ is the standard deviation of either the GWL or the GWLA of well j.

The second approach that can be used to standardize the groundwater levels and to characterize groundwater drought is the SGI method. The method is developed by Bloomfield and Marchant (2013). The solution methodology to obtain SGI is similar to SPI and RDI normalization approach as discussed in chapter 2. While SPI and RDI uses precipitation and potential evapotranspiration in their calculations, SGI uses groundwater level.

The trend of the groundwater level in each location of the study area and the aquifer itself is examined and obtained by averaging the GWLA. The trend analysis is performed using non-parametric Mann–Kendall trend test at a significance level of 5%. The slope of the trend indicating the rate of change in groundwater level in m/year is computed using the non-parametric Sen's slope estimator (Sen, 1968) and the linear regression method.

4.3 Results and Discussions

4.6.1 Trend of Groundwater Level

The temporal variability of groundwater levels due to direct or indirect effect of climate extremes is assessed and quantified using the Mann-Kendall trend test, Sen's slope estimator and linear regression method. Table 4.1 shows the obtained results of these statistical tests in different locations of Güzelyurt/Morphou aquifer and the aquifer itself during the period 1977–2009. Based on the achieved results, the water level at the aquifer was not stable and declined at substantial rate indicating severe groundwater depletion due to mainly increased consumption. The obtained slope of groundwater level indicated that the depletion rate at the aquifer was approximately 0.11 m/year. The depletion of groundwater can be possibly referred to decrease in mean precipitation amount, increase in number of dry years because of frequent occurrence of drought events and extensive withdrawal for irrigation purposes. The trend tests revealed that the decline in water level in different locations of aquifer varied considerably from one location to another. In Yuvacık (Z_S = -2.84) and Zümrütköy (Z_S = -3.22) the groundwater depletion is identified to be severe which is reflected by significantly high decreasing trend. The estimated slope in these two locations indicated a decline rate of 0.25 and 0.65 m/year, respectively. On the other hand, in areas including Güzelyurt city, Bostancı, Yeşilyurt, Sahinler, Aydınköy, Akçay and Mevlevi the result demonstrated a significantly low negative trend with the maximum declining rate of 0.36 m/year in Mevlevi. Locations with negative trend and high declining rate demonstrates the fact that beside the effect of climate change and variability, the aquifer in these areas is heavily utilized for socioeconomic activities specially by irrigated agriculture. This also demonstrates that these areas are the main groundwater discharge areas. However, in Kumköy, Gaziveren and Güneşköy significant weaker positive trend is detected. This is mainly because of the fact that groundwater in these areas are heavily affected by the intrusion of sea water. In Kumköy and Güneşköy because of over exploitation, the salt water has invaded the aquifer. On the other hand, the part of aquifer in Gaziveren region during winter and spring is replenished by seepage from Elye river. However, vast rate of pumping that takes place during summer reduces the groundwater level substantially and this causes the intrusion of salt water during this time. Overall, the difference in groundwater level declining rate among the wells situated in different locations of the aquifer can be the result of heterogeneous soil and aquifer characteristics and non-uniform pattern of groundwater utilization.

Table 4.1: Trend analysis of GWLA in different locations of Güzelyurt Aquifer.

Locations	Z_S	Q_{med} (m/Year)	b (m/Year)
Güzelyurt	-1.31	-0.09	-0.06
Bostancı	-1.44	-0.14	-0.14
Yeşilyurt	-0.50	-0.03	-0.02
Yuvacık	-2.84	-0.25	-0.26
Sahinler	-1.48	-0.17	-0.15
Kumköy	0.34	0.01	0.00
Aydınköy	-1.31	-0.13	-0.15
Akçay	-1.22	-0.23	-0.21
Gaziveren	0.54	0.01	0.00
Güneşköy	0.77	0.16	0.17
Mevlevi	-1.30	-0.36	-0.29
Zümrütköy	-3.22	-0.65	-0.62
Güzelyurt Aquifer	-1.70	-0.11	-0.10

Z_S: Mann-Kendall test

Q_{med}: Sen's slope estimator

b: Slope of linear regression

4.6.2 Spatial Effect of Drought

The assessment of the response of aquifer to drought is conducted by looking into the relationship between meteorological drought and hydrological or groundwater drought. The comparison is done by considering SPI and RDI, two widely used rainfall-based indices and groundwater indices namely, SGWLA and SGI. Correlation analysis is performed to determine the strength in relationship of SGWLA & SGI and SPI & RDI. As shown in Table 4.2 by initially comparing SGWLA and SGI, it is found that the relationship between the SGWLA and SGI is positively high. The coefficient produced between these two indices and the SPI & RDI is fairly similar. In a similar mode, there exists extremely low difference between SPI and RDI performance of demonstrating the degree of the influence of drought on groundwater level. Overall, there exists in general a positive correlation coefficient in different locations of the aquifer between SGWLA & SGI and SPI & RDI at 12-months timescales, indicating that both SPI and RDI behaves in a similar manner in revealing the influence and effect of drought on groundwater. Among the different locations, SGWLA & SGI representing the groundwater level series in Yeşilyurt, Kumköy, Akçay, Gaziveren and Mevlevi showed relatively good correlation to both SPI and RDI. This indicates that the influence of drought severity is high in these locations. On the other hand, this also reflects the fact that these locations are the potential recharge areas of the aquifer. The recharging of the aquifer in these locations is not only due to the natural rainfall but also highly depends upon the seasonal flow of the streams that crosses these locations. A reduction in rainfall during dry years highly influences the flow in streams consequently, affecting the recharging process. In contrast, groundwater level in other locations revealed the least and very low correlation with both SPI and RDI. The weak relationship between the meteorological and hydrological drought indices can possibly be due to complex nature of groundwater system and aquifer hydrology, salt water intrusion, management practices and over exploitation of aquifer (Cui et al. 2017; Lorenzo-Lacruz et al. 2017). Overall, the mean correlation coefficient of SGWLA and SGI in Güzelyurt/Morphou aquifer to both SPI and RDI is estimated as 0.146 and 0.143, 0.148 and 0.145, respectively. The analysis showed that in general, there exists a positively weak relationship between groundwater level and SPI and RDI which indicates that drought is partially associated with the decline in groundwater level.

Table 4.2: Correlation coefficient between SGWLA and SGI and SPI and RDI in different locations of Güzelyurt/Morphou aquifer.

Locations	$SGWLA_{12}$		SGI_{12}	
	SPI_{12}	RDI_{12}	SPI_{12}	RDI_{12}
Güzelyurt	0.023	0.022	0.023	0.022
Bostancı	0.173	0.145	0.173	0.145
Yeşilyurt	0.235	0.242	0.240	0.246
Yuvacık	0.064	0.057	0.069	0.063
Sahinler	0.130	0.135	0.146	0.150
Kumköy	0.332	0.339	0.334	0.341
Aydınköy	0.062	0.049	0.068	0.054
Akçay	0.304	0.302	0.298	0.296
Gaziveren	0.205	0.216	0.205	0.216
Güneşköy	0.009	0.039	0.009	0.039
Mevlevi	0.224	0.238	0.224	0.238
Zümrütköy	0.088	0.074	0.088	0.074
Güzelyurt Aquifer	0.146	0.143	0.148	0.145

4.6.3 Timescale Effect of Drought

The difference in the response of aquifer levels in each individual groundwater well to drought, based on short, medium and long-term drought represented by 3-months, 6-months and 12-months timescales is shown in Figure 4.2. The correlation is performed based on only SGI_{12} with the different timescales of SPI and RDI. The correlation coefficient between these indices showed positive and negative relationship. The positive correlation indicates that the wells are located in close vicinity to streams and rivers that recharges the aquifer. On the other hand, the negative correlation demonstrates that these wells are situated in areas of aquifer where hydrogeological conditions and processes as well as extensive withdrawal dominates the behavior of the alluvial aquifer. The highest positive correlation coefficient was with the groundwater level of well 567 (SPI_{12} = 0.47 and RDI_{12} = 0.48) while the highest negative was with the well 706 (SPI_{12} = -24 and RDI_{12} = -0.25). The analysis also revealed four specific patterns of the influence of the drought in different timescale to groundwater level. The first pattern was visible in the majority of the wells that demonstrated a linearly decreasing relationship between the aquifer and the different timescales of drought. In this case the correlation coefficient was high in short term and constantly decreased in medium and long term (well 517: SPI_3 = 0.29 and RDI_3 = 0.29, SPI_6 = 0.21 and RDI_6 = 0.21 and SPI_{12} = 0.17 and RDI_{12} = 0.18). This show that the area is a discharge area and the aquifer recharges during the short term. Whereas, in the medium and long-term extensive extraction and possible salt water intrusion takes place. The second pattern was the linearly increasing relationship where the correlation coefficient was constantly increasing from short to medium and long term (well 1979: SPI_3 = 0.07 and RDI_3 = 0.08, SPI_6 = 0.16 and RDI_6 = 0.17 and SPI_{12} = 0.26 and RDI_{12} = 0.25). In the third pattern a convex type relationship existed, where the high coefficient in the short term decreased in the medium term but subsequently increased in the long term (well 324: SPI_3 = 0.41 and RDI_3 = 0.41, SPI_6 = 0.25 and RDI_6 = 0.27 and SPI_{12} = 0.30 and RDI_{12} = 0.31). In the fourth pattern the relationship was of concave type. In this case the coefficient increased from short to medium term but decreased in the long term (well 567: SPI_3 = 0.52 and RDI_3 = 0.51, SPI_6 = 0.54 and RDI_6 = 0.54 and SPI_{12} = 0.47 and RDI_{12} = 0.48).

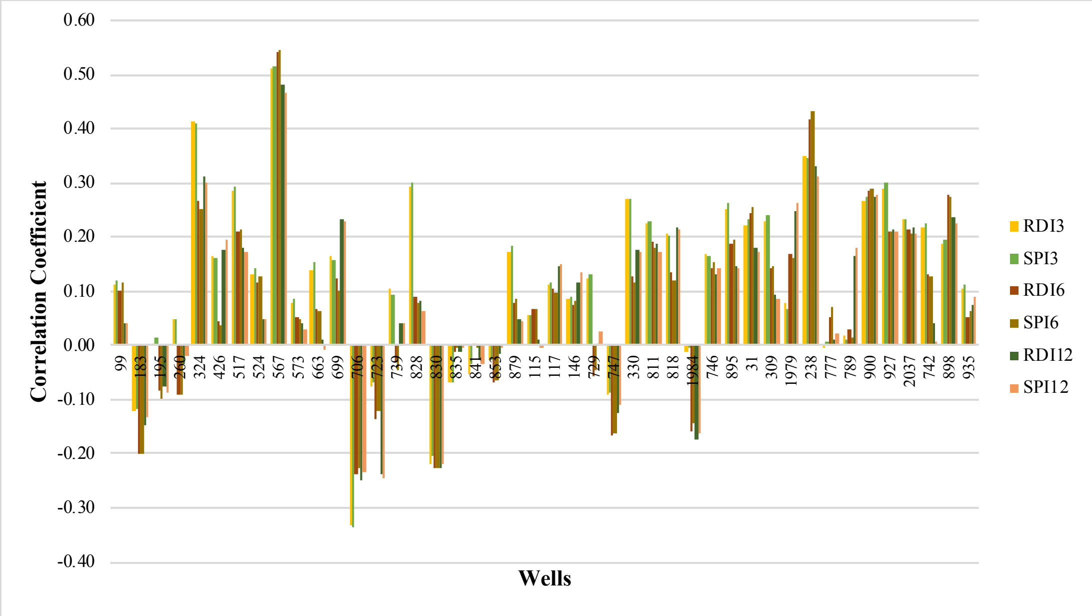


Figure 4.2: Correlation between SGI and SPI and RDI based on the 44 wells at different timescale.

4.6.4 Temporal Response of Aquifer to Drought

The comparison between the groundwater level quantified by SGWLA and SGI and SPI and RDI is depicted by the hydrograph shown in Figure 4.3. The hydrograph demonstrated important features of the response of aquifer in terms of temporal water level fluctuation to extreme events of climate change and variability. The result indicated that the positive and negative values of SGWLA and SGI representing the rise and fall in groundwater level with respect to long term mean, partly resembled the positive and negative SPI and RDI values indicating the wet and dry years. During wet years SGWLA and SGI is mostly positive while during dry years its mostly negative. Exception to this pattern exists in few years where SGWLA and SGI is positive and SPI & RDI values are negative or vice versa. Though the fluctuation in SGWLA and SGI follow the same pattern generally, the rate and magnitude of SGWLA and SGI is not homogeneous in space and time. Another important feature observed is the upward movement of SGWLA and SGI after any drop down during any drought event. This indicates the recovery of the groundwater level to pre-drought condition. However, the rate of recovery after each drought event depending upon different factors is not always the same and constant. Observing the hydrograph, the water table in aquifer is more sensitive to the duration of the drought rather than to its severity. The longer the duration of the drought even with low severity, the higher would be the impact.

Figure 4.3: Spatio-temporal comparison of SGWLA and SGI and SPI and RDI in different locations of Güzelyurt Aquifer.

Figure 4.3(continued): Spatio-temporal comparison of SGWLA & SGI and SPI & RDI in different locations of Güzelyurt/Morphou Aquifer.

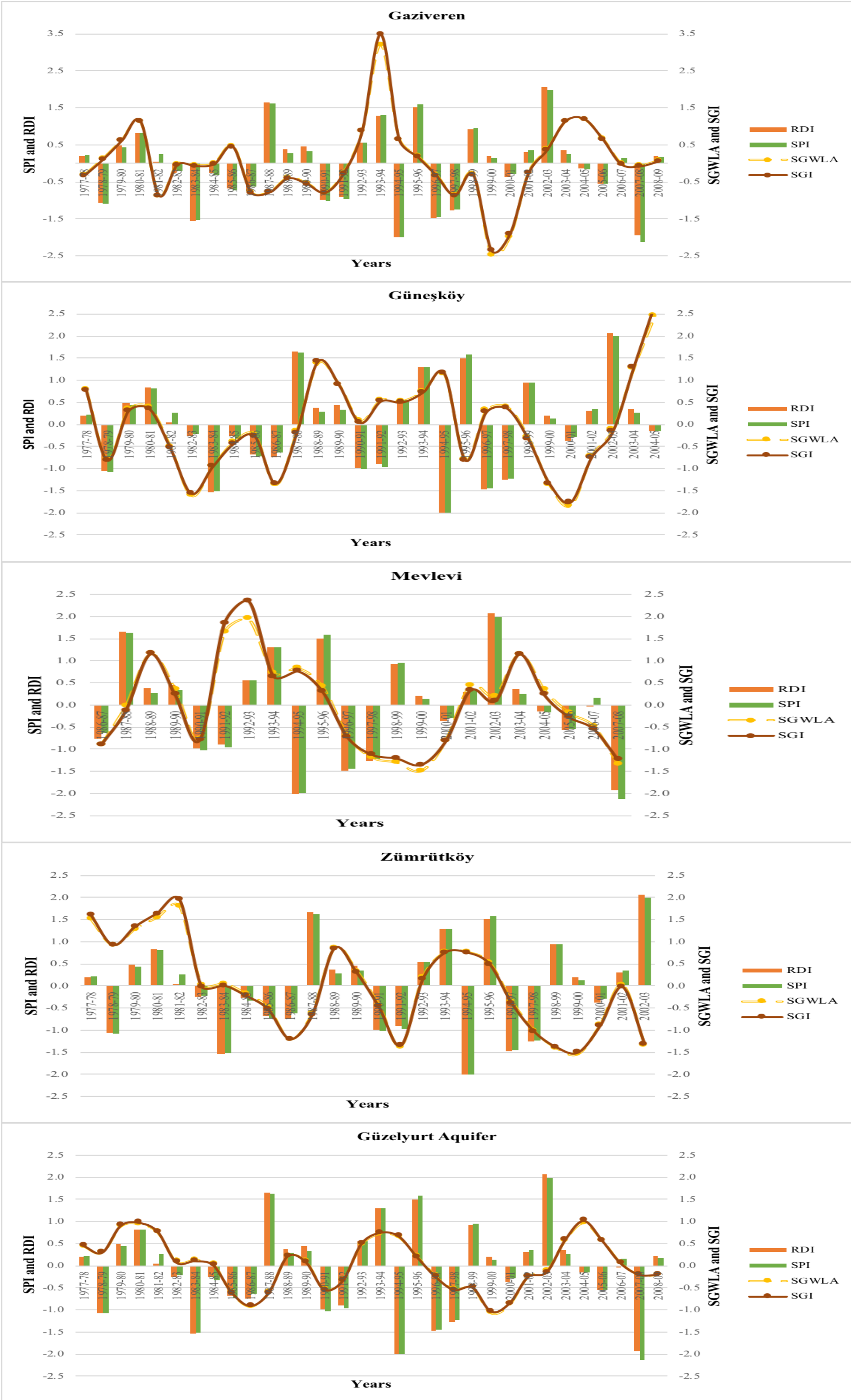


Figure 4.3(continued): Spatio-temporal comparison of SGWLA & SGI and SPI & RDI in different locations of Güzelyurt/Morphou Aquifer.

