Evaluating Drought Indices for Agricultural Drought Monitoring in Gia Lai Province, Vietnam

CHU MINH THU

201526056

July 2017

A Master's Thesis Submitted to
The Graduate School of Life and Environmental Sciences,
University of Tsukuba
in Partial Fulfillment of the Requirements
for the Degree of Master of Environmental Sciences

Abstract

Gia Lai province is located in the Central Highlands which is a major cultivation area of coffee in Vietnam. However, the Central Highlands is exposed to regular drought. In recent years (1989 – 2006), there were 15 droughts in this area. Hence, understanding the characteristics of drought will help to mitigate the adverse effects of drought on agriculture. This study focuses on agricultural drought, which is basically identified by the moisture deficit that leads to reductions of cultivation production. Agricultural drought can be characterized by drought indices. Some indices are commonly applied in drought monitoring, and early warning in drought-prone regions. In addition, according to the definition, crop yield could be a good indicator for evaluating the indices in term of monitoring agricultural drought. Therefore, this study aims to find out the appropriate index for monitoring agricultural drought by comparing with yield of main crops in Gia Lai province. In this study, crop yield residual (CYR) was used for eliminating the effect of farming technology improvement on the growth of crop yield.

By reviewing various droughts indices, four indices were considered. They are Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), Keetch-Byram Drought Index (KBDI) and Crop Drought Index (CDI). During the period from 1980 to 2010, SPI and SPEI were computed at different time steps: 1-month, 3-month, 6-month, and 9-month while KBDI and CDI were calculated monthly. These indices were compared with yield statistics of two major crops in Gia Lai province: spring rice paddy (largely grown in the southeast part of Gia Lai province) and coffee trees (mainly grown in the northwest part) for the period 2000-2010. Then the correlation between the two indices and the CYRs were determined and examined.

The results show that CDI is recommended for agricultural drought monitoring in Gia Lai province due to the highest value of coefficient of determination (R^2 = 0.52 for spring paddy and R^2 = 0.66 for coffee) and the number of times when R^2 was significant. Meanwhile, SPEI1 has the weakest relationship with CYRs due to the R^2 always under significant value for the most of the period of cultivation. Further analysis on comparing the indices with CYRs also indicates that CDI performed better than other selected indices in the ability of capturing drought events. CDI can detect severe drought events as well as moderate drought conditions. It has been found that drought in the developing and mid stages of crop growth period have more impact on crop yield reduction.

Keywords: Agricultural drought, SPI, SPEI, KBDI, Crop Drought Index

Table of Contents

List of Tables

List of Figures

List of Abbreviation and Acronyms

AIT: Asian Institute of Technology
AWC: Available water capacity
CCFSC: the Central Committee for Flood and Storm Control
CGIAR: Consultative Group for International Agricultural Research
CRED EM-DAT: Centre for Research on Epidemiology of Disasters
DEM: Digital Elevation Model
DoNRE: Department of Natural Resources and Environment - Gia Lai province
EM-DAT: Emergency Events Database
FAO: Food and Agriculture Organization
FC: Field capacity
GSO: Gia Lai Statistical Office
GWP: Global Water Partnership
GHWCo: Gia Lai Hydraulic Works Limited Company
HYMENET: Hydro-meteorological and Environmental Station Network Center
IMHEN: Institute of Meteorology, Hydrology, and Environment
INGO: International Non-Governmental Organization
MARD: Ministry of Agriculture and Rural Development
MONRE: Ministry of Natural Resources and Environment
MoH: Ministry of Health
NAWAPI: National Center for Water Resources Planning and Investigation
PACCOM: People's Aid Coordinating Committee
TAW: Total available soil water
UN: the United Nation
VND: Vietnam currency
WB: the World Bank
WMO: the World Meteorological Organization
WP: Wilting point

Acknowledgements

I would like to express my grateful appreciation to my supervisor, Professor Sugita Michiaki, for his transparent support, for being willing to give his time whenever I needed to discuss as well as for giving me valuable guidance during my master thesis.

I would like to thank JDS for awarding me the scholarship. It provided me great opportunity to study in Japan as well as the University of Tsukuba. Thanks to JDS, I have a chance to study in the international environment that helps me to expand the professional network with other students and professors from different countries. Together with, I also thank Ms. Shoko who supported me in accommodation settlement as well as during my study.

I give my special thanks to all my dear friends who have been studying with me almost two years. I also thank all professors and students in Water Environment and Hydrology lab for their advice and comments to improve my research.

I would like to thank the staff of Hydro-meteorological and Environmental Station Network Center, Institute of Meteorology, Hydrology, and Environment, especially thank Mr. Ngo Sy Giai for providing data and documents needed to conduct this thesis. Also, grateful thanks to my managers, Dr. Tong Ngoc Thanh and Mr. Nguyen Van Kenh, allowed me to attend this scholarship as well as my colleagues for their encouragement.

Finally, I would like to acknowledge the continuous support provided by my parents, my husband during my study.

Chapter 1 Introduction

Drought is a recurring climatic phenomenon that is caused by the deficiency of precipitation over a certain period of time, leading to a water shortage for human activities and environment (Sivakumar *et al*., 2010). Drought is not simply dry condition characterized by low precipitation and high evapotranspiration. It would be defined as a moisture condition that is below the normal condition or lower than expectation (Wilhite and Glantz, 1985). Drought is also different from floods, storms, and earthquakes because it is long duration event and difficult to identify (Wilhite, 2010).

Drought is one of the worst disasters in the world. From the international disaster database (CRED EM-DAT database), WMO observed that during 1970 – 2012 droughts accounted for only 6% total number of natural disasters but it caused 35% of deaths and 8% of total economic losses (WMO, 2014). Drought affects all part of our environment and our life in both direct and indirect ways. Its impact can be placed into 3 groups: economic, environmental and social impacts. In term of economic impacts, agriculture is the most vulnerable sector among all the economic sectors. In a report of FAO (2015), it is said that over 80% of the drought damage and losses were in agriculture, mainly livestock and crop production.

1.1 Agricultural drought definition

By reviewing more than 150 definitions of drought, White and Glantz (1985) classified the definitions of drought into 4 groups based on basic approaches to measuring drought: meteorological, agricultural, hydrological, and socioeconomic. The characteristic of each kind of drought can be summarized as follows:

Meteorological drought is defined by the degree of dryness compared to normal condition (average or expected amount) and the duration of the dry period. The meteorological drought definitions differ from region to region because the meteorological conditions which cause the precipitation deficiencies are variable around the world.

Agricultural drought is phenomena when soil moisture is insufficient and which leads to a reduction of agricultural production. It is identified by analyzing the properties of soil moisture and biological characteristics of plant during different stages of crop development.

Hydrological drought is identified by the shortages of surface or subsurface water supply as a result of the meteorological drought. It often has delay sometime after meteorological and agricultural drought. Hydrological drought need to be considered in river basin scale because hydrological drought in an upstream part of a river may have impacts on stream flow at a downstream, even though meteorological drought does not occur in this part of the basin.

Socioeconomic drought can be defined when water demand for good productivity exceeds supply as a result of a weather-related supply deficit.

Although the definitions of four types of droughts are different, they are all water deficit phenomena related to precipitation reduction. Figure 1.1 shows the relationship between four types of drought in a time sequence. Precipitation deficiency and high temperature over a certain period cause a meteorological drought. If meteorological droughts last long enough, it would lead to shortage of moisture in the soil, posing a stress to plant water which results in agricultural drought. Soil moisture deficiency, subsequently, causes the reduction of streamflow and groundwater level which characterize the hydrological drought. Finally, socioeconomic drought occurs as a consequence of a prolonged agricultural and hydrological drought. Sequentially, agricultural drought happens after meteorological drought, so, agriculture is the first economic sector affected by drought.

1.2 Review of previous studies

Drought events are normally characterized by drought indices (Liu *et al*., 2016). However, the disagreement among the definitions of drought makes it difficult to develop a universal drought index (Heim, 2002). As a consequence, hundreds of indices have been introduced. Based on the input data needed for calculating each index, the indices can be grouped into classifications: (1) meteorology, (2) agriculture, and (3) hydrology. Meteorological indices use meteorological data from meteorological stations in their formulas. Agricultural indices consider soil moisture in the calculation so that they need more information on soil characteristics. Hydrological indices focus on hydrologic impacts such as streamflow, lake and reservoir levels, and groundwater levels. As discussed in section 1.1 meteorological drought often occurs first and leads to agricultural drought. Hydrological drought often appears after agricultural drought. Therefore, for the purpose of studying agricultural drought, in addition to studying agricultural indices, this thesis also focuses on meteorological indices. Moreover, another advantage of meteorological indices is that those indices are solely based on climatic data which is monitored frequently over a long period of time. In this section, the most commonly used meteorological and agricultural indices around the world will be discussed.

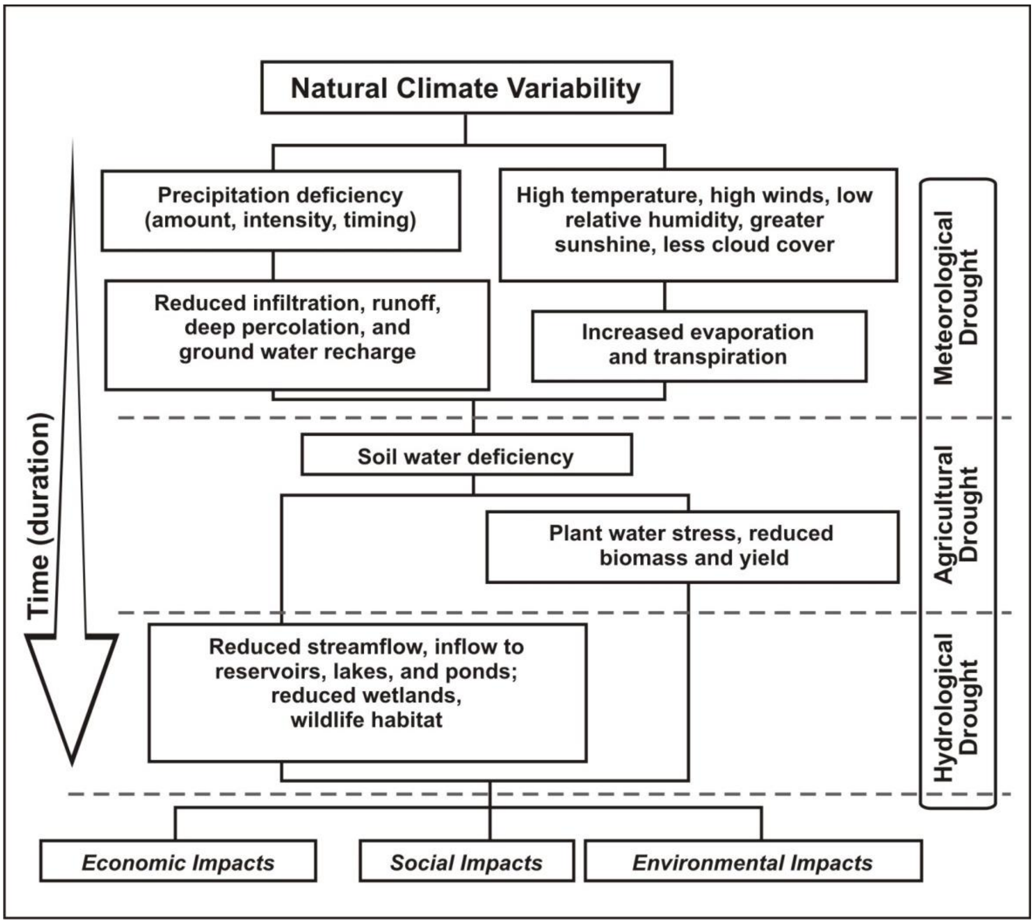


Figure 1.1 Sequence of drought occurrence (derived from National Drought Mitigation Center, University of Nebraska-Lincoln, USA)

1.2.1 Meteorological drought indices

Table 1.1 summarized the characteristics of several meteorological indices. Most early meteorological indices which were proposed for initial drought monitoring are based on precipitation. They include Deciles (Gibbs and Maher, 1967), Munger's Index (Munger, 1916), and Palmer Drought Severity Index (PDSI) (Palmer, 1965). PDSI originated from water balance theory was used widely as an operational drought index, especially in the USA. A shortcoming of PDSI is that it responds slowly to detect short-term dry spells because it has a timescale of nearly nine months (Sivakumar *et al.*, 2010) while the crop season normally lasts maximum six months (excluding perianal crops). Therefore, a flexible index which can be calculated at different time scales is needed to respond the drought condition in crop seasons.