The resemblance and close relationship between the fluctuation of SGWLA and SGI and SPI and RDI can also differentiates the effect of climate extremes on water table within the aquifer and the effect of other natural processes and anthropogenic activities. In this respect, four separate conditions depending upon the rate and magnitude of the fluctuation due to the effect of drought in this case, can be drawn from the hydrograph. The first condition is where the values of SGWLA and SGI is approximately equal to the negative SPI and RDI values. This represents the sole direct effect of drought on the water table of the aquifer. During the drought event of 1985-86, 1991-92, 1997-98 and 1986-87 in Güzelyurt, Bostancı, Yeşilyurt and Yuvacık, respectively, SGWLA and SGI and SPI and RDI values coincide with each other. The second condition is where SGWLA and SGI is smaller than SPI and RDI negative values, possibly signifying the combined direct effect of drought and management actions such as implementing adaptation measures like limiting the withdrawal to certain threshold during the drought event. This is the case in Sahinler, Kumköy, Aydınköy and Akçay during the drought event of 2007-08, 1990-91, 1994-95 and 1978-79, respectively. The third condition is where the values of SGWLA and SGI is greater than SPI and RDI negative values, demonstrating the combined direct effect of drought and indirect effect of heavy extraction from the groundwater for irrigated agriculture. In this case, the indirect effect of withdrawal due to drought outweigh the direct effect of drought on the aquifer. This is the situation during the drought event of 2000-01, 1986-87, 1986-87 and 1991-92 in Gaziveren, Güneşköy, Mevlevi and Zümrütköy, respectively. The fourth condition is where both SGWLA and SGI and SPI and RDI values move in opposite direction. This is the case where SPI and RDI values are negative and have a downward slope and SGWLA and SGI is positive and have an upward slope or vice versa. In this situation, the effect during any drought event can be possibly due to combined effect of drought and other natural processes such as heavy salt water intrusion into the aquifer or combined effect of drought and management actions like completely stopping the water extraction from the aquifer. In these cases, the effect of management actions or natural processes is much more dominant than the effect of drought due to the reduced recharge of the aquifer. The behaviour of SGWLA and SGI and SPI and RDI values based on this condition is visible in Güzelyurt, Yuvacık, Aydınköy and Mevlevi during the drought event of 2004-05, 1994-95, 1983-1984 and 1994-95, respectively.

4.6.5 Quantified Effect of Drought on GWL

In previous sections it was explained about the spatio-temporal effects of drought on groundwater and the response and behaviour of aquifer to this phenomenon. For the purpose of formulating and designing adaptation measures for the protection of aquifer, to estimate the increase in energy due to reduction in groundwater level (GWL), and the combined effect of this on farm level revenue where groundwater is the main source of supplying water, during drought with respect to the different levels of severity, an attempt has been made to approximately calculate the reduction in GWL with respect to the mean GWL. By utilizing the moderate, severe and extreme severity level values obtained from SPI and RDI between years 1977 and 2009 where these events had taken place, the corresponding GWL of 44 wells with only negative values (which represents the reduction with respect to mean GWL) with respect to these years and severity levels are aggregated and their average is obtained. Figure 4.4 depicts the mean, low and high reduction in GWL with respect to mean GWL based on drought severity levels. It was found out that the average reduction in GWL of 44 selected wells during moderate, severe and extreme drought events was approximately 3, 4 and 5 meters, respectively. Meanwhile, the highest reduction in GWL during drought for the same categories was approximately 11, 8 and 13 meters, respectively. Likewise, the lowest reduction was approximately 0.01, 1.46 and 0.74 meters, respectively.

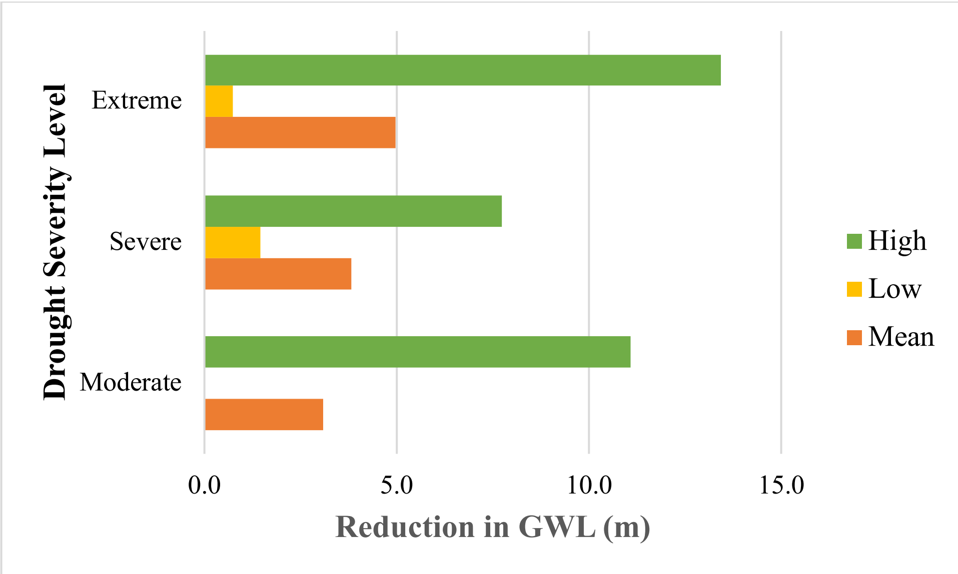


Figure 4.4: Average GWL reduction with respect to mean GWL of 44 wells based on drought severity levels.

4.6.6 Validation of the Results

The findings of this chapter are validated with respect to the results of other published studies. A good agreement has been observed between the results of this study and other relevant studies. Khan et al. (2008) using SPI and different length of groundwater level timeseries data for various locations of Australia found correlation in the range of -0.09 and 0.9 between SPI and groundwater level fluctuation at different timescales. Similarly, Lorenzo-Lacruz et al. (2017) found that the correlation between SGI and SPI representing the response of groundwater level to temporal change in precipitation was in the range of 0.2 and 0.7. Likewise, Lorenzo-Lacruz et al. (2017) showed that the spatial response of aquifer to the variability in precipitation had a correlation between -0.4 and 0.8.

4.4 Chapter Conclusions

Quantifying the spatial and temporal effect of drought on groundwater resources is essential for sustainable management and utilization of groundwater resources under changing climate. Within this context, SPI and RDI is combined with SGWLA and SGI of the groundwater level time series data to produce the required hydrographs in order to investigate and assess the response of groundwater resources to temporal and spatial effect of drought. For in depth understanding, non-parametric Mann–Kendall trend test and Sen's slope estimator and the linear regression method is used to quantify the temporal changes and behavior of aquifer.

The analysis revealed that partially there exists a positively weak relationship between SGWLA and SGI and SPI and RDI at different locations of the aquifer. This indicate that both SPI and RDI behaves in a similar manner in revealing though weak, the influence and effect of drought on groundwater. The weak connection can be attributed to complex nature of hydrogeological processes, aquifer systems and varying pattern of consumption. The groundwater hydrographs also demonstrated that there exists a positive relationship between groundwater levels and SPI and RDI in different years of drought. The temporal fluctuation of SGWLA and SGI in the hydrograph partly resembled the positive and negative values of SPI and RDI.

The groundwater level trend signified that the water in Güzelyurt/Morphou aquifer due to variability in precipitation, increase in frequency of dry years and anthropogenic activities is declining at a mean rate of 0.11 m/year. However, depending upon spatial heterogeneity of climate, soil and hydrogeological conditions and pattern of usage the rate varied across the aquifer areas. Location with highest declining rate can be the potential discharge areas while in those areas where the groundwater is stabilized are the potential recharge areas or are highly affected by the intrusion of the sea water.

Nevertheless, the estimated mean reduction in GWL with respect to mean GWL during moderate, severe and extreme drought is estimated as 3, 4 and 5 meters, respectively.

The result of this study can provide a preliminary information for sustainable and strategic planning, management and monitoring of groundwater resources in the face of climate change. In areas where the trend is significantly negative or where over pumping takes place and are the main discharge areas, the authorities can devise a plan to discourage users to lower the extraction. More research is required to better understand the hydrological and meteorological processes and their impact in an integrated way. Moreover, to better understand the influence of different factors affecting the aquifer it is also recommended to estimate the variation in pumping rate and/or drought induced pumping under different climatic scenarios and conditions as well as assess the effect of the change in land use and management actions.

Chapter 5

WATER-FOOD-ENERGY NEXUS AND DROUGHT

5.1 Introduction

Sustainable development and efficient planning, management and governance of scarce resources across scale and sectors can be achieved through an integrated and holistic approach (Olsson, 2013). As a consequence of unsustainable exploitation of natural resources due to increase in human population, accelerating economic growth, climate change and rapid urbanization, the demand for water, food, and energy is rising exponentially and their security is imminently under immense pressure and threat (Cai et al. 2018; Martinez-Hernandez et al. 2017, Eftelioglu at al. 2016). Over the coming decades it is expected that the demand for food, water and energy will increase between 30% to 50% (Kaddoura and El-Khatib, 2017).

In recent years, the concept of Water-Food-Energy (WFE) nexus has taken a center stage and is rapidly expanding among researchers, scientists, practitioners and decision makers around the world (Liu et al. 2017; Olsson, 2013). The WFE nexus approach is an interconnected, integrated and interdisciplinary platform by linking water, food and energy together and identify the synergies and tradeoffs between them which is mainly based on the strengths of existing disciplines and approaches for efficient utilization, management and governance of scarce resources in the dynamic and non-stationery world (Martinez-Hernandez et al. 2017; Mohtar and Lawford, 2016; FAO, 2014; Hoff, 2011**)**. Because of its inherited holistic and integrated nature, it has turned into a crucial instrument in policy and planning (Liu et al. 2017). Under the varying demand and climatic conditions, the nexus perspective is to maximize benefits, balance and manage trade-offs, minimize risks, internalize impacts, enhance efficiency, capture synergies, reduce social, economic and environmental externalities and explore new opportunities (Albrecht et al. 2018; Yillia, 2016; Olsson, 2013). Meanwhile, being developed and adopted freshly, there is a lack of agreed definition for the nexus, unified concept, development and utilization of varying integrated approaches that differs in scope, objective and understanding (Liu et al. 2017; Smajgl et al. 2016; Daher and Mohtar, 2015).

The conventional 'silo' approach of dealing with water, food and energy independently without considering the synergies and trade-offs between them, is losing ground as such approaches have failed to be efficient under the current changing environment considering the interconnection involved among these scarce resources (Cai et al. 2018; Menegaki et al. 2018; Daher and Mohtar, 2015; Olsson, 2013). In fact, it has become clear that there exists critical spatio-temporal interlinkages, significant interdependences and complex interconnections between water, food and energy (Martinez-Hernandez et al. 2017; Hoff, 2011). Water is required in the production of energy (hydroelectric power generation, thermoelectric power generation, nuclear power generation). Energy is essential in the extraction, production, treating, and distribution of water (surface and groundwater pumping, desalination, wastewater treatment). Food is essential in the production of energy (bioenergy/biofuel). Energy is essential in different activities of food production. In food production, on farm and off farm activities are heavily dependent upon water (Martinez-Hernandez et al. 2017; Yillia, 2016). Meanwhile, nexus approach requires a balanced look into the system by considering the interplay of all dimensions rather than sector focused intervention and giving privilege to one dimension over another

(Liu et al. 2017; Smajgl et al. 2016). With this in mind, investments would be required to be made on the WFE nexus rather than the nexus dimension separately because investing in one dimension can influence the other dimension negatively (Cai et al. 2018; Yillia, 2016; Kaddoura and El-Khatib, 2017).

Climate change is one of the most important drivers that directly affects the nexus system and create conflicts between the different dimensions of the nexus (Olsson, 2013). Climate change impact among others escalate the warmness in air temperature, alter the precipitation regime and increase its uncertainty and give rise to prolonged, frequent and severe occurrence of drought (Liu, 2016; Yillia, 2016; IPCC, 2014). Climate change and drought produce and transmits a ripple effect across WFE system where the effect of drought on one dimension of nexus will propagate to other dimensions and circulate back (Mohtar and Lawford, 2016; Smajgl et al. 2016). Drought effect on one dimension due to the interlinkages will have a wider linear or non-linear consequence on the other dimensions. Regions susceptible to drought and during drought the demand for these resources will rise by the different sectors within the nexus dimensions (Yillia, 2016). As such integrated and holistic perspective to the assessment of WFE system to better understand and manage the cyclic effect within the boundaries of the system across scale and sector is both crucial and is key to sustainable and efficient design and management WFE nexus under extreme events of climate change (Cai et al. 2018; Liu, 2016; Mohtar and Lawford, 2016).

Moving towards an integrated approach with multiple dimensions across different scales and sectors will encompass complexity as well (Liu et al. 2017). Simplifying the complex framework and nexus processes will be a challenge to be resolved efficiently for the operationalization and successful implementation of nexus (McCarl et al. 2017b). Though balanced quantification of nexus dimensions and elements is complex in nature, it depends on establishing an efficient model with the linkages between the elements are clearly defined based on specific problem boundaries and scales (Miralles-Wilhelm, 2016; Yillia, 2016; Bazilian et al. 2011). To model the WFE nexus integrating physical, biophysical, chemical, hydrological, and socioeconomic processes and environments in one integrated model is required for better understanding of the dynamic and interconnected system (Cai et al. 2018). On the other hand, to assess and evaluate the nexus system generally matrices/indicators/indices are used. With this in mind, considering multiple matrices to be representative of all dimensions of WFE system is desirable (Tevar et al. 2016).

Many studies have been conducted on modelling and analyzing the impact of drought on agriculture, water resources and energy with remarkable results. However, the use of integrated approach such as WFE nexus platform that keeps into consideration the intersectoral linkages and interdependences among the nexus elements are both slow and fragmented (Albrecht et al. 2018; Liu et al. 2017; Liu, 2016; Daher and Mohtar, 2015). Likewise, linking drought to WFE nexus to understand the degree of influence of drought on WFE dimensions and the nexus is limited (Liu, 2016). El-Gafy et al. (2017a) used maximization technique to compare the nexus and non-nexus approach for optimal cropping pattern. El-Gafy (2017) using indicators analyzed the agriculture production system within the WFE nexus framework. De-Vito et al. (2017) considering the WFE nexus approach and employing indices evaluated the practices of irrigation water use. Zhang et al. (2017) used the concept of WFE nexus to develop an effective management system to combat agriculture drought. Zhang and Vesselinov (2017) developed an integrated optimization model to quantitively evaluate the synergies and tradeoffs between nexus dimension.

Therefore, the objective of this chapter is to link and combine drought to WFE nexus and quantify the impact of drought on nexus and its respective dimensions through an integrated indexed based model. This will also fill the existing knowledge gap and support the operationalization of WFE nexus. The proposed method is applied at farm level to perform a spatial intensity-based drought impact assessment of 13 different seasonal and perennial rainfed and irrigated crops. Indicators and indices are used to describe the different aspects of the nexus under varying drought conditions with respect to resource consumption and output productivity and profitability. Meanwhile, by having considered different indictors, performance-based drought induced WFE nexus index is derived to quantify the intensity-based drought impact of WFE nexus. Further to this, effect of drought on energy consumption and farm level profitability that also influences the WFE nexus indicators and sub-indices, is also discussed in detail.

5.2 Materials and Methods

5.2.1 Conceptual Framework

The entire methodological framework to carry out the study with respect to WFE nexus is illustrated in detail in the first chapter. In previous chapters, sub-models with respect to drought (chapter 2), agriculture (chapter 3) and groundwater (chapter 4) have been discussed. In this chapter the energy and the socio-economic sub-models of the nexus simulation model is explained. The output of these sub-models is consequently used to assess the effect of drought on WFE nexus through the derivation of the drought induced WFE nexus index (DI-WFENI).

5.2.2 Energy Sub-model

The energy model is based on the approach suggested by El-Gafy (2017) and is used to determine the amount of direct and indirect energy consumption in the process of crop production. Direct energy is the energy provided by fuel and electricity required in different farm activities and indirect energy is the energy used in producing fertilizers and pesticides (El-Gafy et al. 2017b). The total energy per unit land of a crop is calculated by the following equation. As per the requirement of this thesis the original formula provided by El-Gafy (2017) is modified by the author to include the weather condition.

$$\boldsymbol{E}_{(z,c,t,i)}(MJ/ha) = \sum j_h h_{(z,c,t,i)} + j_m m_{(z,c,t,i)} + j_d d_{(z,c,t,i)} + j_e e_{(z,c,t,i)} + j_w w_{(z,c,t,i)} + j_f f_{(z,c,t,i)} + j_p p_{(z,c,t,i)} + j_s s_{(z,c,t,i)} \quad (5.1)$$

where, $E_{(z, c, t, i)}$ is the total energy per hectare (MJ/ha) at location z, crop c, time t, and i weather condition (wet year or dry year based on drought severity level). j_h, j_m, j_d, j_e, j_w, j_f, j_p, and j_s are the energy equivalents of human labor (MJ/hr), machinery (MJ/hr), diesel fuel used for machinery (MJ/l), water for irrigation being pumped using electricity (MJ/kWh), water for irrigation being pumped using fuel pump (MJ/m^3), fertilizer (MJ/kg), pesticides (MJ/kg) and seeds (MJ/kg). The variables $h_{(z, c, t, i)}$, $m_{(z, c, t, i)}$, $d_{(z, c, t, i)}$, $e_{(z, c, t, i)}$, $w_{(z, c, t, i)}$, $f_{(z, c, t, i)}$, $p_{(z, c, t, i)}$ and $s_{(z, c, t, i)}$, are unit quantities of factors of production for human labor (hr/ha), machinery (hr/ha), diesel fuel used for machinery (l/ha), electricity used for irrigation (kWh/ha), irrigation water requirement being pumped using diesel pump (m^3/ha), fertilizer (kg/ha), pesticides (kg/ha) and seeds (kg/ha), respectively.

In the equation 5.1, the energy equivalent of human labor (j_h, MJ/hr) is obtained from El-Gafy et al. (2017). The human labor factor ($h_{(z, c, t, i)}$, hr/ha) is obtained through personal interaction with the farmers and personal calculation using either the total cost of production or the total price to the hired labor.

The energy consumed by the machinery (j_m, MJ/hr) is obtained from El-Gafy et al. (2017). The machinery usage ($m_{(z, c, t, i)}$, hr/ha) is obtained through personal interaction with the farmers and Photiades et al. (1989).

The energy equivalent of diesel fuel per liter of fuel (j_d, MJ/l) is a standard factor (1 L = 38.4 MJ). The fuel $d_{(z, c, t, i)}$ (l/ha) consumed by machinery utilized for the different activities to cultivate one ha of crop c, is calculated by applying the following equation:

$$\boldsymbol{d}_{(z,c,t,i)}(l/ha) = \frac{q_{(z,c,t,i)} * K * HP_{(z,c,t)} * LF}{KPL} \tag{5.2}$$

where, $q_{(z,c,t,i)}$ (hr/ha) is the machine working hours at location z, crop c, time t, and i weather condition (wet year or dry year based on drought severity level), K is the kg of fuel used per brake (kg/kWh), LF is the load factor in (%) and KPL is the weight of fuel in (kg/l). Historical timeseries data between 1995 and 2013 related with number of machinery and machine horse power $HP_{(z,c,t)}$ were obtained from agriculture statistical year book published by Ministry of Agriculture and Forestry of northern part of Cyprus. Data on K, LF, and KPL were obtained from FAO (1992).

The irrigation water requirement being pumped using diesel pump ($w_{(z, c, t, i)}$, m^3/ha) for each crop is obtained from agriculture sub-model discussed in Chapter 3. The energy equivalent j_w to extract one-meter cube of water (MJ/m^3) for irrigation purposes using fuel pump is estimated by the equation as shown below:

$$\boldsymbol{j}_{(w)}(MJ/m3) = \frac{V_w * \rho * g * H_{(z,t,i)}}{\varepsilon} * 10^{-6} \tag{5.3}$$

where, V_w is the volume of water (m^3), ρ is the density of water (1000 kg/m^3), g is the gravitational acceleration (9.81 m/s^2), $H_{(z,t,i)}$ is the total head (groundwater depth and pressure head of the irrigation system (m)) at location z, time t and i weather condition (wet year or dry year based on drought severity level), ε is the efficiency of the pumping system (%) and 10^{-6} is the factor to change J into MJ. The total head is obtained from groundwater sub-model discussed in chapter 4 and the pump efficiency based on different studies is assumed to be 50%.

The energy equivalent of electric pump (j_e, MJ/kWh) to extract water from groundwater is a standard factor (1 kWh = 3.6 MJ). To estimate electricity used for irrigation ($e_{(z, c, t, i)}$, kWh/ha), annual time series data on electricity consumption (kWh) for irrigation purposes between 1995 and 2013 was obtained from the national statistical year book published by State and Planning Organization of northern part of Cyprus. Initially, mean value of electric consumption is computed and is converted into MJ using the standard factor. To estimate the total average amount of water (m^3) withdrawn from the aquifer, the electric consumption in MJ is then divided by the energy equivalent j_w (MJ/m^3) obtained from equation 5.2. The mean electric consumption is then divided by the calculated average amount of withdrawn water in m^3 to obtain a unit value in kWh per m^3. The obtained factor in kWh/m^3 is finally multiplied by the irrigation water requirement of each crop per hectare (obtained in chapter 3) to estimate electricity used for irrigation ($e_{(z, c, t, i)}$, kWh/ha).

The energy equivalent of fertilizer (j_f, MJ/kg) is obtained from El-Gafy et al. (2017b) and the fertilizer usage for each crop per hectare ($f_{(z, c, t, i)}$, kg/ha) is obtained from FAO statistics (www.fao.org), www.datamarket.com and personal interaction with the farmer. The energy equivalent of pesticides $p_{(z, c, t, i)}$ and seeds $s_{(z, c, t, i)}$ is not currently accounted in the calculation of the total energy consumption.

The final equation used in this study is as follow.

$$\boldsymbol{E}_{(z,c,t,i)}(MJ/ha) = \sum j_h h_{(z,c,t,i)} + j_m m_{(z,c,t,i)} + j_d \left(\frac{q_{(z,c,t,i)} * K * HP_{(z,c,t)} * LF}{KPL}\right) + j_e e_{(z,c,t,i)} + \left(\frac{V_w * \rho * g * H_{(z,t,i)}}{\varepsilon} * 10^{-6}\right) w_{(z,c,t,i)} + j_f f_{(z,c,t,i)} \quad (5.4)$$

5.2.3 Socio-economic Sub-model

The socio-economic sub-model is the most important model of the WFE nexus modelling approach presented in this thesis. The output from the rest of the models are all input along with other technical and financial parameters to analyze the impact of drought at the farm level and on WFE nexus utilizing different indicators and indices. A generalized drought induced WFE index under different severity levels of drought is developed. The socio-economic model to be built on is made up of three major parts as shown in Figure 5.1. The first part is to analyze the impact of drought on farm level budget using Cost Benefit Analysis approach. The second part deals with the derivation of indicators, sub-indices and WFE index under the various severity level of drought. The third part is to conduct sensitivity analysis on key and uncertain variables that may affect the different output of the socio-economic sub-model particularly the drought induced WFE index.

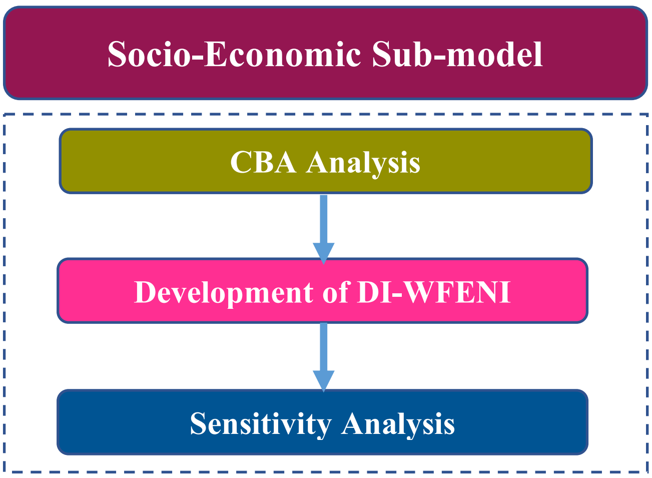


Figure 5.1: Socio-Economic sub-model flowchart.

5.2.4 Cost Benefit Analysis

The first part is the analysis at farm level based on the approach given by Jenkins, Kuo, and Harberger (2011) methodology for Cost Benefit Analysis (CBA). In this part the aim is to conduct financial analysis to produce the cashflow statement from the point of view of farmer (total investment point of view) where all the revenues (potential revenue) items are considered to be cash inflows and all the expenditures (potential expenditure) items are treated as cash outflows (Dhakal et al. 2012). Currently, in this study as per the original approach, cashflow statements from other point of views (bankers' point of view or equity point of view), economic analysis and stakeholder analysis is not analyzed. The first part of the socio-economic model consists of three working tables that includes input parameter table, the preparatory calculation table and the cashflow estimation table. The input parameter table contains data obtained from other models of this study, collected from the field, adopted from statistical reports and other studies. This table is the basis for the computation of the subsequent tables. The preparatory calculation table contains the growth rate indices for different crops (yield, selling and purchase price, input usage, labor usage and wage, machinery usage, rental and fuel price, electricity usage and price, water usage and price), the inflation (for the domestic and US economy) and exchange rate (the exchange rate between the US dollar and the Turkish Lira) indices, the annual crop production amount and the value of production, the input quantity, the operating cost including the input cost and the service cost in the production of crops and the calculation of working capital. The cash-flow statement table is constructed from the viewpoint of the farmer (total investment). The inflow includes the value of home consumption and sale, including the potential revenue the farm earns if the by-product such as straw is sold in the market and the subsidy if received from the government.

The outflow includes all the incurred expenditure including the input costs, the service costs (fixed costs, maintenance costs, transportation and handling costs, land tax, and miscellaneous costs).

For conducting the CBA analysis of the socio-economic sub-model, a variety of multidisciplinary datasets are used including climatic data, crop data, soil data, energy data, groundwater data and financial and technical data. The datasets with respect to financial and technical data are described in the following paragraph. The other datasets are discussed in previous sections and chapters.

The historical production, cultivated area, yield, selling prices (farmgate, wholesale and retail) purchase prices (seeds, fertilizers, pesticides) and irrigation technology between 1995 and 2013 for various crops in each agriculture zone and drought related subsidy paid by the government is obtained from Ministry of Agriculture and Forestry annual statistical books (ASP, 1995-2013). The number of electric and fuel pump, agriculture employment related data, agriculture households and land distribution are extracted from the 1995 general agriculture census published by the Ministry of Agriculture and Forestry. Input requirements (fertilizers, pesticides, labour and machinery), unit cost of labour, machinery and water and other production related costs are obtained from www.datamarket.com, www.ourworldindata.org, FAO statistics (www.fao.org), Photiades et al. (1989), EU (2011b) and field survey. The field data (quantity of inputs used in the production of crops, their respective costs, other production costs and estimated revenue) related are validated based on personal interactions with the farmers. Historical inflation, exchange rate and fuel price from the national statistical year book published by State and Planning Organization of northern part of Cyprus.

5.2.5 Derivation of DI-WFENI Index

The second part within the socio-economic model is the analysis and derivation of WFE nexus indicators, sub-indices and index that is accomplished in two working tables. The first table is the calculation of indicators for each crop under the base scenario and the different severity levels of drought. In this study nine standard indicators specified by El-Gafy et al. (2017), King and Carbajales-Dale (2016) and FAO (2014) are taken into consideration which are then used in the second working table to derive the intensity-based drought induced WFE sub-indices and index. From the nine indicators used in this thesis five sub-indices are derived. The sub-indices include the Consumption, Productivity, Profitability, Efficiency, and Levelized Profit Margin sub-indices. The formulation of the indicators is numbered below.

1- **Water consumption indicator** ($W_{(z,c,t,i)}$, m^3/ha): It is the total blue water (surface and ground water) consumption per hectare (m^3/ha) of land during a season by crop c, at zone z, time t and weather condition i. It is obtained from the crop sub-model discussed in Chapter 3.

2- **Energy consumption indicator** ($\boldsymbol{E}_{(z,c,t,i)}$, (MJ/ha)): It is the total energy consumption per hectare of land (MJ/ha) at location z, for the production of crop c, during time t, and weather condition i. It is obtained from the energy sub-model discussed in section 5.2.2 of this Chapter.

3- **Water productivity indicator** ($\boldsymbol{W}^{\boldsymbol{p}}_{(z,c,t,i)}$, kg/$m^3$): This indicator is calculated using the following formula:

$$W^{p}_{(z,c,t,i)} = \frac{Y_{(z,c,t,i)}}{W_{(z,c,t,i)}} \quad (5.4)$$

where: $Y_{(z,c,t,i)}$ is the yield of crop c (kg/ha), at location z, time t, and weather condition i and $W_{(z,c,t,i)}$ is the total blue water consumption per hectare (m^3/ha) of land during a season by crop c, at zone z, time t and weather condition i. The yield of crop is obtained from annual statistical yearbook.

4- **Energy productivity indicator** ($\boldsymbol{E^{p}_{(z,c,t,i)}}$, kg/MJ): This indicator is calculated using the following formula:

$$E^{p}_{(z,c,t,i)} = \frac{Y_{(z,c,t,i)}}{E_{(z,c,t,i)}} \tag{5.5}$$

where: $Y_{(z,c,t,i)}$ is the yield of crop c (kg/ha), at location z, time t, and weather condition i and $E_{(z,c,t,i)}$ is the total energy consumption per hectare (m^3/ha) of land during a season by crop c, at zone z, time t and weather condition i.

5- **Water profitability indicator** ($\boldsymbol{W^{f}_{(z,c,t,i)}}$, \$/m^3): This indicator is calculated using the following formula:

$$W^{f}_{(z,c,t,i)} = \frac{NCF_{(z,c,t,i)}}{W_{(z,c,t,i)}} \tag{5.6}$$

where: $NCF_{(z,c,t,i)}$ is the net cashflow from farmers point of view for crop c (kg/ha), at location z, time t, and weather condition i and $W_{(z,c,t,i)}$ is the total blue water consumption per hectare (m^3/ha) of land during a season by crop c, at zone z, time t and weather condition i. NCF (total revenue less total cost) is computed in CBA analysis part of socio-economic sub-model discussed in section 5.2.4 of this Chapter.

6- **Energy profitability indicator** ($\boldsymbol{E^{f}_{(z,c,t,i)}}$, \$/MJ): This indicator is calculated using the following formula:

$$E^{f}_{(z,c,t,i)} = \frac{NCF_{(z,c,t,i)}}{E_{(z,c,t,i)}} \tag{5.7}$$

where: $NCF_{(z,c,t,i)}$ is the net cashflow from farmers point of view for crop c (kg/ha), at location z, time t, and weather condition i and $E_{(z,c,t,i)}$ is the total energy consumption per hectare (MJ/ha) of land during a season by crop c, at zone z, time t and weather condition i.

7- **Water efficiency indicator** (**$W^{e}_{(z,c,t,i)}$**, $/m³): This indicator is calculated using the following formula:

$$W^{e}_{(z,c,t,i)} = \frac{TOF_{(z,c,t,i)}}{W_{(z,c,t,i)}} \tag{5.8}$$

where: $TOF_{(z,c,t,i)}$ is the total outflow or the total cost incurred by the farmer in the production of crop c (kg/ha), at location z, time t, and weather condition i and $W_{(z,c,t,i)}$ is the total blue water consumption per hectare (m^3/ha) of land during a season by crop c, at zone z, time t and weather condition i. TOF (the total crop production cost) is calculated in CBA analysis part of socio-economic sub-model discussed in section 5.2.4 of this chapter.

8- **Energy efficiency indicator** (**$E^{e}_{(z,c,t,i)}$**, $/MJ): This indicator is calculated using the following formula:

$$E^{e}_{(z,c,t,i)} = \frac{TOF_{(z,c,t,i)}}{E_{(z,c,t,i)}} \tag{5.9}$$

where: $TOF_{(z,c,t,i)}$ is the total outflow or the total cost incurred by the farmer in the production of crop c (kg/ha), at location z, time t, and weather condition i and $E_{(z,c,t,i)}$ is the total energy consumption per hectare (MJ/ha) of land during a season by crop c, at zone z, time t and weather condition i.

9- **Levelized profit margin indicator** (**$P_{(z,c,t,i)}$**, %): This indicator is calculated using the following formula:

$$P_{(z,c,t,i)} = \frac{NCF_{(z,c,t,i)}}{TOF_{(z,c,t,i)}} \tag{5.10}$$

where: $NCF_{(z,c,t,i)}$ is the net cashflow from farmers point of view for crop c (kg/ha), at location z, time t, and weather condition I and $TOF_{(z,c,t,i)}$ is the total outflow or the total cost incurred by the farmer in the production of crop c (kg/ha), at location z, time t, and weather condition i.

In the second working table, the above indicators are used to derive the intensity-based drought induced WFE index (DI-WFENI). The index is calculated based on weighted arithmetic method as below:

$$DI - WFENI_{(z,c,t,i)} = \frac{\sum_1^m w_n * S_n}{\sum_1^m w_n} \tag{5.11}$$

where: $DI - WFENI_{(z,c,t,i)}$ is the drought induced WFE nexus index at location z, for crop c, time t, and drought severity/intensity level i. w_n is the weight assigned on the indicators, m is the number of indicators used. The highest value for w_n is 1 representing the best situation while worst situation is represented by 0. In this study all the indicators are assigned an equal value of 1. S_n is the normalized and dimensionless unit value of the indicators. S_n is calculated in order to take the effect of different units with respect to each indicator so that indicators can be easily aggregated or compared. It is calculated using the distance to a reference method (Juwana et al. 2012) as:

$$S_n = \frac{X_d}{X_r} \tag{5.12}$$

where: X_d is the value of indicator n during any level of severity of drought and X_r is the value of the indicator during the reference year (year 2012-13 is selected as reference year in this study as discussed in Chapter 3) at zone z, for any crop c and time t.

5.2.6 Sensitivity Analysis

The sensitivity analysis is performed on the energy and socio-economic sub-models. It is generally performed because the absolute values of parameters used in the model are not perfectly error free. As such, there always exists uncertainty in these values and their consequences on the major outputs of the model can be significant (Payab, 2009). The analysis mainly focused on the key variables or variables that are highly uncertain or have the greatest effect on the final major outputs of the models. It is performed by varying the values of these parameters in an arbitrary manner to determine the extent to which the outputs of the models are altered (WEF nexus indices and index, the increase in irrigation water requirement rate (IWR) and the reduction in net cashflow or the profit of rain-fed and irrigated crops). The final values of these outputs are computed with respect to this variation from the baseline. In this Chapter the sensitivity results on DI-WEFNI index is only discussed. The sensitivity results of other outputs are provided in Appendix B.