Standardized Precipitation Index (SPI) developed by McKee *et al*. (1993) can be calculated at different timescales which range from 1 month to 48 months or longer. Specific-duration SPI reflects different water feature as pointed out in Zargar *et al*. (2011). For example, 1-month SPI responds short-term soil moisture and crop stress while 9-month SPI is good for detect drought impacts in agriculture. In addition, Changnon and Easterling (1989) described the relationship between precipitation deficiency and other components of the hydrologic cycle during a hypothetical four-year period (Figure 1.2). Soil moisture deficit which results in agricultural drought responses the precipitation anomalies on a relatively short time scale. Therefore, SPI has been studied in term of agricultural drought monitoring. Quiring and Papakryiakou (2003) used SPI to predict crop yields for the Canadian prairies. Nadir (2013) applied SPI to assess the vulnerability of sorghum and millet to drought in Sub-Saharan Sudan and found a significant relationship between SPIs and crop yield during the early-to-mid growing season. Chhinh and Millington (2015) found a strong relationship between SPI and the area of rice damage in Cambodia. Another advantage of SPI is that the index reflects the standard normalized distribution values. Because of this, SPI can be compared in any region with different climatic regimes.

Nevertheless, SPI is not without limitations. The first is the disagreement on the distribution function to be used to fit rainfall time series. McKee *et al*. (1993) proposed two-parameter Gamma distribution while Guttman (1999) and Vicente-Serrano (2006) suggested three-parameter Pearson Type III is more suitable. However, Angelidis *et al*. (2012) and Stagge *et al*. (2015) agreed that two-parameter Gamma distribution is better. The second weakness of SPI is that SPI uses only precipitation as a primarily dominate factor. Therefore, SPI does not respond other factors that influence droughts, such as temperature or evapotranspiration. For this reason, Li *et al*. (2014) found that SPI cannot detect agricultural drought in a semi-arid region in China.

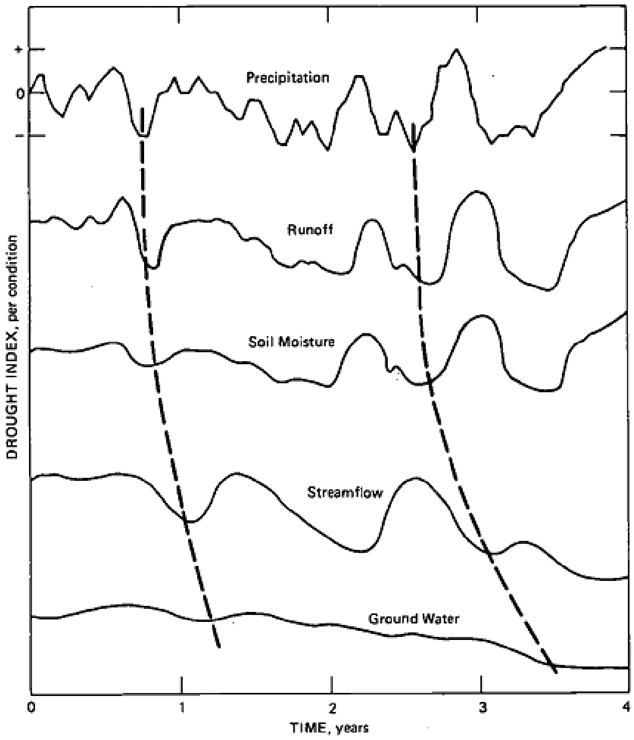


Figure 1.2 Effect of precipitation deficiency on delayed sub-components of the hydrologic cycle during a hypothetical four-year period (Changnon & Easterling, 1989)

To deal with this limitation, Vicente-Serrano *et al*. (2010) established a new index, Standardized Precipitation-Evapotranspiration Index (SPEI). This index takes the multi-scale advantage of SPI and also considers the difference between precipitation and potential evapotranspiration which indicates climatic water balance. Due to this reason, SPEI has become a robust index for drought monitoring (Liu *et al*., 2016). Wang *et al*. (2016) proved that SPEI is advantageous for winter wheat drought monitoring.The usefulness of SPEI in agricultural drought monitoring can be found in several place around the world, such as in the USA (Moorhead *et al*., 2015), in Czech Republic (Potopva *et al*., 2015), in Republic of Moldova (Potopová *et al*., 2016), and in Slovakian (Labudová *et al*., 2017).

Another meteorological drought index based on water balance to estimate soil moisture in the top soil layer is Keetch-Byram Drought Index (KBDI) (Keetch and Byram, 1968). Originally, KBDI was introduced to assess forest fire potential in the USA. It is still being used in wildfire research studies in several regions around the world (Arpaci *et al*., 2013; Varol and Ertugrul, 2016). However, this index quantitates the effect of precipitation and evapotranspiration in changing soil moisture deficit of the top soil layers which is directly related to crop drought stress so that it was found to be useful in agricultural monitoring (WMO and GWP, 2016). This index is validated as drought warning index for rice cultivation in Thailand (AIT, 2017). The applicability of KBDI to assess the impact of drought on rice is also discussed in Takeuchi *et al*. (2015).

1.2.2 Agricultural drought indices

Agricultural drought indices are primarily based on monitoring soil moisture balance. Some of common agricultural drought indices are described in Table 1.2. Agricultural drought indices commonly used are Crop Moisture Index (CMI) (Palmer, 1968), Soil Moisture Deficit Index (SMDI), Evapotranspiration Deficit Index (ETDI) (Narasimhan and Srinivasan, 2005), and Crop Drought Index (CDI) (Brunini *et al*., 2005).

CMI was introduced by Palmer (1968) as an output of PDSI procedure in order to overcome the limitation of PDSI about time scale for monitoring short-term agricultural drought conditions. However, some limitations of PDSI still remains in CMI that were identified by Narasimhan and Srinivasan (2005) and Moorhead *et al*. (2015). The main limitation lies in the assumption of the water capacity of two top soil layers. First, water capacity of the two top soil layers is fixed for the entire region. However, in fact, it varies spatially. Second, the water capacity of the surface layer is assumed 25mm, which is much smaller than the underlying layer, leading to insensibility of water balance in the surface layer. Moreover, CMI was developed to respond to the changing short-term conditions that make

CMI not suitable for a long-term drought monitoring (Mishra and Singh, 2010; WMO and GWP, 2016).

Narasimhan & Srinivasan (2005), after noticing the limitation of PDSI, proposed SMDI and ETDI which have finer temporal and spatial resolution. These indices are calculated based on soil moisture and water stress ratio based on a comparison of actual evapotranspiration and reference evapotranspiration. Then, the water stress ratio is used to calculate water stress anomaly in long-term period. Soil moisture and the water stress ratio reflect the water stress on the plant. Therefore, these indices are good for agricultural drought monitoring. However, the input data of these indices are usually obtained from another model that makes the calculation very complicated (WMO and GWP, 2016).

CDI (Brunini *et al*., 2005) indicates the reduction of evapotranspiration in relation to potential evapotranspiration which is an accurate measure of water stress on crop (Moorhead *et al.*, 2015). This index is superior to ETDI in the use of potential evapotranspiration instead of reference evapotranspiration. Therefore, CDI reflects the drought conditions for each crop. CDI has demonstrated its ability of drought monitoring in Brazil (Bruninni *et al*., 2005) and Poland (Łabędzki and Bąk, 2014).

1.2.3 Previous studies on agricultural drought in Vietnam

Researches on drought in Vietnam are relatively new and mainly concentrated in meteorological drought. Several meteorological indices have been calculated for various regions of Vietnam. Dao (2005) used meteorological indices to analyze meteorological drought characteristics in the Central Highlands of Vietnam. Nguyen (2005) applied SPI for drought prediction in the Central Highlands and South Central region of Vietnam. Vu-Thanh *et al.* (2014) used SPI for studying the drought conditions in Vietnam for the period 1961-2007. Vu *et al.* (2015) also applied SPI to simulate drought in the Central Highlands in the context of climate change. Study on agricultural drought was marked by the research of IMHEN (2008). Several agricultural drought indices were first calculated for the South Central and the Central Highlands, including CMI and PDSI. It has been concluded that these indices are significant in monitoring drought in the study area as well as for the whole of Vietnam. The authors also pointed out that the main obstacle to adopt these indices is the limitation of the data corresponding to each index. Nguyen (2014) applied KBDI in drought monitoring system for Vietnam. The author concluded that KBDI can define the onset time and duration of drought events. However, there are some differences between KBDI and real climatic condition in some regions.

Table 1.1 Descriptions of meteorological drought indices

Index	Reference	Minimum required input data	Note
Deciles	Gibbs & Maher (1967)	Precipitation	
Munger's Index	Munger (1916)	Precipitation	
Palmer Drought Severity Index (PDSI)	Palmer (1965)	Precipitation, temperature, available water content	Slow response to short-term drought.
Standardized Precipitation Index (SPI)	McKee *et al*. (1993)	Precipitation	Adaptable at various time scales, can be used for monitoring agricultural drought
Standardized Precipitation-Evapotranspiration Index (SPEI)	Vicente-Serrano *et al*. (2010)	Precipitation, temperature	Multi time scales as SPI, considered water balance
Keetch-Byram Drought Index (KBDI)	Keetch and Byram (1968)	Precipitation, temperature	Applicability to crop drought monitoring is in validation.

Table 1.2 Descriptions of agricultural drought indices

Index	Reference	Minimum required input data	Note
Crop Moisture Index (CMI)	Palmer (1968)	Precipitation, temperature	Short-term monitoring, not good for long-term monitoring
Soil Moisture Deficit Index (SMDI), Evapotranspiration Deficit Index (ETDI)	Narasimhan and Srinivasan (2005)	Soil moisture and evapotranspiration from model	Complicated to calculate, reference evapotranspiration is not useful for crop monitoring
Crop Drought Index (CDI)	Brunini *et al*. (2005)	Rainfall, evapotranspiration, soil water capacity	Assess the impact of drought on different crop

Although various indices have been considered and studied, all the indices applied for Vietnam have not been evaluated by agricultural drought record. Therefore, the question which is the best indices for representing drought conditions in Vietnam, unfortunately, has remained unanswered (Vu-Thanh *et al*., 2014).