5.3 Results and Discussions

5.3.1 Effect of drought on the consumption of energy for crop production

The energy model based on the WFE nexus approach of this study, estimated the total consumption of energy in the production of different rain-fed and irrigated crops during wet and dry conditions. Figure 5.2 and Figure 5.3 demonstrates the energy profile of the reference year with respect to cropping system at the various agricultural zones. As can be observed, the joint contribution of energy provided by fertilizers and diesel fuel for rain-fed crops is estimated as 90 % of the total energy consumption by the crops. While, the contribution of energy provided by human and machinery in the production of crops is about 10 %. However, for irrigated crops the profile is varied due to the energy utilization for pumping water. In this case, the percent consumption of energy for irrigation, fertilizers and diesel fuel is estimated as 34 %, 36 % and 24 %, respectively. Meanwhile, human and machinery constituted about 6 % of the total energy input in this case.

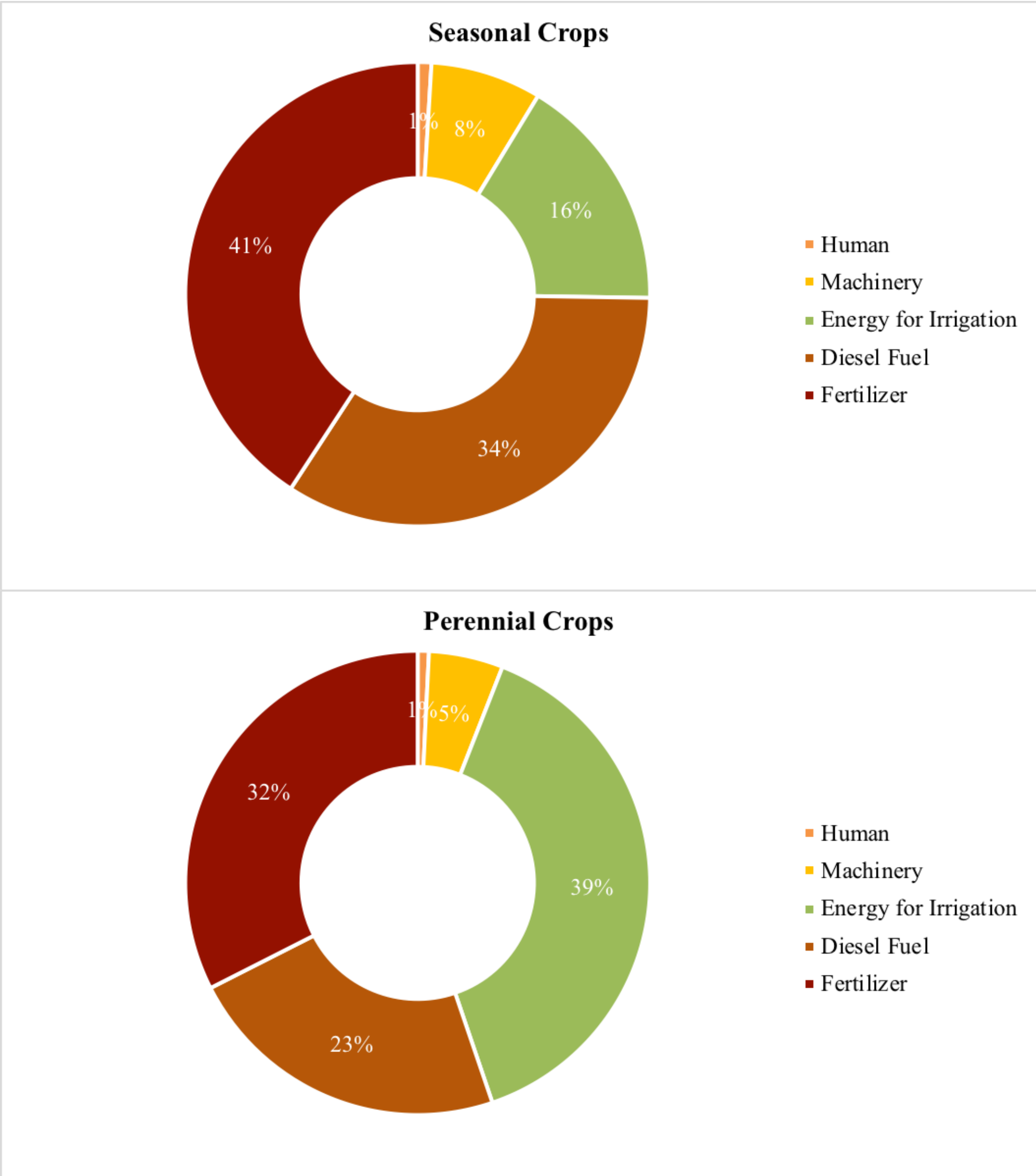


Figure 5.2: Energy consumption profile of crops based on crop categories.

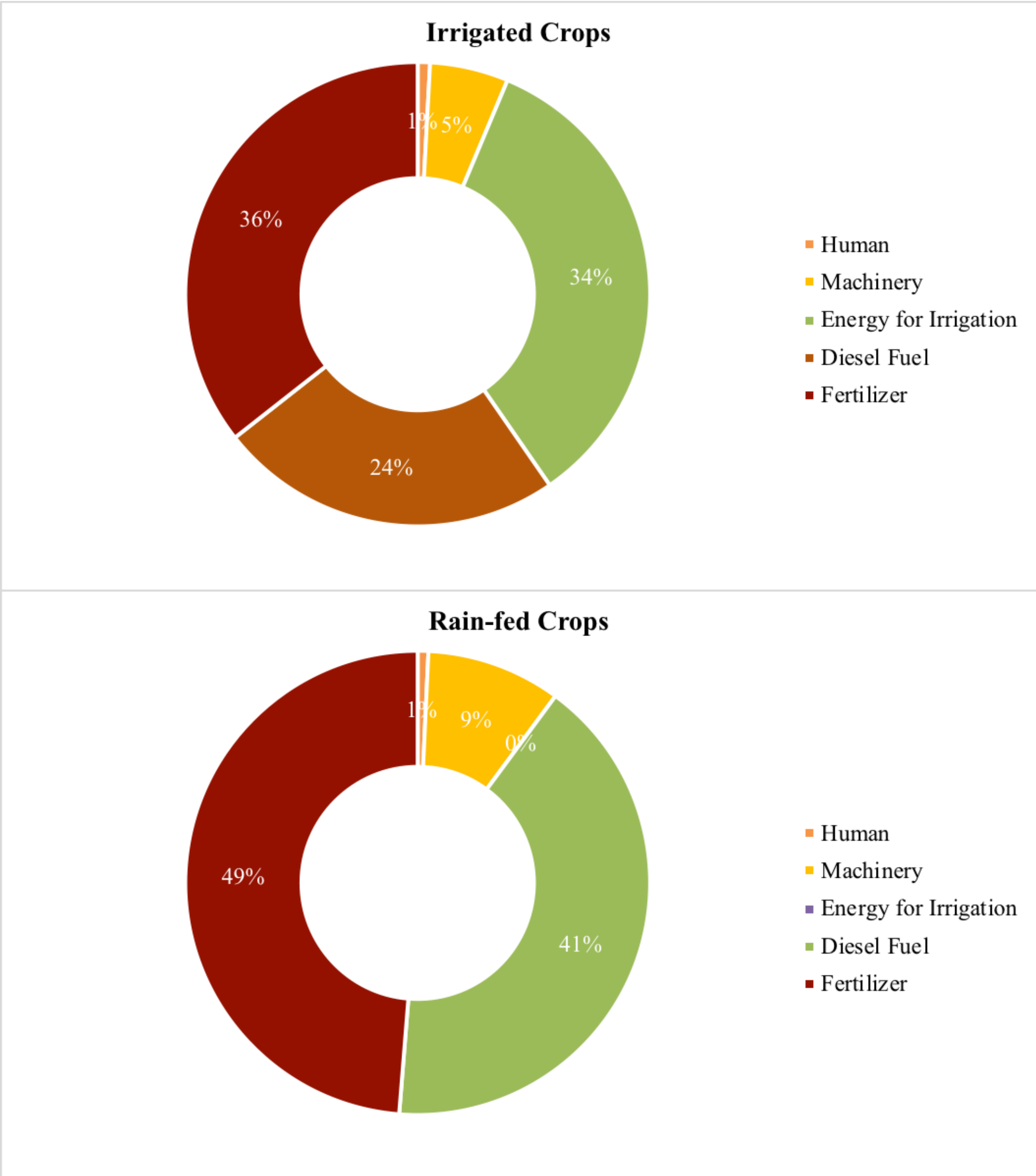


Figure 5.3: Energy consumption profile of crops based on agricultural systems.

Drought has direct and indirect effect on the energy consumption profile utilized in the production of agricultural crops. The direct effect is due to the increase in irrigation energy requirement for pumping caused by increased irrigation water requirement of crops from the water source and the reduction in the water level of the source which in turn increases the pumping head. In this study, the estimated energy increase for irrigation purposes is for pumping water from aquifer where the water efficiency of groundwater pumping system is high. In terms of surface water, as the overall efficiency (conveyance and application efficiency) is low, the increase in the rate of energy can be relatively high.

The indirect effect of drought on energy consumption is mainly caused by the direct effect in terms of extra hours of work required by human labor and machinery for the different crop production activities and the increase in the consumption of diesel fuel for machinery. However, in this study due to non-availability of data on the indirect effect of drought on energy consumption of crop production, only direct effect is accounted in the analysis. Figure 5.4 depicts the drought severity based spatial increase in the rate of energy consumption required for irrigating the crops with respect to the reference years. The inner circle of the figure represents the moderate drought, the middle circle shows the severe drought while extreme drought is represented by the outer circle of the figure. According to this, for Lefkosa the increase in energy consumption during the different severity levels of drought is highest (moderate drought = 15 %, severe drought = 20 % and extreme drought = 27 %) while the change in G. Magusa is the lowest (moderate drought = 7 %, severe drought = 11 % and extreme drought = 16 %). Overall, the mean increase in energy rate for irrigation in Lefkosa, G. Magusa, Girne, Guzelyurt and Iskele is estimated as 21 %, 11 %, 20 %, 13 % and 12 %, respectivley.

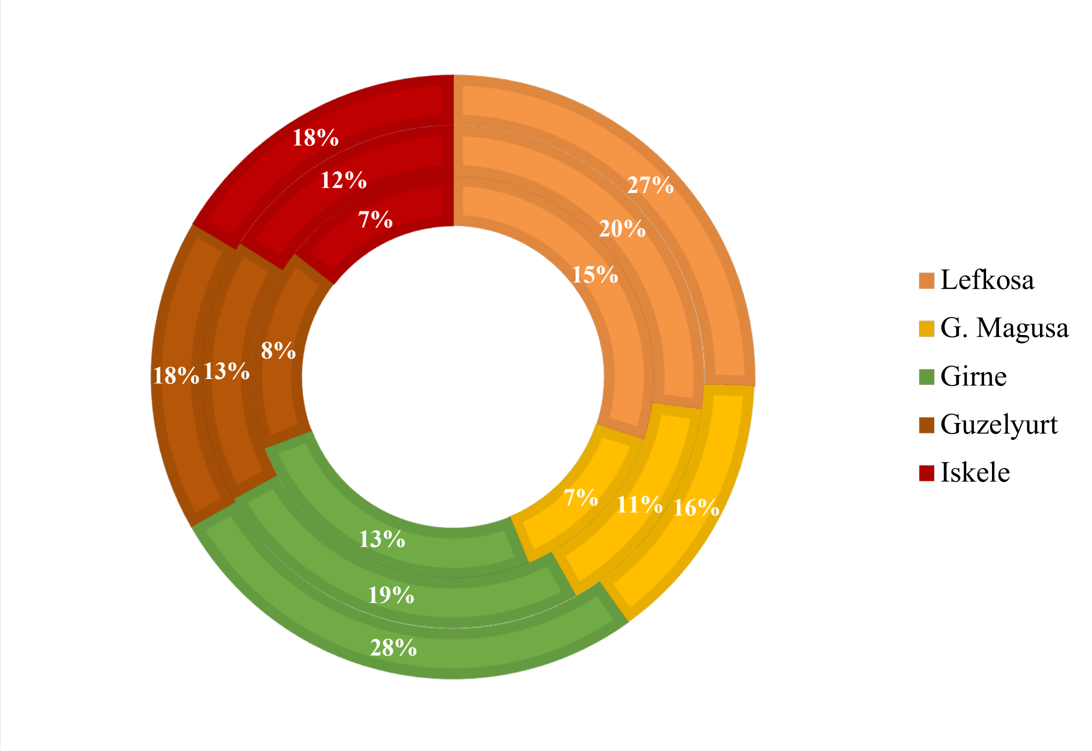


Figure 5.4: Spatial increase in irrigation energy consumption rate with respect to moderate, severe and extreme levels of drought.

The increase in rate of energy for irrigation with respect to crops during moderate, severe and extreme drought levels is shown in Figure 5.5. Among the perennial crops, the highest and lowest energy change is estimated for citrus and almond, respectively. The approximate rate of increase calculated for citrus during moderate, severe and extreme droughts is 14 %, 21 % and 28 %, respectively. While for almond considering the same drought levels, the rate is estimated as 7 %, 10 % and 15 %, respectively. On the other hand, for seasonal crops the effect is highest on potato (moderate drought = 10 %, severe drought = 17 % and extreme drought = 28 %) and lowest for sweet melon (moderate drought = 8 %, severe drought = 12 % and extreme drought = 18 %). Overall, the increase in energy consumption required for irrigation during moderate drought is approximately 10 %, 15 % for severe drought and for extreme drought it is calculated as 22 %. In general, the mean increase in irrigation energy consumption in the production of agricultural crops is computed as 15 %.

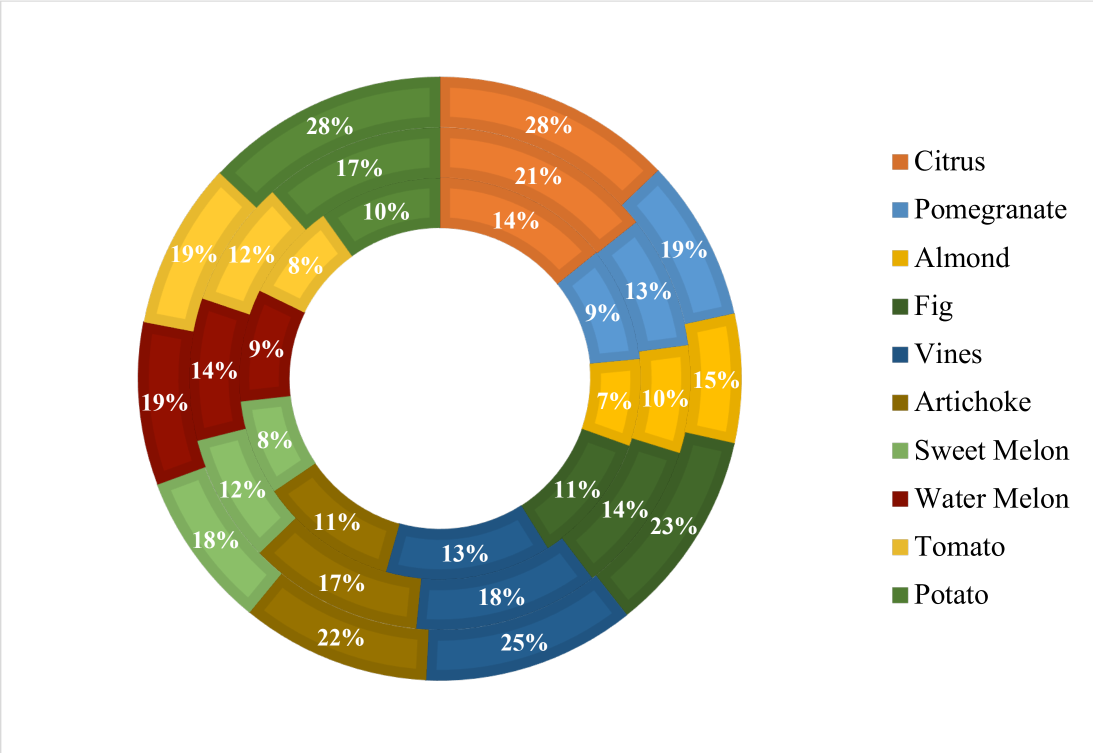


Figure 5.5: Increase in irrigation energy consumption rate of irrigated crops with respect to moderate, severe and extreme levels of drought.

5.3.2 Consequences of drought on farm profitability

The net cashflow (NCF) derived in the socio-economic model depicts the profit at the farm level achieved by the farmer. Table 5.1 demonstrates the NCF during the reference wet year on agricultural zonal basis estimated according to the drivers used in the methodology of this study. The profit obtained for rain-fed cereal crops in all regions of northern part of Cyprus is extremely low. The farmer hardly breakeven and covers its production cost because of lower yield as well as due to lower market price. On the other hand, olive has relatively better return mainly because of its high economic value. Conversely, irrigated crops considered in this study which makes up around 80-85% of the total irrigated area has high return because of higher yield and high economic value in the market. However, there exists high variation in the NCF among the different crops in different agricultural zones. Among the high return crops, vines (11,845 $/ha), sweet melon (9,145$/ha) and tomato (17,244 $/ha) are the most profitable crops. Whereas, pomegranate (3,468 $/ha) and almond (3,719 $/ha) with return lower than other crops are the less profitable crops. Meanwhile, the return for other irrigated crops is approximately identical (5400 $/ha). Based on the current policy of the government, farmers are encouraged to grow more pomegranate. As a result, by providing certain incentives the farmers are attracted towards growing more pomegranate. However, looking into the overall profitability of the crop, there exists other crops as an alternative to pomegranate that can bring more return. But for this, other factors such as market demand, consumers preferences, the nutritional value and a complete value chain analysis of each crop is needed to be considered. Meanwhile, the result of higher profitability of most of the irrigated crops suggests that, although the irrigation water requirement for some of these crops (for instance vines) may be high which will put the aquifer under tremendous stress and demand more energy, their production might be considered sustainable and justifiable.

Table 5.1: The net cashflow ($/ha) of different crops in different agricultural zones during the reference year 2012-2013.

	Lefkosa	G.Magusa	Girne	Guzelyurt	Iskele
	Net Cashflow ($/ha)				
Wheat	384	395	424	468	353
Barley	109	207	207	170	132
Olive	2,137	1,074	1,050	2,373	1,202
Citrus	1,076	12,413	1,945	10,006	3,548
Pomegranate	369	6,655	1,135	2,612	6,567
Almond	2,172	4,598	2,089	6,974	2,762
Fig	2,293	6,707	4,012	6,452	1,979
Vines	13,624	21,482	9,677	5,697	8,745
Artichoke	6,098	8,800	5,086	1,153	5,255
Sweet Melon	10,891	12,251	8,168	3,723	10,692
Water Melon	5,076	8,097	6,124	2,501	6,846
Tomato	14,910	17,391	19,446	8,164	26,311
Potato	5,004	6,248	5,952	5,325	6,170

Figure 5.6 shows the reduction in NCF of crops at different severity level of drought by subtracting the values of NCF of the wet reference years (without drought case) from the values of NCF during these events (with drought case). The effect on rain-fed crops is mainly due to reduction in the yield of the crop while on irrigated crops it is because of an increase in crop irrigation water requirement which in return increases the consumption of energy required to irrigate the cultivated land. The impact of drought on crop return per unit land for both the rain-fed and irrigated crops was approximately similar during the extreme events while differing during the moderate and severe drought events. In total, the total aggregated NCF reduction of rain-fed crops during moderate, severe and extreme drought is estimated as 5,910 $/ha; 7,197 $/ha and 8,060 $/ha, respectively. On the other hand, for irrigated crops the total effect under the same categories is estimated as 3,563 $/ha, 5,565 $/ha and 8,356 $/ha, respectively.

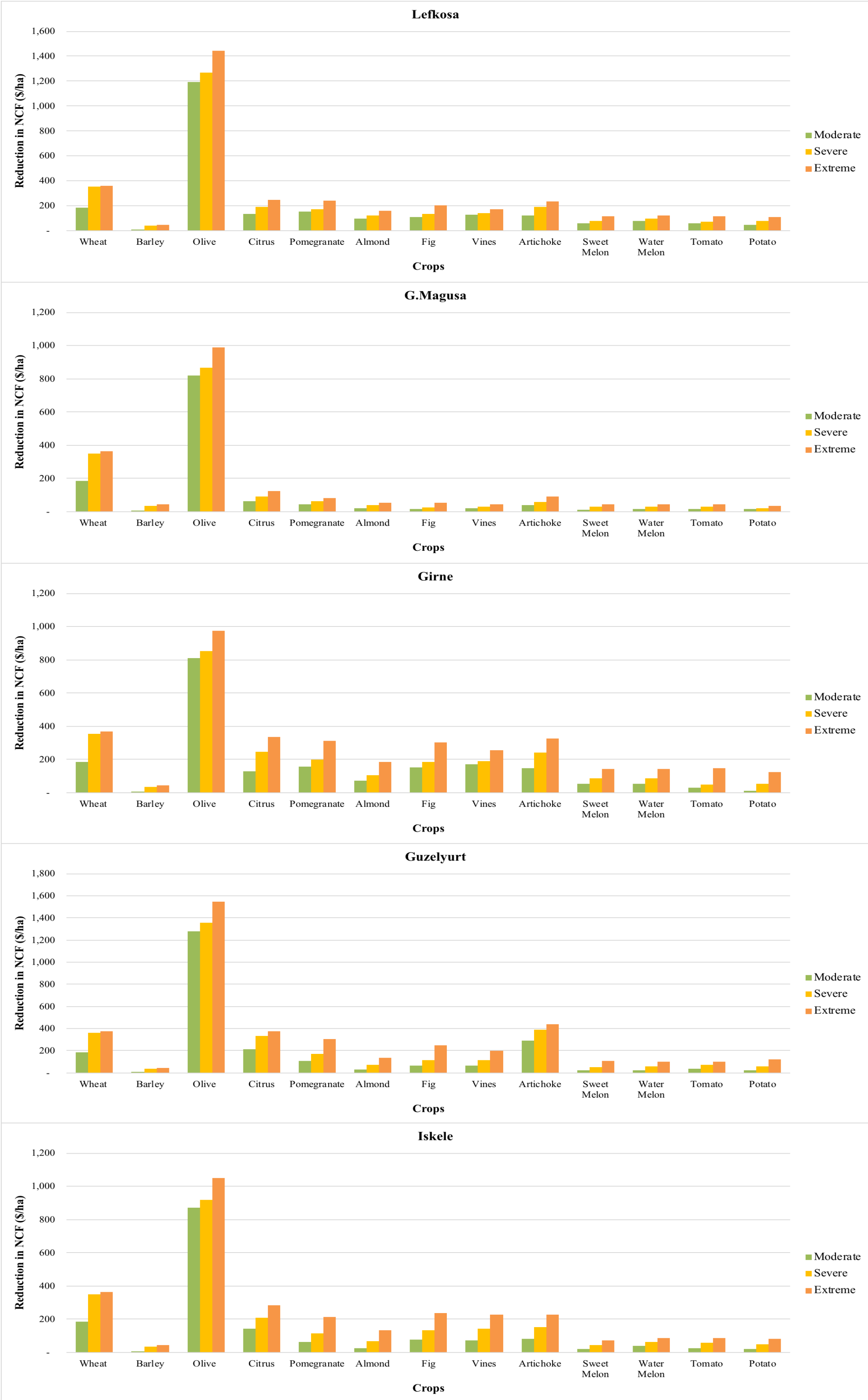


Figure 5.6: The reduction in net cashflow ($/ha) of different crops during the moderate, severe and extreme drought events.

The total aggregated loss incurred by the agriculture sector in terms of reduction in crop return at farm level is shown in Figure 5.7. It is obtained by considering the average total area of each crop under consideration. As can be observed, the aggregated loss during any event of moderate drought is approximately 5.8 million USD. For severe drought the loss is estimated as 10.5 million USD while for extreme drought it is approximately 12.2 million USD. It's worth mentioning that the amount paid by the government in the form of subsidy to the farmers (for instance during 2007-2008 extreme drought the government paid the farmers approximately 100 $/ha) to compensate the losses of rain-fed crops during drought, specifically the cereal crops, is not sufficient. Meanwhile, knowing the fact that in future occurrence and frequency of drought will increase, the government can devise drought adaption measures within the nexus framework by keeping into consideration the total aggregate losses of drought to minimize and effect and risk of drought on water, agriculture and energy sectors.

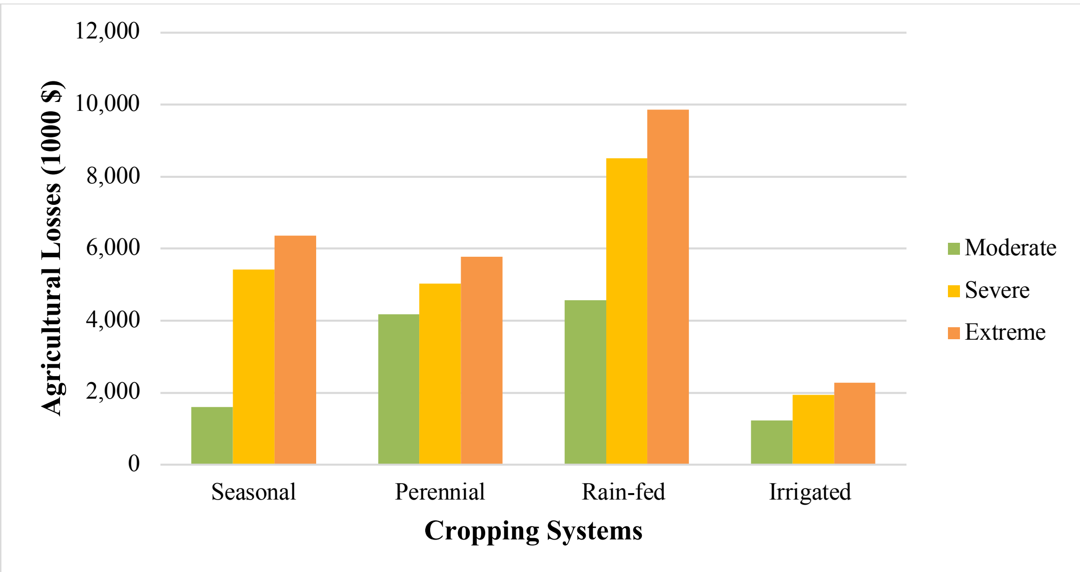


Figure 5.7: The total aggregated incurred losses of agriculture sector based on cropping systems at farm level during the moderate, severe and extreme drought events.

5.3.3 Assessment of the drought-induced WFE nexus index

The WFE nexus is a multi-dimensional approach that allows to analyze the underlining effect of a specific problem in hand on different elements of nexus in a balanced manner by considering the interlinkages, synergies and tradeoffs between the elements. Keeping into consideration this important aspect of nexus, in this study indicators of WFE nexus are determined for rain-fed and irrigated crops under various severity level of drought. The indicators are normalized using reference from a distance method to obtain the severity-based drought-induced WFE nexus sub-indices and drought-induced WFE nexus index (DI-WFENI) during dry condition of climate by considering different severity levels of drought. However, it can be applied on an annual basis also to assess the effect of different factors and drivers on the functioning of nexus.

In this study five drought induced WFE nexus sub-indices are derived that depends on factors such as yield, cost and NCF. A comparative analysis of these sub-indices is shown in Figure 5.8. It basically indicates the specific positive and negative level of influence of each sub-index on DI-WFENI which are linked to the key aspects and drivers involved in the production of the crops. Moreover, comparison of sub-indices helps to determine the root causes of inefficiency within the system that can be beneficial for in depth investigation and devise sustainable strategies. As can be observed from the spider graph, during the different conditions of drought the effect of productivity and profitability sub-indices is high on DI-WFENI as compared to other sub-indices. The score of productivity sub-index during moderate, severe and extreme drought is estimated as 0.81, 0.77 and 0.75, respectively. Profitability sub-index values for the same categories of drought was approximately 0.78, 0.73 and 0.69, respectively.

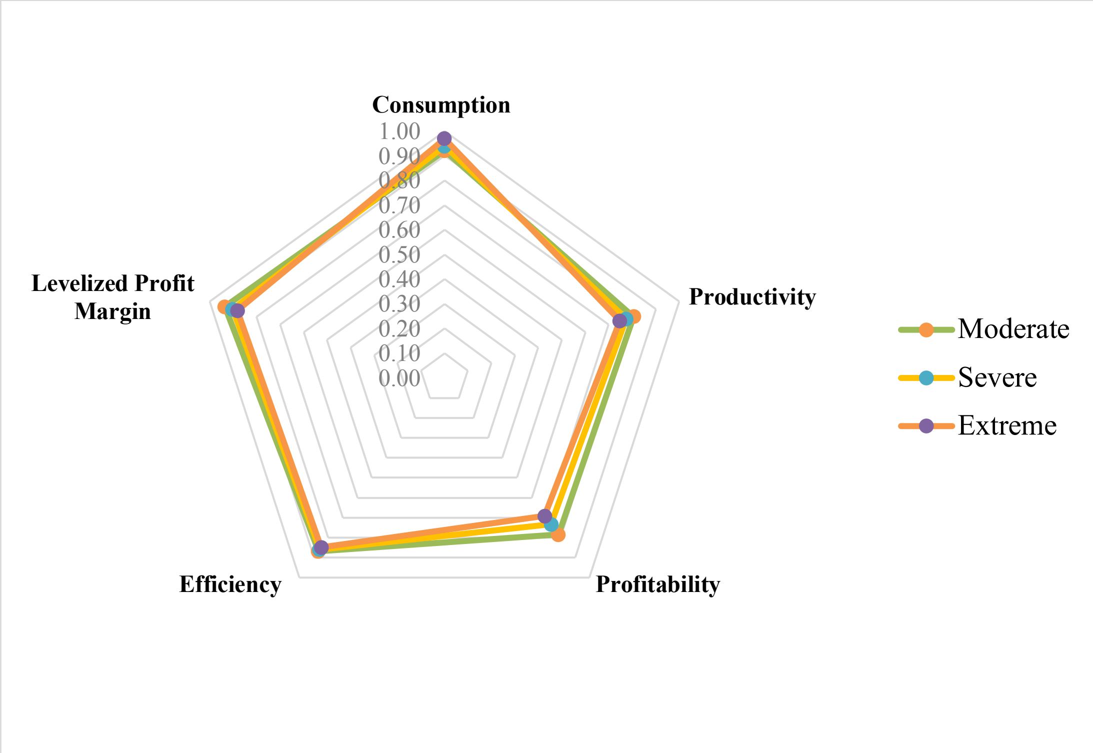


Figure 5.8: Spider graph of five drought induced WFE nexus sub-indices.

The spatial DI-WFENI scores for the five agricultural zones is relatively identical. In the analysis, drivers such as crop prices at farm gate, human labor hours, usage of machinery, and change in groundwater level with respect to different levels of drought, is assumed to be constant. However, in reality, all such factors may differ from place to place under different conditions. As, shown in Figure 5.9 Among the zones, Lefkosa has the lowest DI-WFENI score (moderate drought = 0.84, severe drought = 0.82 and extreme drought = 0.80) while G. Magusa has the highest value (moderate drought = 0.86, severe drought = 0.85 and extreme drought = 0.84).

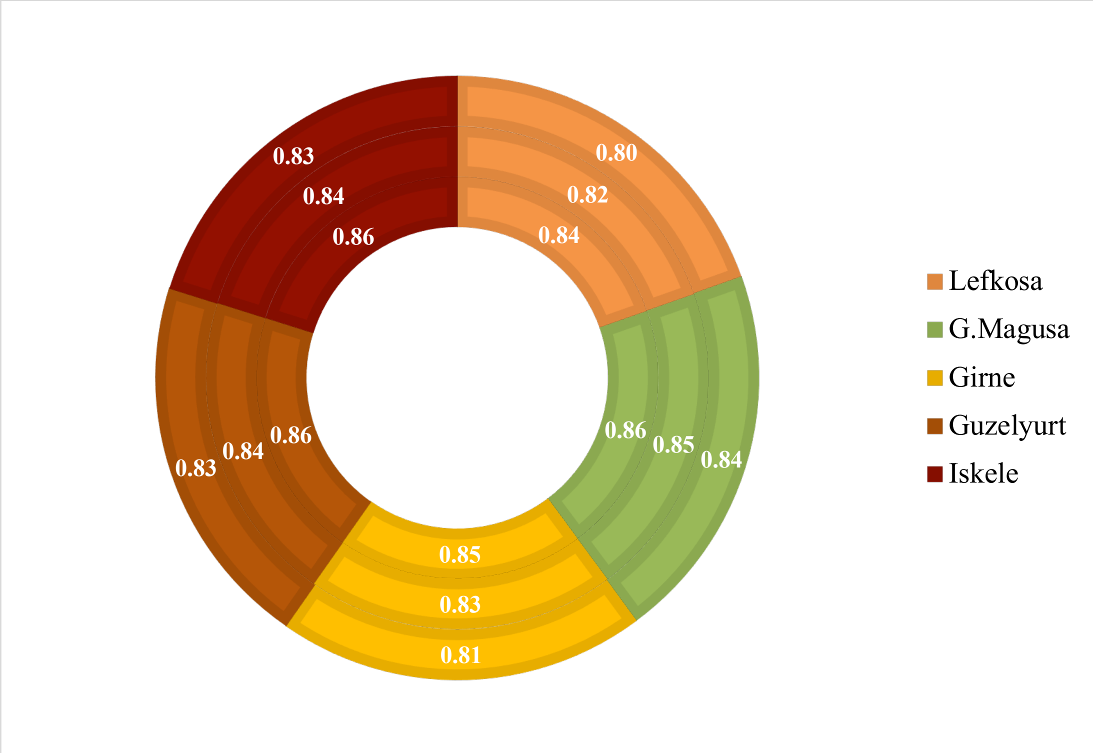


Figure 5.9: Spatial score of DI-WFENI in different agricultural zones.