According to the definition of droughts, agricultural drought is related to soil moisture deficiency or crop water stress. Therefore, the indices which can measure water condition in the soil or crop are good for agricultural drought monitoring. Based on the review of previous studies, four indices selected to study are SPI, SPEI, KBDI, and CDI. SPI is recommended by WMO for meteorological drought monitoring. However, the flexibility in selecting time periods gives it the benefit in reflecting other kinds of drought (as shown in Figure 1.2). Therefore, SPI could be used for monitoring agricultural drought by choosing a suitable time scale in SPI calculation. SPEI uses the difference between precipitation and evapotranspiration (ET), the major components of the water budget. The difference between the two components represents irrigation demand to fulfill inadequate precipitation during the growing season which indicates the condition of agricultural drought. KBDI is defined as "the net effect of evapotranspiration and precipitation in producing a moisture deficiency in the upper layers of the soil" (Keetch and Byram, 1968). It is also considered as the amount of water that is needed for saturation of the top soil layer to stop drought stress. SPI, SPEI, and KBDI are meteorological indices, and CDI is an agricultural index. Therefore, CDI is considered to be an accurate measure of water stress of crop.

1.3 Purpose of the study

The study aims to determine the appropriate index for monitoring agricultural drought in Gia Lai province (see chapter 2). Therefore, the purposes of this study are:

- To explore the relationship between drought indices and crop yields.

- To investigate the ability of drought indices to capture drought events in Gia Lai province.

Chapter 2 Study area and methodology

2.1 Study area

2.1.1 Topography, climate, and soils

Gia Lai province lies between 12°58’ N - 14°36’ N and 107°27’ E - 108°54’ E located in the northern part of the Central Highlands. Figure 2.1 shows the location and terrain of Gia Lai province. The topography changes lower from north to south and from east to west. Elevations range from 70 m to 1800 m above the sea level. Gia Lai has complex topography: mountains, plateaus, and valleys. Mountainous area dominates the majority of Gia Lai province, located in the northeast of the province. Plateaus cover 33% of natural area spreading from the east to the border with Cambodia. Valley topography with a small area lying over southern part of the province, distributed along the river basin. This kind of terrain forms many steep slopes which lead to a limited ability of water storage.

Gia Lai is situated in a tropical monsoon region, with average annual rainfall from 2,200 to 2,500 mm. The rainy season begins in May and ends in October while dry season lasts from November to April in the following year. Dry season coincides with spring crop seasons but its average rainfall is only 5 - 15% of the annual rainfall that results in frequent droughts in this area (NAWAPI, 2015).

Figure 2.2 shows the soils of Gia Lai province. Gia Lai has five main groups: Ferralsols, Acrisols, Fluvisols, Humic Acrisols, and others (IMHEN, 2008). The soil of the study area is mainly Ferralsols which accounts for 68% of the natural area. This kind of soil is good for planting perennial industrial trees like coffee, tea, pepper, and rubber, as well as annual crops like corn, sugar cane and vegetables. However, this soil is easy to be drained; therefore, storage capacity of water is small.

2.1.2 Land-use, cultivation and water use

Gia Lai has 601×10^3 ha agricultural production land, accounting for 38.7% of the natural area, of which annual crop land was 345×10^3 ha and 257×10^3 ha was used for perennial cropland in 2011 (GSO, 2012). Annual cropland is distributed along the valleys, mainly concentrates in the Ba River basin while perennial cropland dominates in the western part of the province where Pleiku plateau is located. (Figure 2.3)

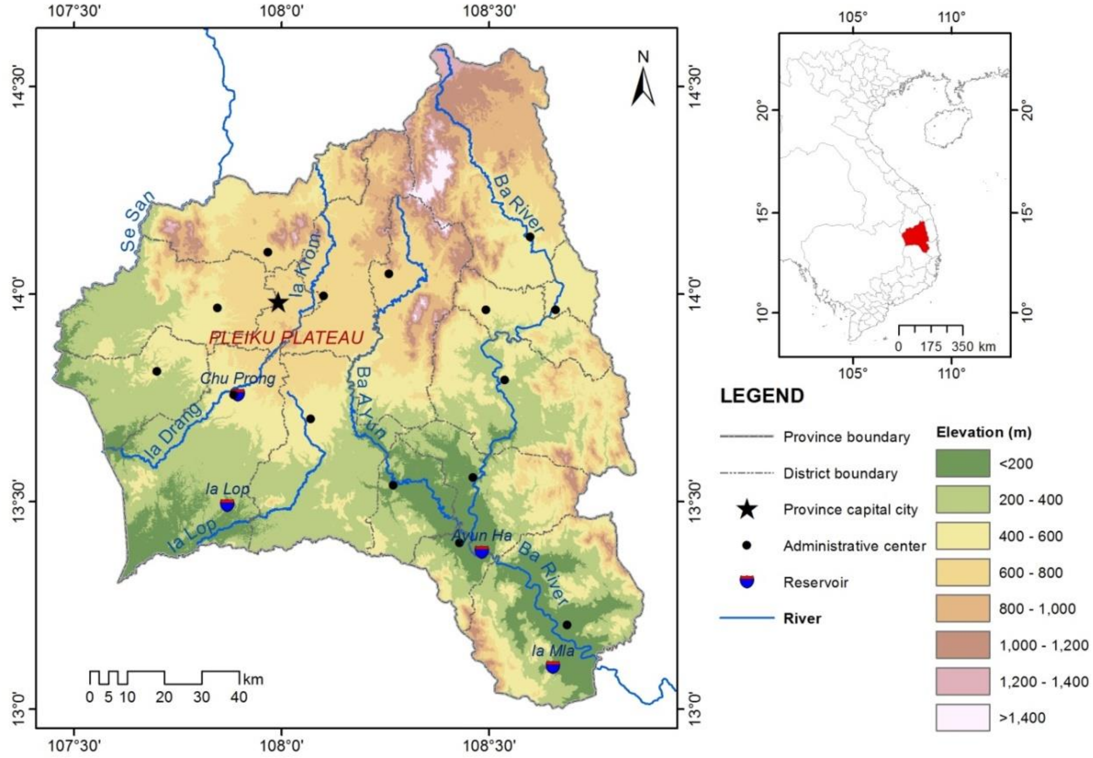


Figure 2.1 Topographic map of Gia Lai province created based on DEM source subtracted from NASA LP DAAC (2011)

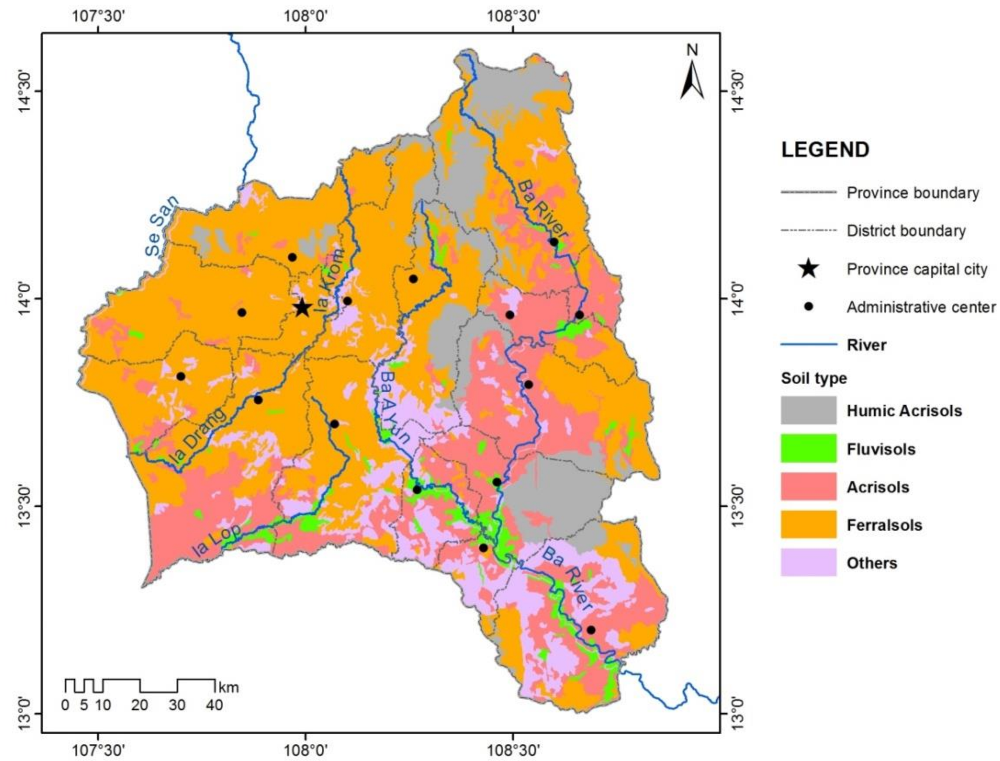


Figure 2.2 Soil map of Gia Lai province created from IMHEN (2008)

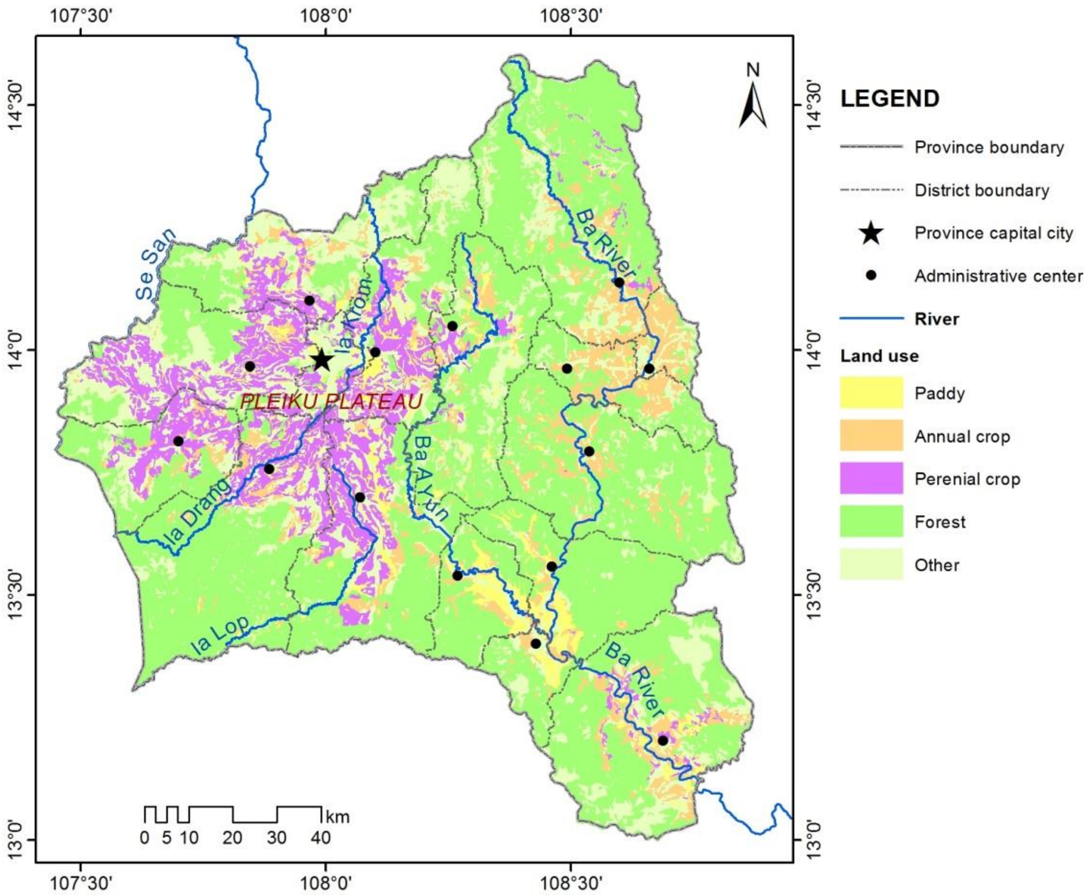


Figure 2.3 Land-use map of Gia Lai province in 2010 (DoNRE, 2013)

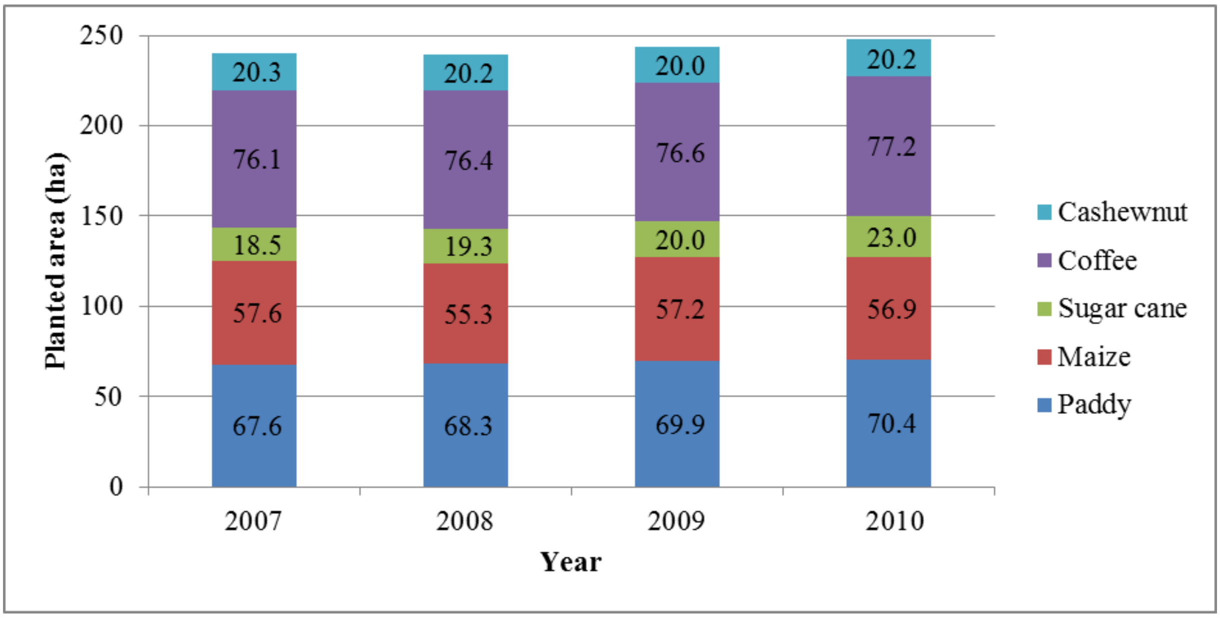


Figure 2.4 Planted area of major crops in Gia Lai province (GSO, 2012)

With the advantage of fertile soils, coffee is a major crop in Gia Lai. In 2010, planted area of coffee reached 77.2×10^3 ha, accounted for 17.3% total planted area. It was followed by paddy with 70.4×10^3 ha (including 24.0×10^3 ha of spring rice and 46.4×10^3 ha of winter rice), maize with 56.0×10^3 ha, sugar cane with 23.0×10^3 ha, and cashew of 20.2×10^3 ha. In general, planted area tended to increase slightly over the years. That means water demand for cultivation increased correspondingly. (Figure 2.4)

Irrigation systems in Gia Lai province have been invested since the 1970s. By the year 2010, irrigation systems in Gia Lai province have 311 concrete structures, with 107 reservoirs, 180 dams, and 44 pumping stations (NAWAPI, 2015). The systems have covered 40.0×10^3 ha, including 25.2×10^3 ha of cultivating rice and 14.5×10^3 ha of industrial plants and crops. Apart from irrigation systems, temporary structures can supply water for 9.1×10^3 ha of cultivated land (NAWAPI, 2015). However, irrigation capacity of irrigation systems and temporary structures is sufficient for only 10% of cultivated land.

Irrigated cultivated area expanded from 10×10^3 ha since 1990 to 39.7×10^3 ha in 2010. Since 2000, irrigation systems have supplied water to 100% area of spring paddy after constructing Ayun Ha, Ia Lop, Ia Mla reservoirs (Figure 2.1). Particularly, Ayun Ha reservoir locating in two districts Phu Thien and Chu Se has the volume of 256×10^6 m^3. The reservoir supplies water to 13.5×10^3 ha of cultivated land, accounting for one-half of total spring paddy area of Gia Lai province. Meanwhile, irrigated area of industrial crops and plants was only 6.5×10^3 ha (3.0%) in 1990 and expanded up to 18.1×10^3 ha (8.2%) in 2010.

2.1.3 Drought history

The study area is prone to droughts in many years. Drought often occurs in a winter-spring season (from January to April). In 1997/1998, due to the influence of strong El Nino during November 1997 to May 1998, widespread drought affected whole Vietnam with the total economic losses in term of agricultural production estimated about 5,000 billion VND (Nguyen, 2014). This extreme drought period destroyed 14,000 ha of coffee and 5,200 ha of paddy in the Central Highlands. The drought in 2002 affected 2,000 ha of crops, of which 1,300 ha was paddy (400 ha was destroyed) in Gia Lai province. In 2003, a severe drought occurred in the Central Highland that led to water shortage for 41,670 ha of coffee and 62,900 people lacking fresh water. In winter-spring 2004/2005, the water level in the Central Highlands was 20 – 30% lower than long term average water level. As a consequence, 13,859 ha of crops were affected, of which there was 10,500 ha of coffee and 349 ha was destroyed (Dao, 2005).

Since 2014, a prolonged El Nino phenomenon has affected Vietnam. The drought associated with the El Nino has impacted at least one-third of Vietnam’s 63 provinces. In the

Central Highlands, water volumes in most of the irrigation reservoirs have been lowered to 10 - 50% of their designed capacity and hundreds of small lakes have been dried up (CGIAR, 2016). This extreme drought spell has a significant impact on agriculture, food security, and livelihoods in Gia Lai province. There were 58,568 persons, including 15,230 children in emergency food aid (MARD *et al.*, 2016) and 21,998 ha of crop area (rice was 5,378 ha, coffee was 6,317 ha) damaged due to lack of water (CGIAR, 2016). Due to the severe damage, Gia Lai province has declared an emergency status as of March 2016.

Before 2011, the Central Committee for Flood and Storm Control (CCFSC) has an official responsibility of measuring natural disasters' damage and loss for each event by province. Unfortunately, it did not cover losses from drought. Therefore, the value of damage was inadequate or under-estimated. After 2011, a database of natural disasters, including drought impact, was stored in Central Steering Committee for Natural Disaster Prevention and Control (CCDPC) and Disaster Management Center (DMC). Thus, information about losses caused by drought was found in several reports (Nguyen, 2005; Dao, 2005; Nguyen, 2007; and Nguyen, 2014). Table 2.1shows the impact of drought on agriculture in Gia Lai province and the Central Highlands until 2005 (Dao, 2005; Nguyen, 2005). However, those data are insufficient. For example, the years 2007, 2009, 2010 were recorded as drought years (Nguyen, 2007; Nguyen, 2014) but crop damage was not statistically recorded.

Table 2.1 Agricultural impact due to drought in the Central Highlands and Gia Lai province until 2005 (Dao, 2005; Nguyen 2005)

Year	The Central Highlands		Gia Lai province	
	Affected area (ha)	Damaged area (ha)	Affected area (ha)	Damaged area (ha)
1997/1998	134,660	26,890	2000	No data
1999	2,000	No data	1,500	No data
2002	No data	No data	2,000	400
2003	41,670	No data	1,500	No data
2004	No data	No data	27,428*	10.278*
2004/2005	No data	No data	13,859	349

*: after autumn cropping season.

2.2 Dataset and statistics

2.2.1 Meteorological and hydrological data

There are three meteorological stations over Gia Lai province, as shown in Figure 2.5. However, data at two stations were selected. One is Pleiku station, located in Pleiku Plateau where coffee is mainly planted. The area of coffee in this plateau accounts for over 80% of the total cultivated coffee land in Gia Lai province. The other is Ayunpa station, situated in the Ba River valley where rice paddy field is concentrated. Therefore, Pleiku and Ayunpa stations were used to represent coffee and paddy rice, respectively. Daily rainfall, mean humidity, mean wind speed, sun duration, mean air temperature, maximum air temperature, and minimum air temperature at these two stations were collected. Most of these elements have been observed since 1980 except Pleiku station which has a dataset over longer time period. Hence, records from 1980 to 2010 were used. Some records with missing data over several months were gap-filled by using a linear regression with records from nearby, highly correlated stations. Due to the missing data of wind speed at Ayunpa station, the wind speed at Pleiku station was taken into consideration. The details of the procedure are explained in Appendix A.

Daily discharge of two hydrological stations was used in this thesis (Figure 2.5). Ayunpa hydrological station’s catchment belongs to the Ba River basin, covering Ayunpa meteorological station. Kon Tum station is situated in the Se San River basin which covers Pleiku station. The observations at these stations were from 1977. Records from 1980 to 2010 were selected in order to synchronize with the meteorological records.

The meteorological and hydrological data set was acquired from the Institute of Meteorology Hydrology and Environment (IMHEN) and Hydro-meteorological and Environmental Station Network Center (HYMENET).