Focusing on individual crops, the comparative analysis of DI-WFENI between the various crops is depicted in Figure 5.10. The calculated DI-WFENI have scores that varies between 0.44-0.99 under moderate drought, 0.35-0.97 under severe drought and 0.35-0.96 under extreme drought. Olive has the minimum DI-WFENI score (moderate drought = 0.38, severe drought = 0.38 and extreme drought = 0.35). Though the variation between other crops except wheat, barley and olive is extremely low, the maximum score is achieved by almond, sweet melon and tomato. Overall, the rain-fed crops (Figure 5.11) have the lowest DI-WFENI values while irrigated crops have the highest score. The DI-WFENI score for rain-fed crops during moderate, severe and extreme drought is estimated as 0.45, 0.40 and 0.38, respectively. Conversely, for irrigated crops the DI-WFENI values for the same level of drought is computed as 0.98, 0.97 and 0.95, respectively.

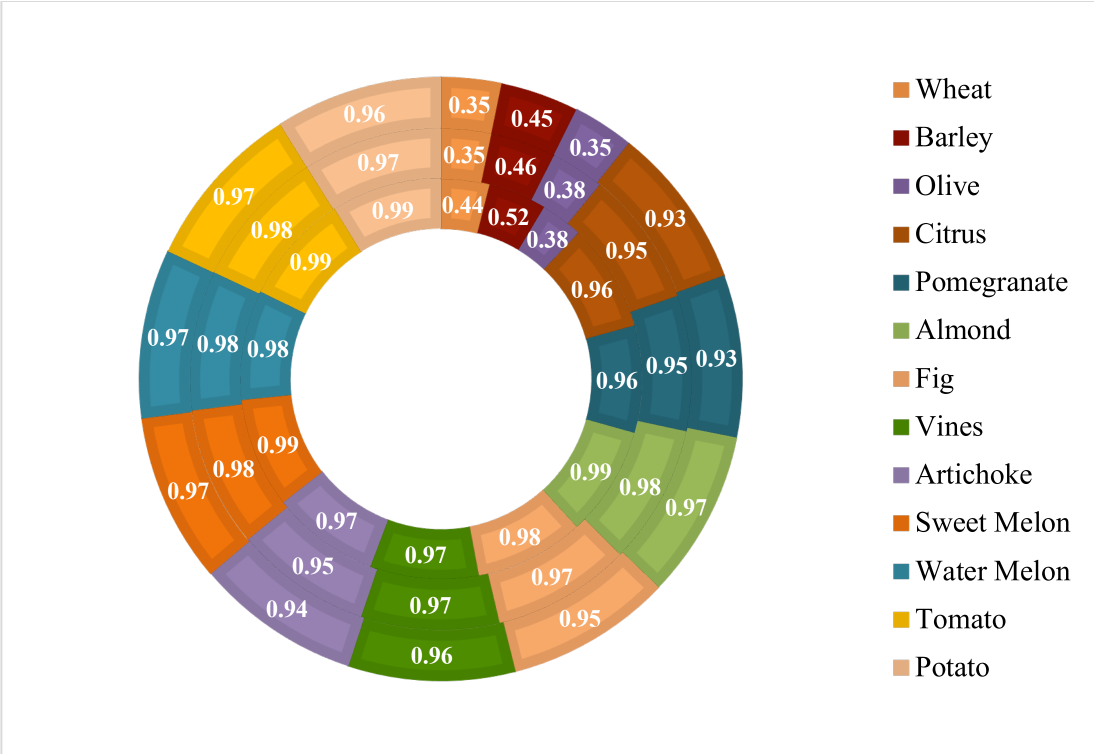


Figure 5.10: Score of DI-WFENI for the considered crops.

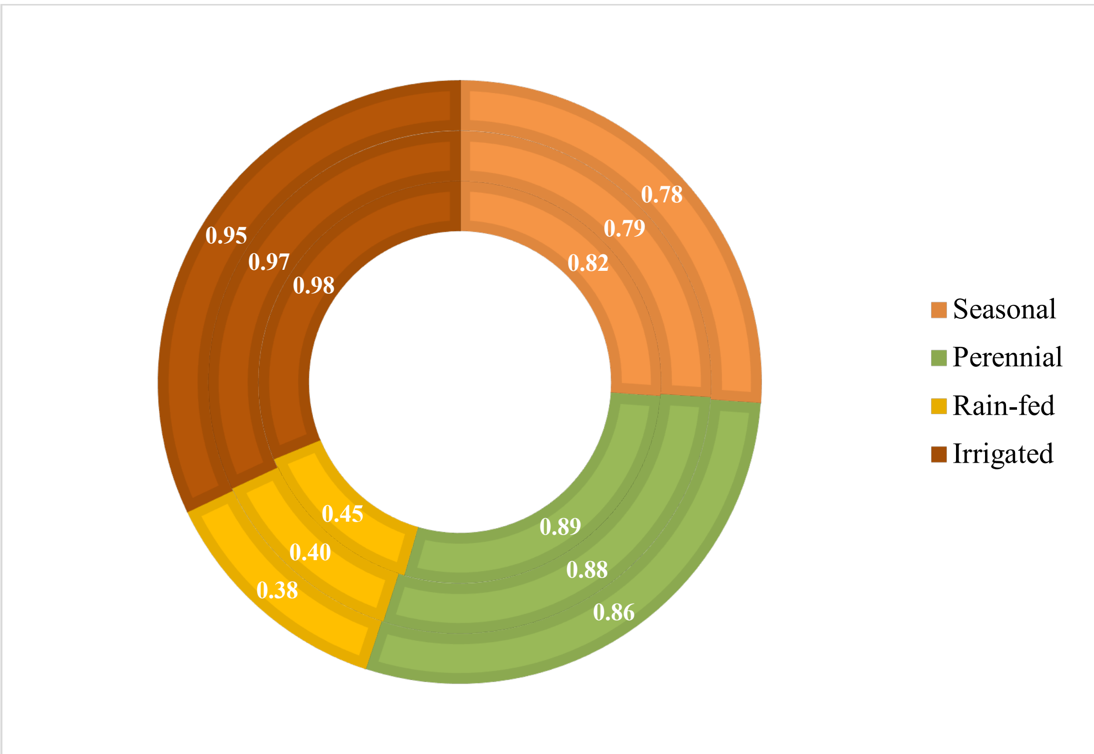


Figure 5.11: Score of DI-WFENI under different cropping system.

In general, the mean DI-WFENI score for moderate, severe and extreme drought is computed as 0.85, 0.84 and 0.82, respectively.

5.3.4 Sensitivity Analysis

Sensitivity test is performed on the socio-economic sub-model of the study to check the effect of key input variables on the outcome of the main findings. By considering a range of possible values, it is implemented by changing one parameter at a time. The outcome of the test is on the DI-WFENI. Several parameters are analyzed, however, crop yield, crop price and change in IWR are discussed here because of having relatively high impact on the DI-WFENI values. Other variables do not have significant impact on the outcome of the study. For the test the range considered for all the variables is between -20 % and +20 % with an increment of 5 %.

The sensitivity analysis revealed that variation in yield and market price of various crops have relatively high effect on the outcome of DI-WFENI, as shown in Table 5.2. A 20% unexpected reduction on either yield or price of crops causes the DI-WFENI to decline from 0.85, 0.84 and 0.82 to 0.76, 0.74 and 0.73 during moderate, severe and extreme drought, respectively. This also implies the negative effect of these variables on NCF of farmers which will affect their livelihood significantly. The other variable is the change in IWR where sensitivity test is carried out to determine the impact of it on the DI-WFENI value. The result showed that DI-WFENI is moderately sensitive to changes in the IWR of irrigated crops during drought. But the effect is low as compared to yield or price of crops. Having an increase in IWR by 20% during moderate, severe and extreme drought, the DI-WFENI value changes to 0.82, 0.80 and 0.79, respectively.

Table 5.2: Sensitivity analysis result of key variables.

	Drought Severity Level		
	Moderate	**Severe**	**Extreme**
Yield			
-20%	0.76	0.74	0.73
-15%	0.78	0.77	0.76
-10%	0.81	0.79	0.78
-5%	0.83	0.81	0.80
0%	0.85	0.84	0.82
5%	0.88	0.86	0.84
10%	0.90	0.88	0.87
15%	0.93	0.90	0.89
20%	0.95	0.93	0.91
Real Selling Price			
-20%	0.76	0.74	0.73
-15%	0.78	0.77	0.76
-10%	0.81	0.79	0.78
-5%	0.83	0.81	0.80
0%	0.85	0.84	0.82
5%	0.88	0.86	0.84
10%	0.90	0.88	0.87
15%	0.93	0.90	0.89
20%	0.95	0.93	0.91
Change in IWR			
-20%	0.92	0.89	0.88
-15%	0.90	0.88	0.86
-10%	0.88	0.86	0.85
-5%	0.87	0.85	0.83
0%	0.85	0.84	0.82
5%	0.84	0.82	0.81
10%	0.83	0.81	0.80
15%	0.82	0.81	0.80
20%	0.82	0.80	0.79

5.4 Chapter Conclusions

In this study a method to support the evaluation of extreme event of climate change and its effect for sustainable utilization of scarce resources within the WFE nexus framework is conducted. This resulted in operationalizing the WFE nexus perspective at farm level under various severity level of historical drought events. The integrated approach utilized in this study quantitatively describes the dynamics of WFE nexus with respect to different severity levels of drought by assessing the drought induced WFE nexus index (DI-WFENI). The methodology is simple and can be easily adopted and replicated, however, data availability might the limiting factor in the implementation of it.

The method consists of different models where the output of one model is the input of another model. In this chapter focus was on energy and socio-economic sub-models. The energy sub-model is utilized to determine the direct consumption of energy in the production of crop as well as to examine the effect of drought on the energy consumption. Within the socio-economic sub-model input of other models along with other technical and financial parameters of different rain-fed and irrigated crops were used to compare and analyze the multiple implications of drought on different dimensions of the nexus and on WFE nexus itself by assessing the drought induced WFE nexus index (DI-WFENI). Meanwhile, the DI-WFENI also reflects the influence of various other aspects and drivers within the system that can be of major concern for the WFE nexus. The effect of drought is analyzed by considering moderate, severe and extreme severity levels of drought WFE nexus system.

The energy model demonstrated that drought increases the consumption of energy for irrigation. The energy consumption required for irrigation during moderate drought is increased by 10 %; 15 % increase is estimated for severe drought and for extreme drought the calculated value is 22 %. Overall, the mean increase in irrigation energy consumption in the production of agricultural crops is computed as 15 %.

The socio-economic analysis revealed that due to increase in irrigation water requirement, increase in pumping, and reduction of yield the net cashflow (profit) of farmers at farm level is reduced. The total aggregated reduced values of the NCF for rain-fed crops during moderate, severe and extreme drought was approximately 5,910 $/ha; 7,197 $/ha and 8,060 $/ha, respectively. On the other hand, for irrigated crops the total effect under the same categories is estimated as 3,563 $/ha, 5,565 $/ha and 8,356 $/ha, respectively.

The computation of drought-induced WFE nexus index (DI-WFENI) revealed that the computed mean score of DI-WFENI for moderate, severe and extreme drought is approximately 0.85, 0.84 and 0.82, respectively. During the different conditions of drought, the comparative analysis revealed that the reduction of DI-WFENI is highly influenced by the productivity and profitability sub-indices.

The result of this study demonstrates the importance of integrated approach to policy makers for enabling them to make informed decisions with respect to sustainable management of water, food and energy. The model developed can pave the way for the development of comprehensive drought impact methodology of WFE nexus at a larger scale as sustainability factor is at the core of this integrated approach through the utilization of indices. It can be utilized by decision makers as a near real-time drought management tool to analyze and evaluate WFE nexus dimensions under varying drought conditions.

Chapter 6

CONCLUSION AND RECOMMENDATIONS

Water, food and energy are vital and scarce resources that continue to be under stress due to increased demand and inefficient utilization. External drivers like climate change and its extreme event will further exacerbate this situation as it is anticipated that climate change will increase the frequency and occurrence of drought.

Assessment and decisions in traditional approaches were focusing only on either water or food or energy in a disintegrated manner without considering the fact that these three resources are interlinked and requires a balanced and integrated perspective. As such, keeping into consideration the above-mentioned drivers, now the focus from individual resource centric solutions is changing towards an integrated approach of Water-Food-Energy nexus which can result in a sustainable and efficient development and management of these resources.

Drought manufactures a ripple effect where the effect of drought on one dimension will propagate and affect the other dimensions. As such interlinking drought to WFE nexus and identify the response of WFE elements towards drought are key to sustainable and efficient design and management of WFE nexus under extreme events of climate change.

Keeping into consideration the importance of integrated approach, the suggested methodology in this study supports the evaluation of extreme event of climate change and its effect for sustainable utilization of scarce resources within the WFE nexus framework and to operationalize the WFE nexus perspective at farm level under drought event. The integrated approach utilized in this study quantitatively describes the dynamics of WFE nexus with respect to different severity levels of drought. Different rain-fed and irrigated crops were used and compared to analyze the multiple implications of drought on different dimensions of the nexus and on WFE nexus by assessing the drought induced WFE nexus index (DI-WFENI). The methodology is simple and can be easily adopted and replicated, however, data availability might the limiting factor in the implementation of it.

The method consists of utilizing several sub-models where the output of one model is used as an input in another sub-model. Drought sub-model is used to assess and characterize the historical drought using SPI and RDI. The crop sub-model is used to investigate the effect of drought on agriculture crops by combining RDI with crop simulation model (CROPWAT) at various severity levels of drought. Groundwater drought is used to scrutinize the response of groundwater level to drought utilizing meteorological (SPI and RDI) and groundwater drought indices (SGI and SGWLA). Energy model is utilized to determine the direct consumption of energy in the production of crop as well as to examine the effect of drought on the energy consumption. And finally, within the socio-economic model, input of other sub-models along with other technical and financial parameters of different rain-fed and irrigated crops were used to compare and analyze the multiple implications of drought on different dimensions of the nexus and on WFE nexus itself by assessing the drought induced WFE nexus index (DI-WFENI). Meanwhile, the DI-WFENI also reflects the influence of various other aspects and drivers within the system that can be of major concern for the WFE nexus. The effect of drought is analyzed by considering moderate, severe and extreme severity levels of drought WFE nexus system. Further to this, to validate the results of the findings of this study computed using the above-mentioned sub-models, the results are also cross checked with other studies. It is found out that these findings are in line and in good agreement with the findings of other authors.

The analysis result of drought sub-model revealed that performance of both SPI and RDI in recognizing drought events was quite similar. The 3-months, 6-months and 12-months timescales have fairly strong relationship in showing drought events of any specific year. These timescales showed that northern part of Cyprus suffered from three major long duration drought events. Based on 12-months SPI, northern part of Cyprus experienced extreme drought in 2007-2008 and severe drought in 1996-1997 and 1994-1995. On average 79% and 78% of 3-months timescales drought propagated into 6 months and 12-months drought events while 90% of 6-months timescales drought events propagated into 12-months drought events. The highest annual rainfall range for moderate, severe and extreme droughts were estimated at 310-370 mm, 255-310 mm, and less than 255mm, respectively. The findings of this research work are summarized as shown below.

1. The result of crop sub-model indicated that the mean reduction in yield of wheat, barley and olive during drought was 37, 28, 49%, respectively. The yield reduction of wheat for moderate, severe and extreme drought was 28, 38 and 44%, respectively. For barley the yield reduction was 19, 29, and 35% and olive yield reduction was 45, 48, and 54%. From the analysis it is also discovered that the increase in IWR of perennial crops during drought was 11% while for seasonal crops it was 8%. In terms of drought severity levels, during moderate, severe and extreme drought the increase in IWR for perennial crops was approximately 7, 10 and 15%, respectively. Meanwhile, the approximate

estimated rate for seasonal crops was 3, 7 and 12%, respetively. Overall, the mean increase in IWR during dry years of drought is estimated as 10%.

2. The groundwater sub-model analysis exhibited that partially there exists a weak positive relationship between SGWLA and SGI and SPI and RDI at different locations of the aquifer, indicating that both SPI and RDI behaves in a similar manner in revealing the influence and effect of drought on groundwater. The weak connection can be attributed to complex nature of hydrogeological processes, aquifer systems and varying pattern of consumption. The groundwater hydrographs also demonstrated that there exists a partially positive relationship between groundwater levels and SPI and RDI in different years of drought. The temporal fluctuation of SGWLA and SGI in the hydrograph partly resembled the positive and negative values of SPI and RDI.
3. The energy model demonstrated that drought increases the consumption of energy for irrigation. The energy consumption required for irrigation during moderate drought is increased by 10 %; 15 % increase is estimated for severe drought and for extreme drought the calculated value is 22 %. Overall, the mean increase in irrigation energy consumption in the production of agricultural crops is computed as 15 %.
4. The socio-economic analysis revealed that drought reduces yield, increases the irrigation water requirement which in turn increase the pumping rate and as a result causes reduction in the net cashflow (profit) of farmers at farm level. For rain-fed crops during moderate, severe and extreme drought, the total aggregated reduction in the value of NCF was approximately 5,910 $/ha; 7,197 $/ha and 8,060 $/ha, respectively. On the other hand, for irrigated crops the

total reduction under the same categories is estimated as 3,563 $/ha, 5,565 $/ha and 8,356 $/ha, respectively.

5. The computation of drought-induced WFE nexus index (DI-WFENI) revealed that the computed mean score of DI-WFENI for moderate, severe and extreme drought is approximately 0.85, 0.84 and 0.82, respectively. During the different conditions of drought, the comparative analysis revealed that the reduction of DI-WFENI is highly influenced by the productivity and profitability sub-indices.
6. The result of this study provided preliminary information and laid the basis for sustainable and strategic planning and management of water, food and energy in the face of climate change. The results also revealed that there is a dire need to combat the negative effect of drought on various elements of WFE to improve water, food and energy security. As such, several measures are proposed to combat the impact of climate change, essential not only for agriculture sector but also for other sectors under the changing environment. The proposed solutions are related to managing the land, water, soil and crops sustainably.