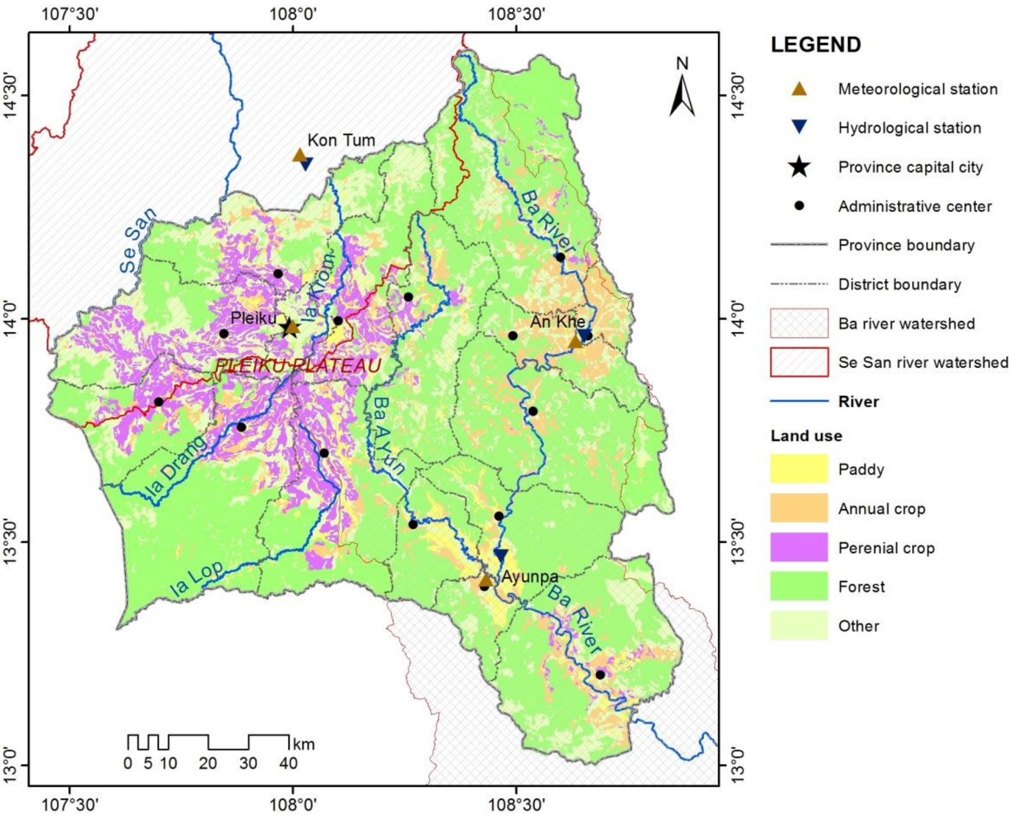


Figure 2.5 A map showing meteorological and hydrological stations in Gia Lai province

2.2.2 Field capacity and wilting point

Field capacity (FC) and wilting point (WP) data were collected for obtaining total available soil water (TAW) which is required for calculation of agricultural drought indices. The FC and WP data for Gia Lai province were obtained from the project conducted by IMHEN (2008). In this project, FC and WP for 15 districts and three types of soils (Ferralsols, Acrisols, and Fluvisols) of Gia Lai province at different depth within a 1-m depth soil column were measured. FC and WP vary due to the type of soils. Among three kinds of soils which were measured, Ferrasols has the highest value of FC and WP while Acrisols has the lowest value (Table 2.2). Therefore, water holding capacity of Ferrasols is better than Acrisols. In other words, Acrisols is more susceptible to drought than Ferrasols.

TAW is determined as the difference between FC and WP. In the study area, coffee is largely planted on the Ferralsols land and paddy rice is mainly cultivated on the Fluvisols land, so that average value of FC and WP for the two soils was employed for the analysis (Table 2.3). Root zone of paddy rice distributes in the soil layer from 0-50 cm (IMHEN, 2008) where the TAW ranges from 101 to 105 mm. The average root length of coffee is 100 cm so that TAW of root zone of coffee is 188 and 220 for Ferrrasols and Fluvisols, respectively. Thus, with the reference evaporation from 90-200 mm/month during 6 months in dry season (NAWAPI, 2015), the available water in the soil is enough for rice and coffee in 1-2 months. In the remaining months, if there is no rain or irrigation, the crop would face a high risk of drought.

2.2.3 Design irrigation rate

One hundred percent of spring paddy rice area and about 8% coffee area are watered by irrigation systems. Hence, irrigation rate is an important parameter in the calculation of agricultural drought indices. Unfortunately, this kind of data is not observed in the study area. Therefore, irrigation rate will be estimated by adjusting the design rate (Figure 2.6). The exact procedure is explained in section 2.3.1 (c)

According to report of water exploitation from Chu Prong reservoir (GHWCo, 2016), this reservoir is designed for supplying water to paddy rice 103 ha and coffee tree, pepper and other upland crops 597 ha for Chu Prong district (Figure 2.1). Spring paddy rice is watered during cropping season, from late December to early May. Coffee tree is watered only in first 3 months of the year, coinciding with the flowering stage of coffee.

Table 2.2 Field capacity (FC) and permanent wilting point (WP) (mm) of three soil type within a 1-m depth soil column in Gia Lai province (IMHEN, 2008)

Soil type	Number of sampling point	FC			WC		
		Average	Max	Min	Average	Max	Min
Ferralsols	8	390.5	420.3	372.0	202.9	215.5	183.4
Acrisols	6	268.3	324.0	197.5	110.8	152.7	59.8
Fluvisols	1	371.7			151.5		

Table 2.3 Average field capacity (FC), permanent wilting point (WP), and total available soil water (TAW) (mm) of Ferralsols and Fluvisols at different depth in Gia Lai province (IMHEN, 2008)

Depth (cm)	Ferralsols			Fluvisols		
	FC	WP	TAW	FC	WP	TAW
0 – 30	117	53	64	94	31	63
0 – 50	196	95	101	169	64	105
0 – 60	235	116	119	208	83	125
0 – 70	274	136	137	244	101	143
0 – 100	390	203	188	372	151	220

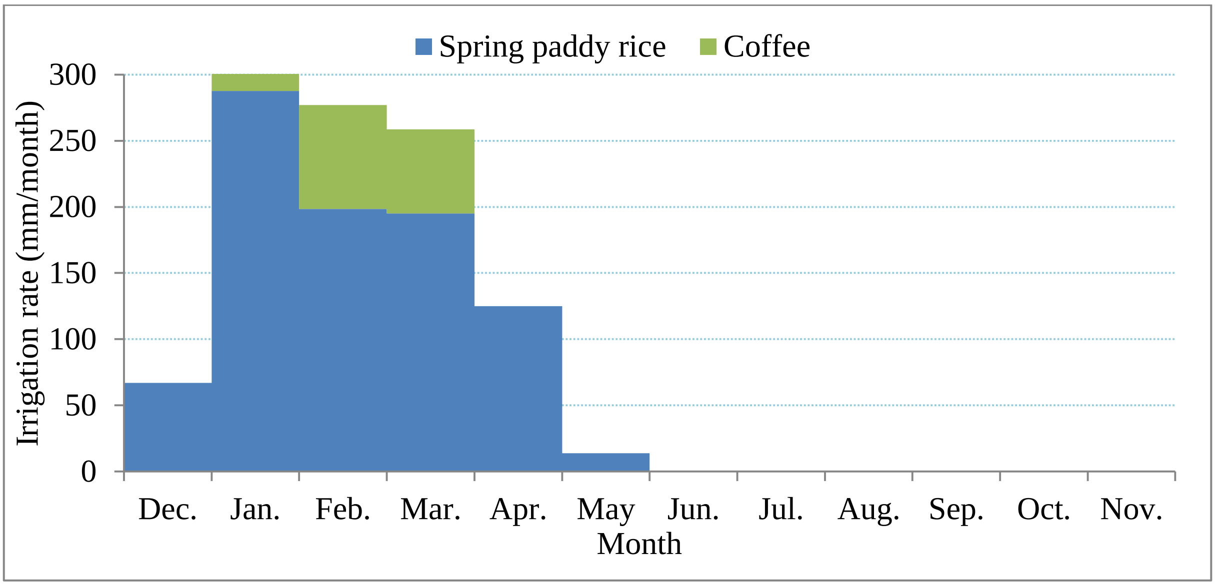


Figure 2.6 Design irrigation rate at paddy and coffee field from Chu Prong reservoir (GHWCo, 2016)

2.2.4 Crop yields and crop coefficient

According to a survey conducted by FAO (2016), drought was blamed for crop yield losses in the Central Highlands, including Gia Lai province. Therefore, crop yield losses can be used as an indicator of drought and to examine drought indices. Annual crop yield data of Gia Lai province were acquired from the website of GSO (2017) and MARD (2017). Paddy and coffee were chosen due to the extensive cultivation in the study area (Figure 2.4). Paddy rice in Gia Lai province is cultivated in two cropping seasons, spring season and winter season. Spring cropping season coincides with dry season and winter cropping season coincides with rainy season. Hence, spring paddy is vulnerable to drought while winter paddy is vulnerable to both drought and flood. Therefore, in order to study drought, this thesis focused on spring paddy. The data is available for 16 years (1995 – 2010) for spring paddy and 10 years (2001 – 2010) for coffee (Table 2.4).

Table 2.5 shows the duration and crop coefficient (Allen *et al*., 1998; MARD, 2011; and GHWCo, 2016; see also equation (2.1)) of each stage for spring paddy and coffee. The durations of each stage are adopted from Allen *et al*. (1998) and GHWCo (2016) while the planting dates and crop coefficients were obtained from MARD (2011). MARD provides various crop coefficients of paddy rice and other crops which were measured by different research institutes for different regions and provinces in Vietnam. From that, crop coefficients of paddy rice which were identified by experiments in Binh Dinh province, the neighbor province of the study area, were chosen for this study. Spring paddy has four growing stages: initial stage (from planting date to 10% ground cover), development stage (from 10% ground cover to initiation of flowering), mid-season stage (from flowering to the start of maturity), and late season stage (from the start of maturity to harvest) (Allen *et al*., 1998). Coffee is a perennial plant and it has only three stages: development, mid-season and late season. Due to the unstable weather, the planting date and the duration of each growing stage of spring paddy change from year to year. Spring paddy is planted during December and harvested in early of May so the planting date in Table 2.5 is chosen as the average value of planting date.

Table 2.4 Yield of spring paddy and coffee in Gia Lai province (GSO, 2017; MARD, 2017)

Year	Spring paddy	Coffee
1995	47.3	
1996	44.8	
1997	48.7	
1998	40.2	
1999	46.4	
2000	50.7	
2001	50.7	17.9
2002	47.1	13.9
2003	51.1	16.3
2004	51.6	15
2005	48.8	14
2006	56.2	
2007	55.9	16.5
2008	56.5	17.8
2009	55.7	18.7
2010	56.3	19.2

Table 2.5 The phenological times and crop coefficient of spring paddy and coffee (adopted from Allen *et al*., 1998; MARD, 2011; and GHWCo, 2016)

Crop		Planting date	Initial stage (stage 1)	Development stage (stage 2)	Mid-season stage (stage 3)	Late season stage (stage 4)	Ending date
Spring paddy	Duration (days)	Dec. 21	30	30	60	20	May 10
	k_c		0.98	1.19	1.27	1.12	
Coffee	Duration (days)	-	-	90	185	90	-
	k_c	-	-	1.05	1.1	1,1	

2.3 Methods

The suitable index was obtained through the process shown in Figure 2.7. First, four selected indices were calculated while drought years for coffee and spring paddy were identified by combining the information of crop yields (Table 2.4) and drought record (Table 2.1). Then the relationship between drought indices and crop yields was identified by a correlation analysis. The ability of each index to detect drought conditions was examined. Finally, the suitable index was recommended based on the qualification analysis of the results from step 3 and step 4.

2.3.1 Drought indices calculation

As mentioned in section 1.2 this thesis examined four drought indices, which are Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), Keetch-Byram Drought Index (KBDI) and Crop Drought Index (CDI).

a) Standardized Precipitation Index and Standardized Precipitation-Evapotranspiration Index

The input data of SPI are precipitation time series while SPEI needs a time series of the difference between precipitation and evapotranspiration. Vicente-Serrano *et al*. (2010) used the Thornwaite (1948) method to calculate reference ET but noticed that other methods give similar results in drought indices calculation. Moorhead *et al*. (2015) suggested using crop ET rather than reference ET. In this study, crop ET were used. The equation of crop ET is expressed in (2.1).

$$ETc = k_c ET_0 \tag{2.1}$$

where ETc is crop evapotranspiration; k_c is crop coefficient (Table 2.5); and ET_0 is reference evapotranspiration in a day, according to the Penman-Monteith equation (Allen *et al*., 1998) (mm/day), expressed as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2.2}$$

where R_n is net radiation at the crop surface (MJ/m^2/day); G is soil heat flux density (MJ/m^2/day); T is air temperature at 2 m height (°C); u_2 is wind speed at 2 m height (m/s); e_s is saturation vapor pressure (kPa); e_a is actual vapor pressure (kPa); Δ is slope vapor pressure curve (kPa/°C); and γ is psychrometric constant (kPa/°C).

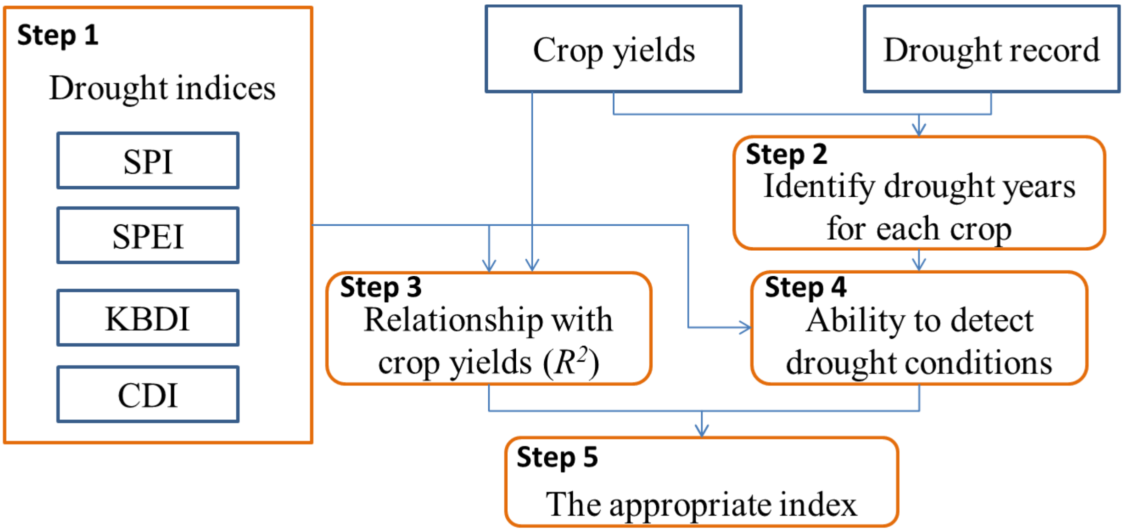


Figure 2.7 Flow diagram of the study

SPI and SPEI are simply defined as the standardized anomaly of the precipitation or the difference between precipitation and evapotranspiration.

$$\text{SPI or SPEI} \quad = \frac{X - \bar{X}}{\sigma} \tag{2.3}$$

$$\text{For SPI,} \quad X = P \tag{2.4}$$

$$\text{For SPEI,} \quad X = P - ETc \tag{2.5}$$

where P is precipitation, $\bar{X}$ is long term mean of X, and σ is standard deviation of X.

In this study, the different time scale of SPI and SPEI were considered so that time series for different time scale were estimated. X and $\bar{X}$ in equation (2.3) is replaced by D and $\overline{D}$

$$D_{i,j}^{k} = \sum_{t=13-k+j}^{12} X_{i-1,t} + \sum_{t=1}^{j} X_{i,t} \quad (j < k) \tag{2.6}$$

$$D_{i,j}^{k} = \sum_{t=j-k+1}^{j} X_{i,t} \quad (j \geq k) \tag{2.7}$$

where D is the accumulation of X for month j in year i with k time scale; and $\overline{D}$ is long term mean of D.

For example, 1-month and 3-month scale calculation in the year 1981 can be expressed by:

$$D_{1981,1}^{1} = X_{1981,1} \tag{2.8}$$

$$D_{1981,1}^{3} = X_{1980,11} + X_{1980,12} + X_{1981,1} \tag{2.9}$$

However, D is not normally distributed for accumulation periods of 12 months or less (McKee *et al.*, 1993). In order to transform X into a normal distribution, some calculation steps are applied. First, time series is fitted to a probability distribution. According to the authors of these indices, gamma distribution is suitable for SPI and log-logistic distribution is suggested for SPEI. The cumulative probability is given by the equation (2.10) for the gamma distribution and the equation (2.11) for the log-logistic distribution.

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

$$F(x) = \left[1 + \left(\frac{\alpha}{x - \gamma}\right)^{\beta}\right]^{-1} \tag{2.11}$$

where $\Gamma(\alpha)$ is gamma function; α, β, γ are scale, shape, and origin parameters, respectively.

To avoid the undefined gamma function when precipitation is equal to zero, the cumulative probability is written as follows:

$$H(x) = q + (1 - q)G(x) \tag{2.12}$$

$$H(x) = F(x) \tag{2.13}$$

where q is the probability of no precipitation.

Finally, the cumulative probability is transformed into the standard normal random variable by using the approximate conversion of Abromowitz and Stegun (1965), the standardized value is SPI or SPEI.

$$\text{SPI or SPEI} = \begin{cases} -\left(W - \dfrac{C_0 + C_1W + C_2W^2}{1 + d_1t + d_2W^2 + d_3W^3}\right) \; 0 < H(x) \leq 0.5 \\ \left(W - \dfrac{C_0 + C_1W + C_2W^2}{1 + d_1t + d_2W^2 + d_3W^3}\right) \; 0.5 < H(x) \leq 1 \end{cases} \tag{2.14}$$

$$W = \begin{cases} \sqrt{-2\ln(H(x))} \; 0 < H(x) \leq 0.5 \\ \sqrt{-2\ln(1 - H(x))} \; 0.5 < H(x) \leq 1 \end{cases} \tag{2.15}$$

where 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.

The calculation steps are summarized in Figure 2.8. This thesis uses the R package for computing SPI and SPEI which was downloaded from https://cran.r-project.org/web/packages/SPEI/. This package computes SPI and SPEI for monthly data so monthly data of precipitation and ET were calculated from daily data before starting the calculation. Classification of drought according to SPI and SPEI is presented in Table 2.6.

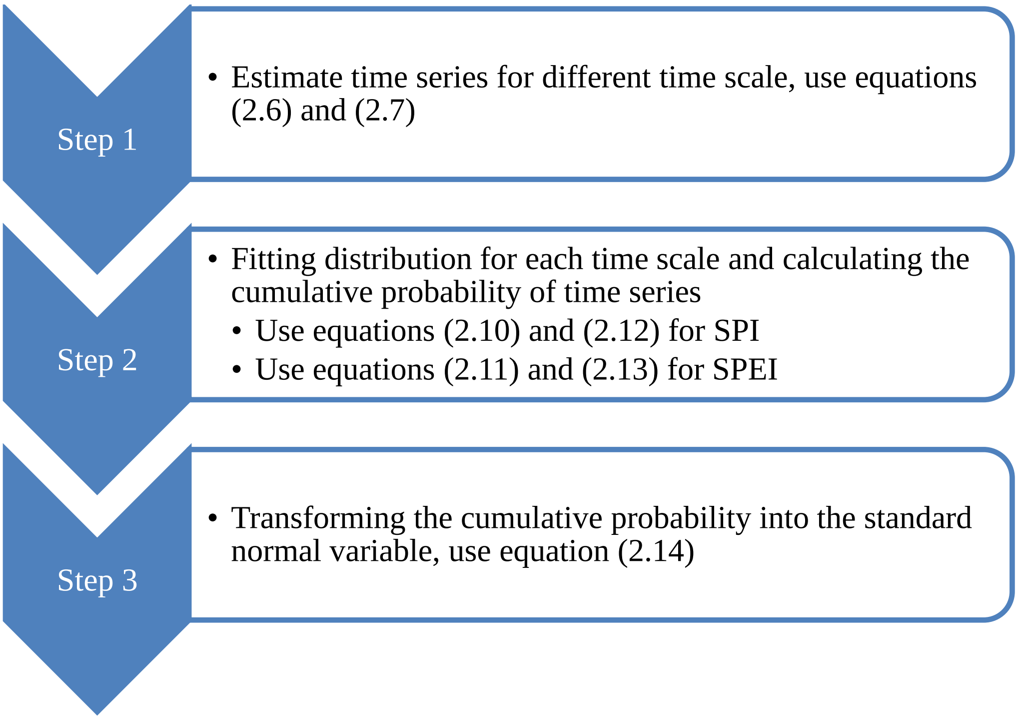


Figure 2.8 The steps to calculate SPI and SPEI

b) Keetch-Byram Drought Index (KBDI)

KBDI is a number indicating the amount of water need to saturate the top soil layers and is calculated by the soil moisture balance equation:

$$KBDI_t = (KBDI_{t-1} - 100r) + dQ \tag{2.16}$$

where $KBDI_t$ and $KBDI_{t-1}$ are KBDI (0.01 inch) on day t and $t-1$, r is daily precipitation (inch), and dQ is drought factor or the incremental rate of change of the index (0.01 inch) which is calculated as:

$$dQ = \frac{[800 - KBDI_{t-1}][0.968e^{0.0486T} - 8.30]dt}{1 + 10.88e^{-0.0441R}} \times 10^{-3} \tag{2.17}$$

where T is daily maximum temperature (°F), R is mean annual precipitation (inch), and dt is time increment set equal to 1 day.

The two original equations (2.16) and (2.17) can be changed into equations in SI unit:

$$KBDI_t = (KBDI_{t-1} - r) + dQ \tag{2.18}$$

$$dQ = \frac{[203.2 - KBDI_{t-1}][0.968e^{0.0875T+1.5552} - 8.30]dt}{1 + 10.88e^{-0.001736R}} \times 10^{-3} \tag{2.19}$$

where unit of $KBDI$, dQ, r, R is mm and unit of T is °C.

The values of KBDI range from 0 to 8 inch or 203.2 mm, with 8 or 203.2 indicating extreme drought and 0 indicating saturated soil. The classification of drought according to KBDI is shown in Table 2.6. KBDI was calculated daily, so the monthly KBDI is an average of daily value in a month.

c) Crop Drought Index (CDI)

Crop Drought Index is a water stress ratio which indicates the reduction of evapotranspiration in relation to potential evapotranspiration and is calculated as:

$$\text{CDI} = 1 - \frac{AET}{PET} \tag{2.20}$$

where *AET* is actual evapotranspiration under water stress condition (mm); and *PET* is potential evapotranspiration under sufficient soil water content (mm);

CDI value has a range from 0 to 1. If CDI is equal to zero, *ET* is at the potential rate which indicates no water stress in the soil and CDI =1 indicating no evapotranspiration. The

AET and PET were calculated using methodology described by Allen *et al*. (1998). AET in daily time scale was calculated as:

$$AET = k_s ETc \tag{2.21}$$

when there is no water stress k_s = 1, evapotranspiration is at potential rate or crop evapotranspiration ETc, and

$$AET = ETc = PET \tag{2.22}$$

CDI can be rewritten from (2.20) to (2.22) as:

$$CDI = 1 - k_s \tag{2.23}$$

Water stress occurs when available soil water becomes smaller than total available soil water, and is calculated as:

$$k_s = \frac{ASW_r}{(1-p)TAW} \tag{2.24}$$

where ASW_r is available soil water in the root zone (mm); TAW is total available soil water in the root zone (mm); and p is fraction of TAW that a crop can extract from the root zone without suffering water stress, according to Allen *et al*. (1998). For ETc = 5 mm/day, the p value is 0.2 for rice and 0.4 for coffee. For different ETc, p value can be adjusted according to:

$$p = p_5 + (5 - ETc) \tag{2.25}$$

where $p_5$is p value for ETc = 5 mm/day.