The result of this study demonstrates the importance of integrated approach to policy makers for enabling them to make informed decisions with respect to sustainable management of water, food and energy. The findings have several policy implications essential for sustainable adaptation and drought risk management strategies to reduce vulnerability, increase coping capacity, and build resilience of water, food and energy within the framework of WFE nexus. The developed integrated approach can also pave the way for the development of comprehensive drought impact methodology of WFE nexus at a larger scale (both at local and regional level) as sustainability factor is at the core of this integrated approach through the utilization of indices. It can be utilized by decisions makers as a near real-time drought management tool to analyze and evaluate WFE nexus dimensions under varying drought conditions. Meanwhile, to initiate and successfully implement the concept of WFE nexus approach within the northern part of Cyprus, a task force consisting of scientists and researchers of all disciplines, government official, private sector, water user association or irrigation association members and farmers is required to be created. Relatedly, for the development of sustainable and efficient solutions, policies and plans, universities, other research institutes and government agencies needs strengthen their collaboration and allocate more resources for multidisciplinary research within the framework of WFE nexus.

The findings of this research, opens the door for many future opportunities. As such, for future studies, it is recommended to:

- integrate other related ecosystem processes (surface water, impact of flood), land use and management, national trade, water and energy footprint and concept of virtual water into WFE nexus under drought conditions and quantify the effect of drought on these processes.
- include economic analysis into the model for comprehensive view of the impact of drought on the society and environment as whole.
- implement the proposed drought mitigation and adaptation measures that includes both supply and demand interventions, compare the costs of these measures with the cost of potential drought in future.
- examine the viability and sustainability of these measures by using multi criteria analysis, optimization, cost effectiveness analysis and the socio-economic model developed in this study.

- conduct more in-depth research on hydrological, hydrogeological and meteorological processes in order to understand the behaviour of these processes much better.
- estimate the variation in pumping rate and/or drought induced pumping under different climatic scenarios and conditions.
- perform research about the impact of drought on quality of water within the aquifer.
- create future climate scenarios using satellite data and estimate the impact of future drought events by making use of the WFE model developed in this study.

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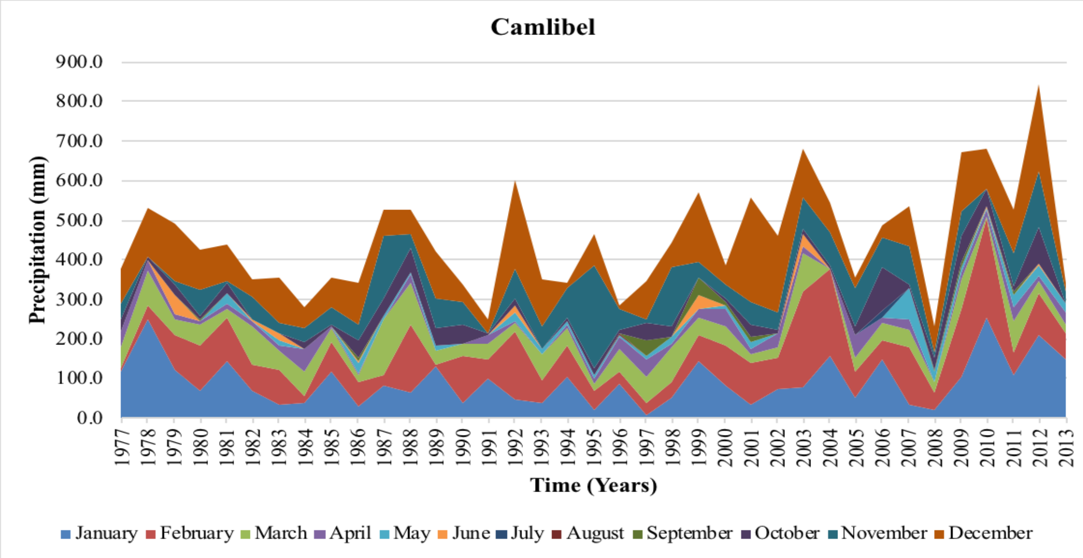
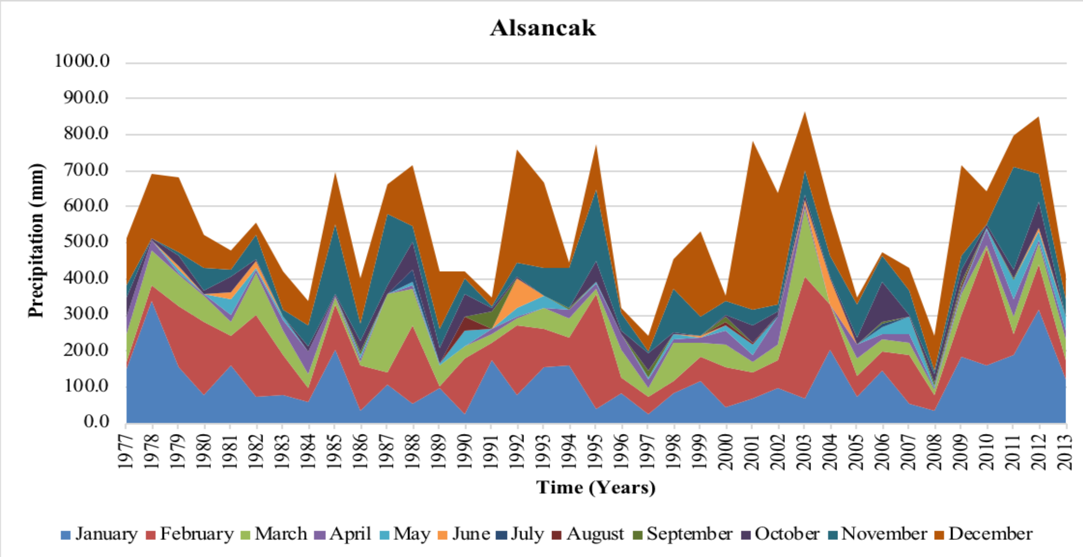
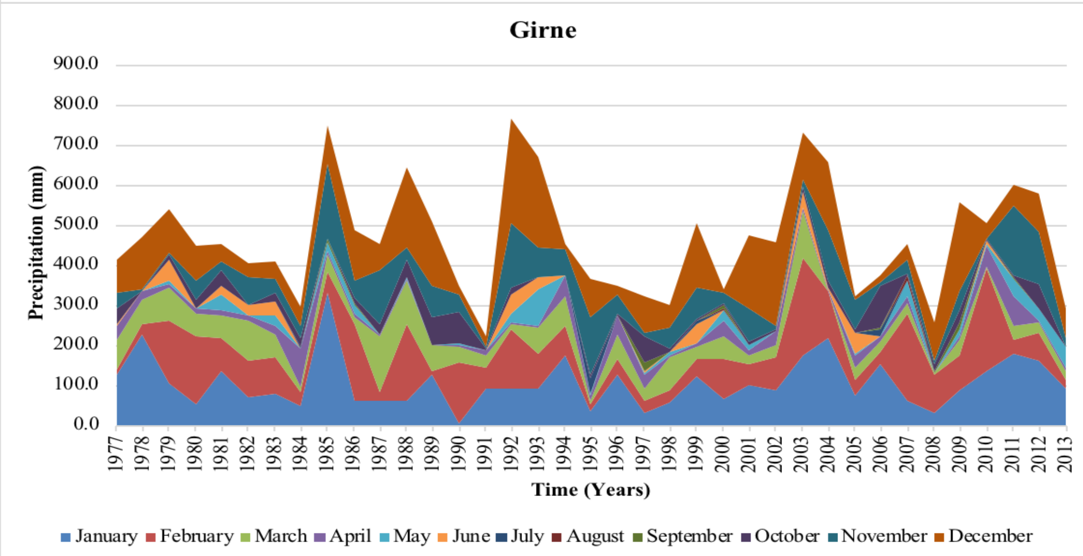
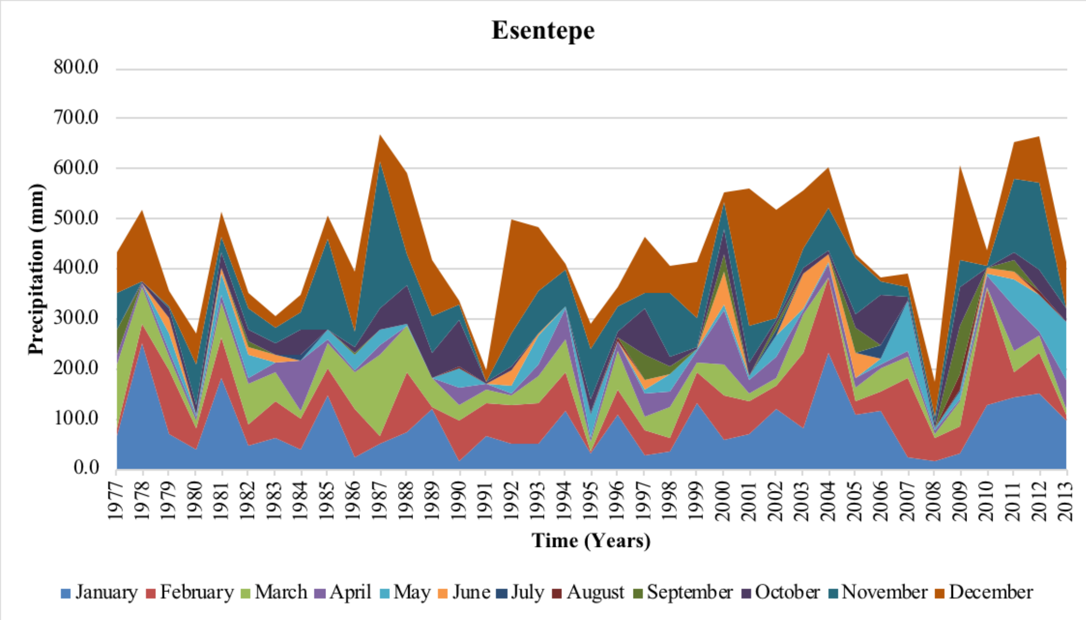
APPENDICES

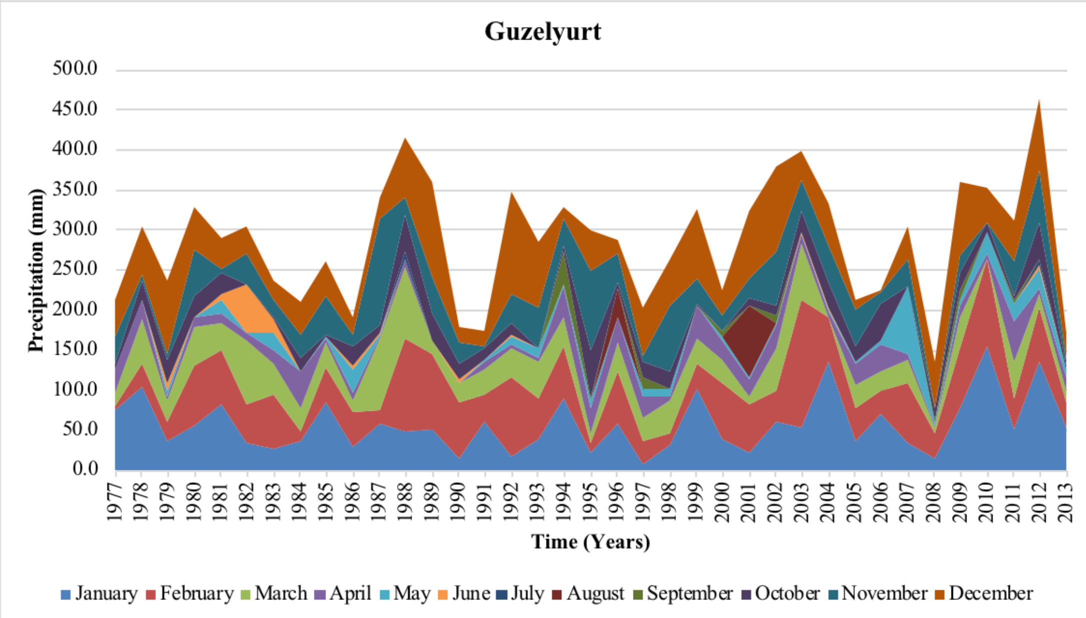
Appendix A: Annual Monthly Temporal Fluctuation of Precipitation