Total available soil water TAW is calculated in the root zone, changing in time according to the root depth d, and determined from Table 2.3.

Because coffee is a perennial plant, root depth of coffee trees is assumed not to change during growing season and set equal to 1.0 m (Allen *et al*., 1998). For rice, root depth in a day was estimated from Moghaddasi *et al*. (2010) which gave estimation equation for root depth based on a review of depth development of roots with time for 55 crop species (Borg and Grimes, 1986).

$$d_t = 10\left(r + d_{max}\left(0.5 + 0.5\sin\left(\frac{3.03t}{T} - 1.47\right)\right)\right) \tag{2.26}$$

where d_t is root depth on day t (m); r is planting depth (= 5cm for rice); d_{max} is maximum of root depth (is 50 cm for rice; IMHEN, 2008); t is day t in growing season, counted from the planting date; T is total day number of the growing season to reach maturity stage (T = 120 day for rice; Table 2.5).

ASW_r is obtained by a daily water balance in the root zone as:

$$ASW_{r,i} = ASW_{r,i-1} + P_{i-1} + Ir_{i-1} - AET_{i-1} \tag{2.27}$$

where $ASW_{r,i}$ and $ASW_{r,i-1}$ is available soil water in the root zone on day i and day i-1 (mm); P_{i-1} is precipitation on day i-1 (mm); Ir_{i-1} is estimated irrigation depth of day i-1 (mm); and AET_{i-1} is actual evapotranspiration of day i-1 (mm).

Irrigation depth was estimated by multiplying the design irrigation depth shown in Figure 2.6 by a reduction factor (f). According to Vietnam technical regulation on hydraulic structures, irrigation facilities in the study area were designed to get $Q75$ (MARD, 2012). $Q75$ is defined as the flow which is equaled or exceeded for 75% of the flow record in dry season. It means irrigation facilities can extract water from the rivers if the discharges exceed $Q75$ (Table 2.7). Therefore, the reduction factor is determined as:

$$f = \begin{cases} 1 & (Q \geq Q75) \\ 0 & (Q < Q75) \end{cases} \tag{2.28}$$

where Q is river discharge.

Detail of calculation of $Q75$ is expressed in Appendix B.

Actual and potential evapotranspiration were calculated daily. Therefore, to calculate CDI of a month or other time periods, a sum of daily actual and potential evapotranspiration was used. As specified by Łabędzki & Bąk (2014), CDI is classified into different categories as shown in Table 2.6. Łabędzki & Bąk (2014) determined that CDI indicates drought if the reduction of evapotranspiration exceeds 10% of potential evapotranspiration.

Table 2.6 SPI, SPEI, KBDI and CDI classification

<table>
<tr><th rowspan="2">Category</th><th rowspan="2">SPI/SPEI</th><th colspan="2">KBDI</th><th rowspan="2">CDI</th></tr>
<tr><th>(0.01 inch)</th><th>(mm)</th></tr>
<tr><td>Extreme wet</td><td>≥ 0.2</td><td rowspan="4"><200</td><td rowspan="4"><50.8</td><td rowspan="4">0 to 0.1</td></tr>
<tr><td>Severe wet</td><td>1.5 to 2.0</td></tr>
<tr><td>Moderate wet</td><td>1.0 to 1.5</td></tr>
<tr><td>Normal</td><td>-1.0 to 1.0</td></tr>
<tr><td>Moderate drought</td><td>-1.5 to -1.0</td><td>200 to 600</td><td>50.8 to 152.4</td><td>0.1 to 0.19</td></tr>
<tr><td>Severe drought</td><td>-2.0 to -1.5</td><td rowspan="2">600 to 800</td><td rowspan="2">152.4 to 203.2</td><td>0.2 to 0.49</td></tr>
<tr><td>Extreme drought</td><td>-2.0</td><td>0.5 to 1.0</td></tr>
</table>

Table 2.7 $Q75$ of Kon Tum and Ayunpa station

Station	$Q75$ (m^3/s)
Kon Tum	45.5
Ayunpa	13.7

2.3.2 Crop yield residuals

As stated in section 2.1.3 data of drought impact on agriculture in Gia Lai province were insufficient. Therefore, it is necessary to identify drought years by using statistical crop data. Crop yield was used in Todisco *et al*. (2008) and Nadir (2013). Yield energy was suggested in Li *et al*. (2014) due to the variation of the meaning of crop yield in different cities in Inner Mongolia. Crop yield residual was chosen by Potopová et al. (2016) for agricultural drought assessment and by Wu *et al*. (2004) for defining drought-risk years. Crop yield residual in Potopová et al. (2016) was calculated by comparing the statistical crop yield with the long-term field experiments. Wu *et al*. (2004) obtained crop yield residual by detrended yield after the onset of increasing trend in yields of corn and soybeans.

Figure 2.9 shows a significantly positive trend of yield for the spring paddy. Spring paddy yield has increased from 4.7 ton/ha in 1995 to 5.6 ton/ha in 2010, nearly 20%/16 years. Meanwhile, coffee yield grew slower. The increasing trend is due to the improvement of farming technology, such as the expansion of irrigated area, increase the fertilizer consumption (WB, 2017), and new varieties application (Lai, 2011). According to WB (2017), fertilizer consumption in Vietnam increased from 305 kg/ha of arable land in 2002 to 323 kg/ha of arable land in 2010. The variation around the trend line reflects the impact of climate condition on yield. Therefore, the yield was detrended to eliminate the effect of farming technology improvement on the growth of the yield by using a linear time trend analysis. The residuals of crop yield are the yield departures from the trend expressed as follows:

$$CYR_i = Y_i - \hat{Y} \tag{2.29}$$

where CYR_i is crop yield residual of year i; Y_i is crop yield of year i; and $\hat{Y}$ is linear a trend of crop yield estimated from a regression analysis fitted to the data of Figure 2.9 and Figure 2.10.

The residuals make the variable of yield affected by climate condition more clearly. Positive residuals indicate that the yield was above the multi-year average yield, while a negative value means the yield was below the multi-year average yield, reflecting drought years.

2.3.3 Evaluation of the selected drought indices

The indices were evaluated to determine the most appropriate index for agricultural drought monitoring in the study area. A time series of monthly indices were compared to the crop yield residuals during the crops growing seasons by using a goodness-of-fit measure: coefficient of determination (R^2). The formula of this measurement is presented as follow:

$$R^2 = \left(\frac{\sum_{i=1}^{N}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{N}(X_i - \bar{X})^2 (Y_i - \bar{Y})^2}} \right)^2 \tag{2.30}$$

where N is length of time series, X_i and Y_i are value of indices and crop yield residuals, respectively, and $\bar{X}$ and $\bar{Y}$ are mean of corresponding variables.

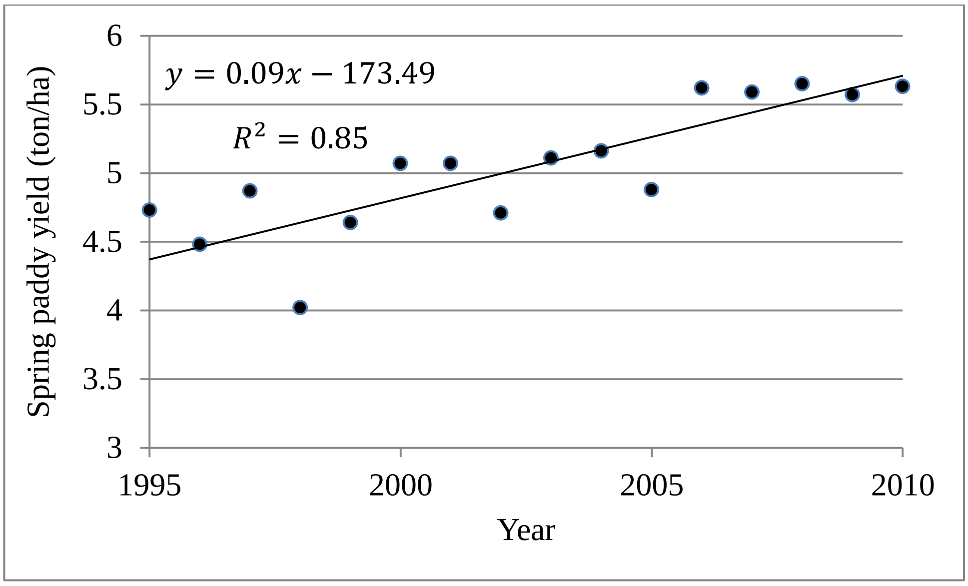


Figure 2.9 Annual changes in annual yield of spring paddy in Gia Lai province. The solid line indicates the linear trend.

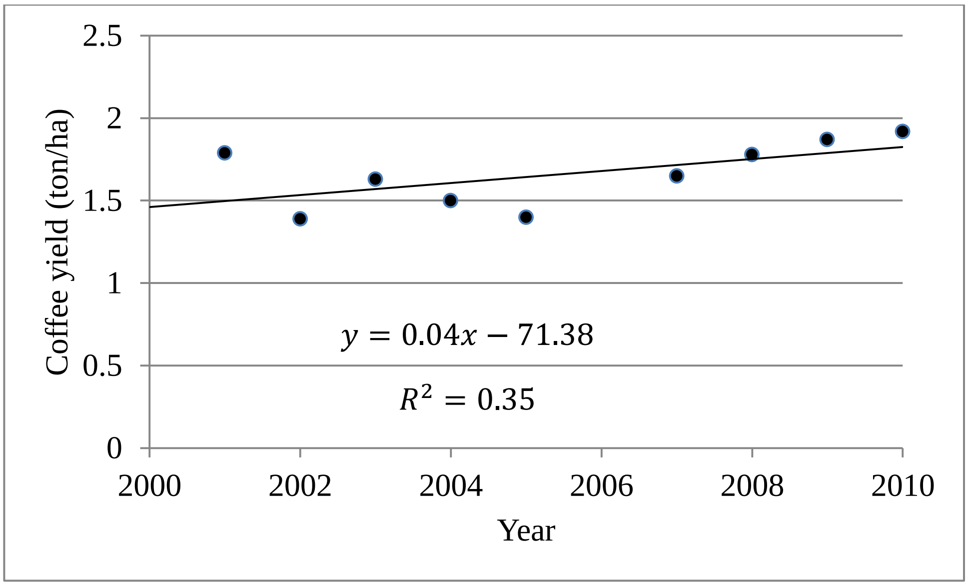


Figure 2.10 Annual changes in annual yield of coffee in Gia Lai province. The solid line indicates the linear trend.

Chapter 3 Results and discussion

3.1 Actual and potential evapotranspiration

Figure 3.1 illustrates the monthly PET and AET at Pleiku and Ayunpa stations during the study period. PET and AET at Pleiku station represent coffee area and those at Ayunpa station represent paddy area. PET at Pleiku and Ayunpa stations had the similar trend. PET increased during dry season from Dec. to Mar. or Apr., particularly rose rapidly in the late dry season and fell as soon as rainy season began. PET at Pleiku station decreased faster than at Ayunpa station because the rainy season in Pleiku came sooner and had more rainfall. The comparison of precipitation and PET shows that precipitation met a very small portion of crop water demand during spring cropping season and the remaining has to come from irrigation.