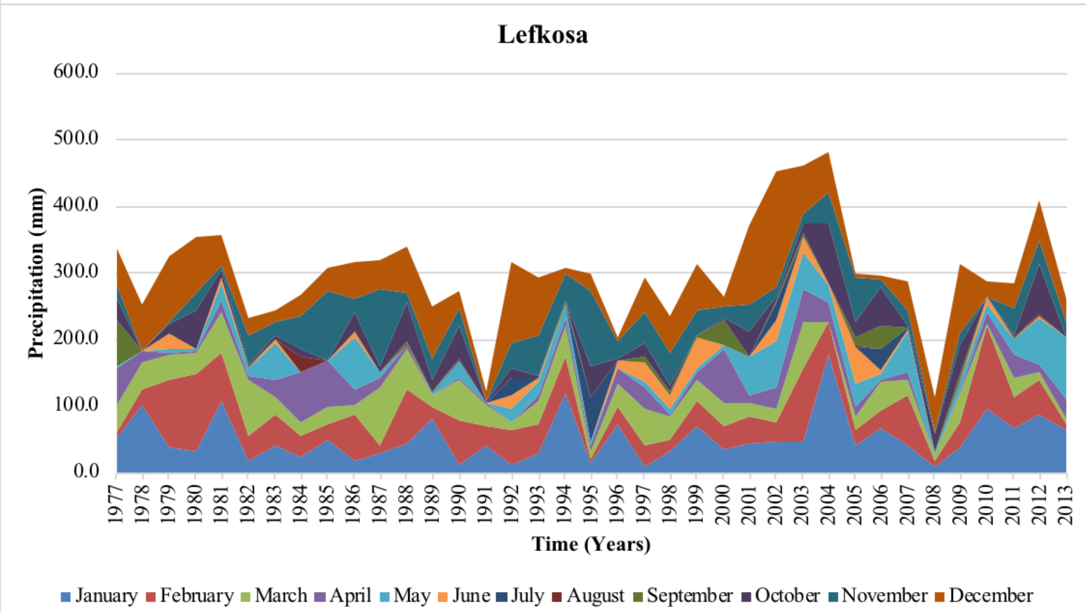


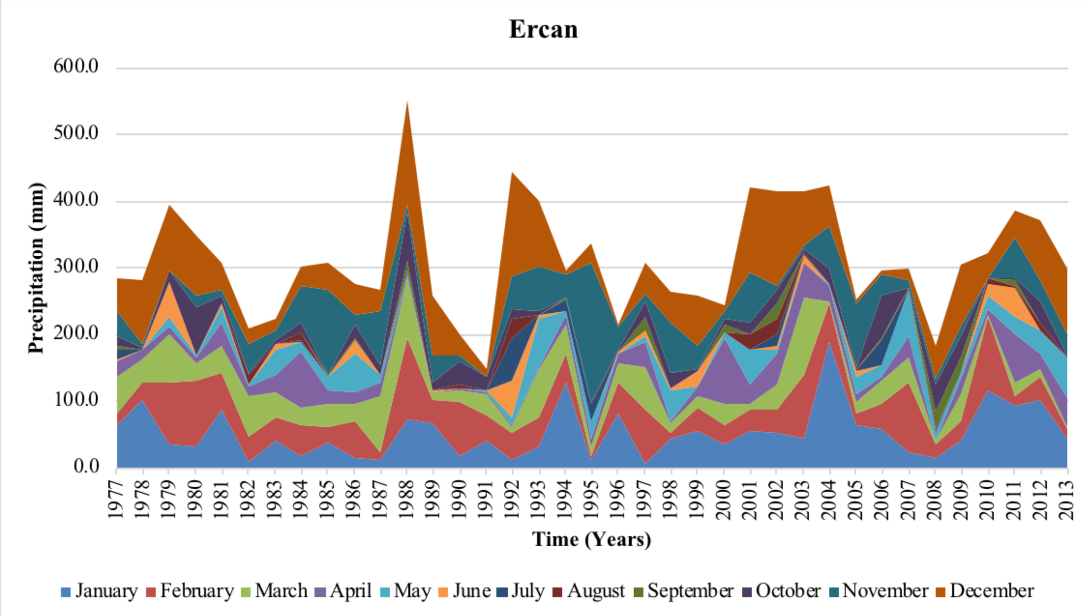


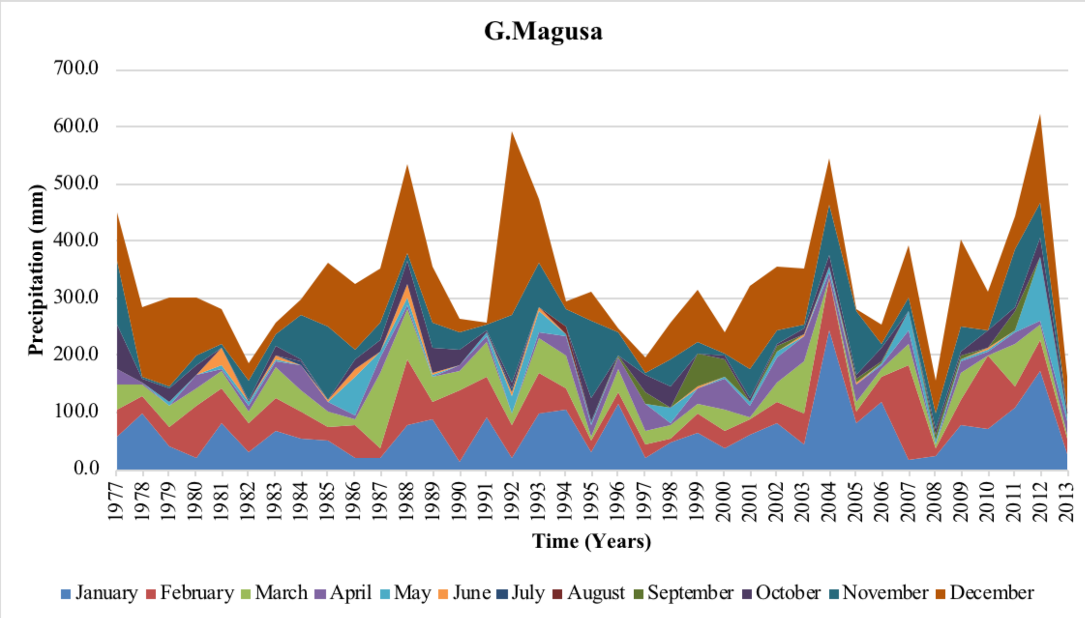


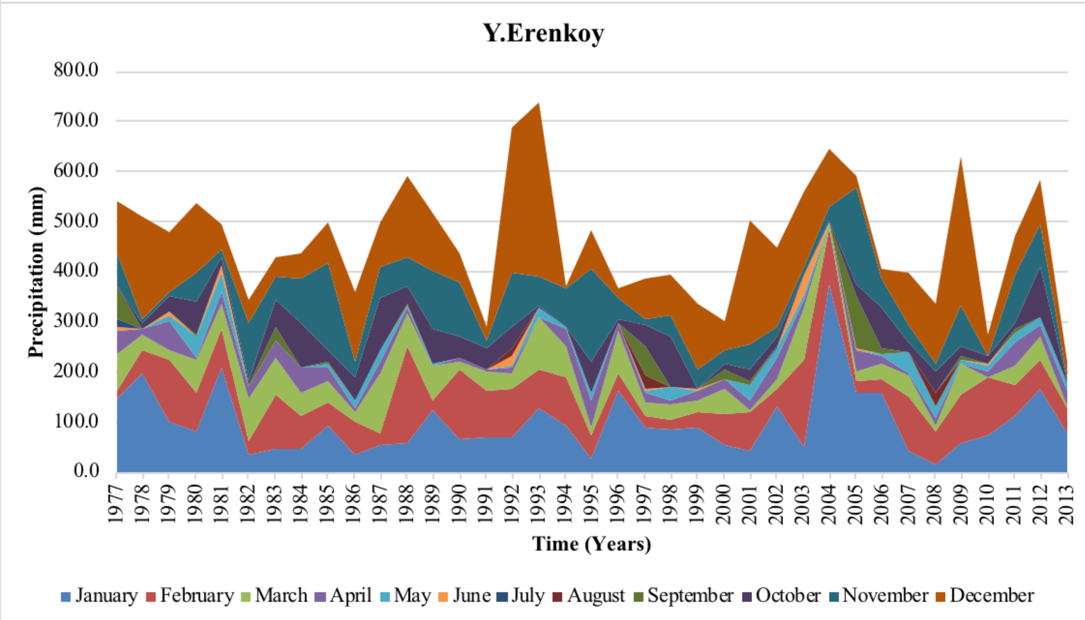

Esentepe
Precipitation (mm)
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013
Time (Years)
January February March April May June July August September October November December


Guzelyurt
Precipitation (mm)
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013
Time (Years)
January February March April May June July August September October November December


Lefkosa
Precipitation (mm)
600.0
500.0
400.0
300.0
200.0
100.0
0.0
1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013
Time (Years)
January February March April May June July August September October November December


Ercan
Precipitation (mm)
Time (Years)
January February March April May June July August September October November December


G.Magusa
Precipitation (mm)
Time (Years)
January February March April May June July August September October November December


Y.Erenkoy
Precipitation (mm)
Time (Years)
January February March April May June July August September October November December

Appendix B: Sensitivity Analysis Results

Lefkosa							
		Change in IWR			Change in Electricity Usage		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
Increase in Irrigation Energy Consumption Rate	-20%	-8%	-4%	2%	10%	15%	22%
	-15%	-2%	2%	8%	12%	16%	23%
	-10%	4%	8%	14%	13%	18%	25%
	-5%	9%	14%	21%	14%	19%	26%
	0%	15%	20%	27%	15%	20%	27%
	5%	21%	26%	34%	16%	21%	28%
	10%	27%	32%	40%	18%	23%	30%
	15%	32%	38%	46%	19%	24%	31%
	20%	38%	44%	53%	20%	25%	32%
Reduction in Net Cashflow or Profit for Rain-fed Crops ($/ha)		Yield			Real Selling Price		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
	-20%	720	782	835	720	782	835
	-15%	655	724	781	655	724	781
	-10%	591	666	726	591	666	726
	-5%	527	608	672	527	608	672
	0%	463	550	618	463	550	618
	5%	399	493	563	399	493	563
	10%	335	435	509	335	435	509
	15%	270	377	454	270	377	454
	20%	206	319	400	206	319	400
		Real Purchase Price			Input Usage		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
	-20%	378	466	533	378	466	533
	-15%	400	487	554	400	487	554
	-10%	421	508	575	421	508	575
	-5%	442	529	596	442	529	596
	0%	463	550	618	463	550	618
	5%	484	571	639	484	571	639
	10%	505	593	660	505	593	660
	15%	526	614	681	526	614	681
	20%	547	635	702	547	635	702
Reduction in Net Cashflow or Profit of Irrigated Crops ($/ha)		Yield			Real Selling Price		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
	-20%	1886	1915	1960	1886	1915	1960
	-15%	1439	1468	1513	1439	1468	1513
	-10%	992	1021	1066	992	1021	1066
	-5%	545	574	618	545	574	618
	0%	98	126	171	98	126	171
	5%	-350	-321	-276	-350	-321	-276
	10%	-797	-768	-723	-797	-768	-723
	15%	-1244	-1215	-1170	-1244	-1215	-1170
	20%	-1691	-1662	-1617	-1691	-1662	-1617
		Change in IWR			Change in Price of Water		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
	-20%	-71	-48	-12	-12	14	53
	-15%	-29	-5	33	15	42	83
	-10%	13	39	79	43	70	112
	-5%	55	83	125	70	98	142
	0%	98	126	171	98	126	171
	5%	140	170	217	125	155	201
	10%	182	214	263	152	183	230
	15%	224	258	309	180	211	260
	20%	267	301	355	207	239	289

G.Magusa							
		Change in IWR			Change in Electricity Usage		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
Increase in Irrigation Energy Consumption Rate	-20%	-14%	-11%	-7%	5%	9%	14%
	-15%	-9%	-6%	-2%	6%	9%	14%
	-10%	-4%	0%	4%	6%	10%	15%
	-5%	2%	5%	10%	6%	10%	15%
	0%	7%	11%	16%	7%	11%	16%
	5%	12%	16%	21%	7%	11%	16%
	10%	18%	22%	27%	8%	12%	17%
	15%	23%	28%	33%	8%	12%	17%
	20%	28%	33%	39%	9%	13%	18%
Reduction in Net Cashflow or Profit for Rain-fed Crops ($/ha)		Yield			Real Selling Price		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
	-20%	441	609	648	441	609	648
	-15%	414	561	602	414	561	602
	-10%	388	513	556	388	513	556
	-5%	361	464	510	361	464	510
	0%	335	416	465	335	416	465
	5%	309	367	419	309	367	419
	10%	282	319	373	282	319	373
	15%	256	271	327	256	271	327
	20%	230	222	281	230	222	281
		Real Purchase Price			Input Usage		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
	-20%	302	331	380	302	331	380
	-15%	310	352	401	310	352	401
	-10%	319	374	422	319	374	422
	-5%	327	395	443	327	395	443
	0%	335	416	465	335	416	465
	5%	343	437	486	343	437	486
	10%	352	458	507	352	458	507
	15%	360	479	528	360	479	528
	20%	368	500	549	368	500	549
Reduction in Net Cashflow or Profit of Irrigated Crops ($/ha)		Yield			Real Selling Price		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
	-20%	2623	2639	2659	2623	2639	2659
	-15%	1974	1990	2009	1974	1990	2009
	-10%	1324	1340	1360	1324	1340	1360
	-5%	675	691	710	675	691	710
	0%	25	41	61	25	41	61
	5%	-624	-608	-589	-624	-608	-589
	10%	-1274	-1257	-1238	-1274	-1257	-1238
	15%	-1923	-1907	-1887	-1923	-1907	-1887
	20%	-2572	-2556	-2537	-2572	-2556	-2537
		Change in IWR			Change in Price of Water		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
	-20%	-77	-64	-49	-21	-6	12
	-15%	-52	-38	-21	-9	6	24
	-10%	-26	-11	6	2	18	37
	-5%	0	15	34	14	30	49
	0%	25	41	61	25	41	61
	5%	51	68	88	37	53	73
	10%	77	94	116	48	65	85
	15%	102	121	143	60	77	97
	20%	128	147	170	71	89	110

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Increase in Irrigation Energy Consumption Rate

	Change in IWR			Change in Electricity Usage		
	Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
-20%	-10%	-5%	3%	3%	8%	17%
-15%	-4%	1%	9%	5%	11%	20%
-10%	2%	7%	16%	8%	13%	23%
-5%	7%	13%	22%	10%	16%	26%
0%	**13%**	**19%**	**28%**	**13%**	**19%**	**28%**
5%	18%	25%	35%	15%	21%	31%
10%	24%	30%	41%	18%	24%	34%
15%	30%	36%	48%	20%	26%	37%
20%	35%	42%	54%	23%	29%	40%

Reduction in Net Cashflow or Profit for Rain-fed Crops ($/ha)

	Yield			Real Selling Price		
	Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
-20%	438	607	645	438	607	645
-15%	411	559	600	411	559	600
-10%	385	510	554	385	510	554
-5%	358	462	508	358	462	508
0%	**332**	**414**	**462**	**332**	**414**	**462**
5%	305	365	416	305	365	416
10%	279	317	370	279	317	370
15%	252	269	325	252	269	325
20%	225	220	279	225	220	279

	Real Purchase Price			Input Usage		
	Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
-20%	299	329	378	299	329	378
-15%	307	350	399	307	350	399
-10%	315	371	420	315	371	420
-5%	323	393	441	323	393	441
0%	**332**	**414**	**462**	**332**	**414**	**462**
5%	340	435	483	340	435	483
10%	348	456	504	348	456	504
15%	356	477	525	356	477	525
20%	365	498	546	365	498	546

Reduction in Net Cashflow or Profit of Irrigated Crops ($/ha)

	Yield			Real Selling Price		
	Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
-20%	1979	2025	2109	1979	2025	2109
-15%	1509	1554	1639	1509	1554	1639
-10%	1038	1084	1168	1038	1084	1168
-5%	568	613	698	568	613	698
0%	**97**	**143**	**227**	**97**	**143**	**227**
5%	-373	-328	-243	-373	-328	-243
10%	-844	-798	-714	-844	-798	-714
15%	-1314	-1269	-1184	-1314	-1269	-1184
20%	-1785	-1739	-1655	-1785	-1739	-1655

	Change in IWR			Change in Price of Water		
	Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
-20%	-125	-88	-21	-77	-39	33
-15%	-69	-31	41	-34	7	81
-10%	-14	27	103	10	52	130
-5%	42	85	165	54	97	179
0%	**97**	**143**	**227**	**97**	**143**	**227**
5%	153	200	289	141	188	276
10%	208	258	351	185	233	324
15%	264	316	413	228	279	373
20%	319	374	475	272	324	421

Guzelyurt							
		Change in IWR			Change in Electricity Usage		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
Increase in Irrigation Energy Consumption Rate	-20%	-13%	-10%	-6%	-8%	-4%	0%
	-15%	-8%	-4%	0%	-4%	0%	5%
	-10%	-3%	1%	6%	0%	4%	9%
	-5%	3%	7%	12%	4%	8%	14%
	0%	8%	13%	18%	8%	13%	18%
	5%	14%	18%	24%	12%	17%	22%
	10%	19%	24%	30%	16%	21%	27%
	15%	24%	30%	36%	20%	25%	31%
	20%	30%	35%	41%	24%	29%	35%
Reduction in Net Cashflow or Profit for Rain-fed Crops ($/ha)		Yield			Real Selling Price		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
	-20%	658	836	894	658	836	894
	-15%	616	773	834	616	773	834
	-10%	573	710	775	573	710	775
	-5%	531	647	716	531	647	716
	0%	489	584	657	489	584	657
	5%	446	521	597	446	521	597
	10%	404	458	538	404	458	538
	15%	361	395	479	361	395	479
	20%	319	333	420	319	333	420
		Real Purchase Price			Input Usage		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
	-20%	456	500	572	456	500	572
	-15%	464	521	593	464	521	593
	-10%	472	542	614	472	542	614
	-5%	480	563	636	480	563	636
	0%	489	584	657	489	584	657
	5%	497	606	678	497	606	678
	10%	505	627	699	505	627	699
	15%	513	648	720	513	648	720
	20%	522	669	741	522	669	741
Reduction in Net Cashflow or Profit of Irrigated Crops ($/ha)		Yield			Real Selling Price		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
	-20%	1905	1961	2031	1905	1961	2031
	-15%	1451	1507	1576	1451	1507	1576
	-10%	996	1052	1122	996	1052	1122
	-5%	542	598	667	542	598	667
	0%	87	143	213	87	143	213
	5%	-367	-311	-242	-367	-311	-242
	10%	-822	-766	-696	-822	-766	-696
	15%	-1276	-1220	-1151	-1276	-1220	-1151
	20%	-1731	-1675	-1605	-1731	-1675	-1605
		Change in IWR			Change in Price of Water		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
	-20%	-286	-241	-186	-231	-184	-126
	-15%	-193	-145	-86	-152	-102	-41
	-10%	-100	-49	14	-72	-20	43
	-5%	-6	47	113	8	61	128
	0%	87	143	213	87	143	213
	5%	180	239	312	167	225	297
	10%	274	335	412	246	307	382
	15%	367	431	511	326	389	467
	20%	460	527	611	405	470	551

Iskele							
		Change in IWR			Change in Electricity Usage		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
Increase in Irrigation Energy Consumption Rate	-20%	-14%	-11%	-6%	-4%	1%	6%
	-15%	-9%	-5%	0%	-1%	3%	9%
	-10%	-3%	1%	6%	2%	6%	12%
	-5%	2%	6%	12%	5%	9%	15%
	0%	7%	12%	18%	7%	12%	18%
	5%	13%	17%	24%	10%	15%	21%
	10%	18%	23%	29%	13%	18%	24%
	15%	23%	29%	35%	15%	20%	27%
	20%	29%	34%	41%	18%	23%	30%
Reduction in Net Cashflow or Profit for Rain-fed Crops ($/ha)		Yield			Real Selling Price		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
	-20%	573	631	672	573	631	672
	-15%	518	582	625	518	582	625
	-10%	462	533	579	462	533	579
	-5%	407	484	532	407	484	532
	0%	352	435	486	352	435	486
	5%	297	386	439	297	386	439
	10%	241	336	393	241	336	393
	15%	186	287	346	186	287	346
	20%	131	238	300	131	238	300
		Real Purchase Price			Input Usage		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
	-20%	267	350	401	267	350	401
	-15%	289	371	422	289	371	422
	-10%	310	392	444	310	392	444
	-5%	331	414	465	331	414	465
	0%	352	435	486	352	435	486
	5%	373	456	507	373	456	507
	10%	394	477	528	394	477	528
	15%	415	498	549	415	498	549
	20%	436	519	570	436	519	570
Reduction in Net Cashflow or Profit of Irrigated Crops ($/ha)		Yield			Real Selling Price		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
	-20%	2319	2366	2427	2319	2366	2427
	-15%	1754	1800	1861	1754	1800	1861
	-10%	1188	1234	1295	1188	1234	1295
	-5%	622	668	729	622	668	729
	0%	56	103	164	56	103	164
	5%	-509	-463	-402	-509	-463	-402
	10%	-1075	-1029	-968	-1075	-1029	-968
	15%	-1641	-1594	-1534	-1641	-1594	-1534
	20%	-2206	-2160	-2099	-2206	-2160	-2099
		Change in IWR			Change in Price of Water		
		Moderatee	Severe	Extreme	Moderatee	Severe	Extreme
	-20%	-228	-191	-142	-173	-134	-82
	-15%	-157	-117	-65	-116	-75	-21
	-10%	-86	-44	11	-58	-15	41
	-5%	-15	29	87	-1	44	102
	0%	56	103	164	56	103	164
	5%	127	176	240	114	162	225
	10%	198	249	316	171	221	286
	15%	269	323	393	229	280	348
	20%	340	396	469	286	339	409

Appendix C: Detailed Map of the Study Area