A reversal trend of AET in comparison to the trend of PET can be seen in Figure 3.1. The higher value of AET is found in the rainy season while the lower value is observed during the dry season. The AET could not reach the PET during the dry season because the amount of rainfall was very small so that the water in the soil was insufficient for evaporation. The difference between AET and PET became largest in Mar. or Apr. That means water shortages for crop often occurred in these months. In other words, crop was vulnerable to drought during these months. The AET was only equal to PET when there was enough rainfall. In view of the fact that amount of rainfall during the rainy season at Pleiku station was much higher than at Ayunpa station, the number of months when AET was equal to PET at Pleiku station was more than at Ayunpa station. AET curve at Pleiku station could approach AET curve from June. while those at Ayunpa station had to wait until Sep. Therefore, drought in Ayunpa area might occur longer in Pleiku area.

Figure 3.2 illustrates that the years with low value of AET coincided with the years listed in section 2.1.3 . However, there is a significant difference between AET at Pleiku station and Ayunpa station in 1994, 1995, and 1996. While AET at Pleiku station remained quite high value, AET at Ayunpa station was very low. This can be explained by looking at rainfall data (Figure 3.3). Rainfall at Pleiku station in these years did not decrease much compared to the remaining years but the rainfall at Ayunpa station shows a significant decrease.

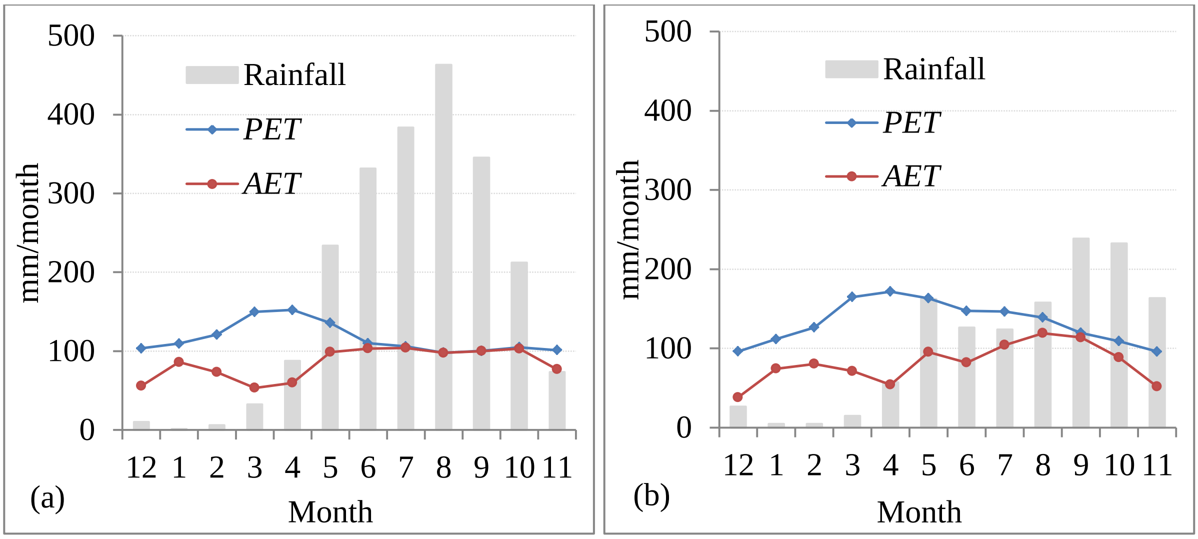


Figure 3.1 Mean monthly potential (*PET*, blue line) and actual evapotranspiration (*AET*, red line) at a) Pleiku and b) Ayunpa stations during 1980-2010

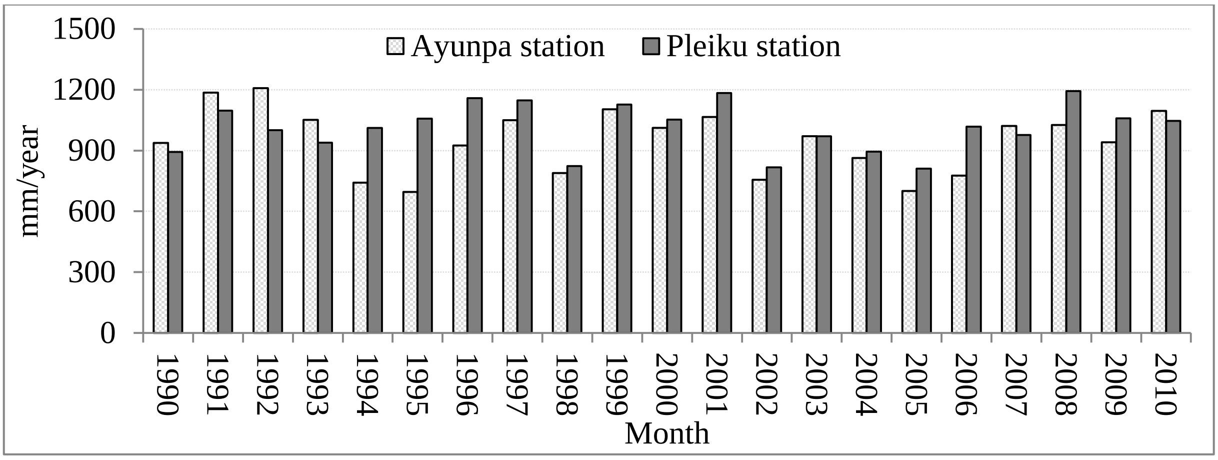


Figure 3.2 Annual actual evapotranspiration (*AET*) for the period 1990-2010

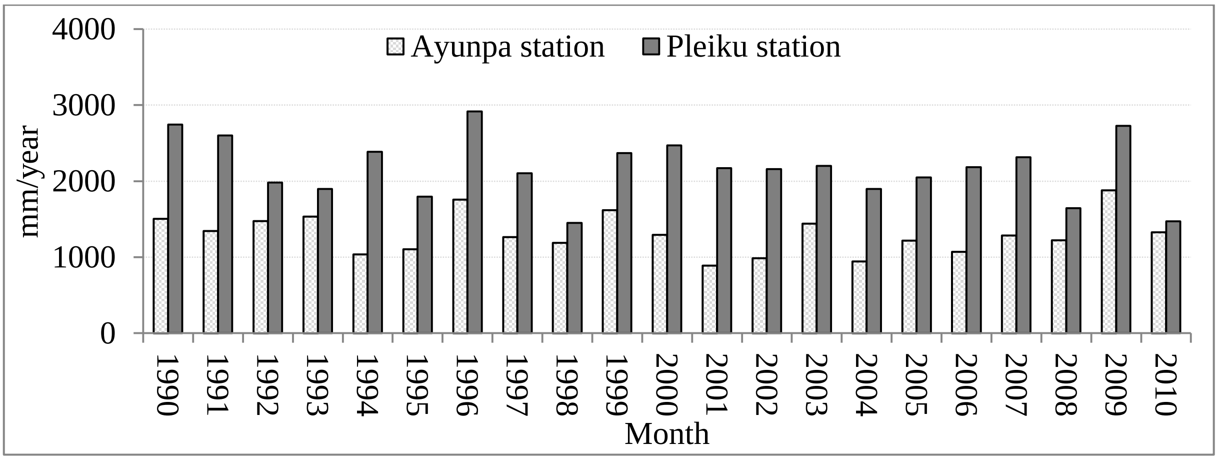
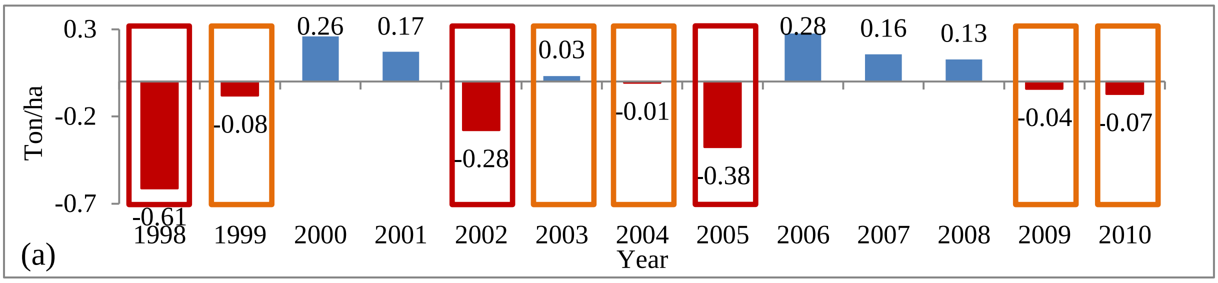


Figure 3.3 Annual rainfall for the period 1990-2010

3.2 Crop yield and drought relation

Figure 3.4 compares yield residuals of spring paddy and coffee and the historical drought years over Gia Lai province. The negative values of yield residuals were marked by red color in the figure while positive values were in blue color. The recorded severe and moderate drought years were highlighted in red and orange boxes, respectively. Figure 3.4 shows the agreement between historical drought years and the significant reduction of crop yields in the years 1998, 2002, 2005. In 2004, Gia Lai province also was suffered by a severe drought indicated by the statistical affected area in Table 2.1. However, the severe drought occurred in second half of the year, so most of the statistical affected area is winter paddy and coffee. Accordingly, yield reduction of coffee in 2004 was significant in Figure 3.4. It also illustrates that in the severe drought years, yield losses were seen in both spring paddy and coffee, except the year 1998 for which no data were available for coffee yield. In the moderate drought years, yield reductions are found in either coffee or rice. This reveals that drought has a different impact on different crops (Moorhead *et al*., 2015) or happened in a small area rather than in the whole province. For this reason, CYRs could be considered to be a good indicator of agricultural drought. However, there was inconsistency in 2003. CYRs of spring rice and coffee show the positive value while Table 2.1 indicates the affected area was about 1,500 ha, equivalent to the year 1999. This may be explained by the ratio of affected area to the total cultivated area. In 1999, the affected area was account for about 12% of the total cultivated that was higher than this ratio in 2003 (about 8%) (Nguyen, 2005). Therefore, small affected area did not impact the final yield in 2003.

Based on affected area by drought and crop yield residuals, spring paddy was suffered from eight drought years: 1998, 1999, 2002, 2003, 2004, 2005, 2009, and 2010; coffee was suffered from five drought years: 1998, 2002, 2004, 2005, and 2007.



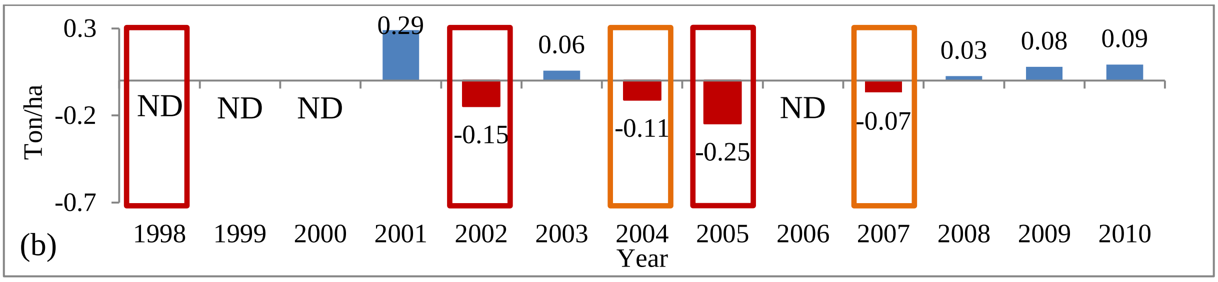


Figure 3.4 Yield residuals of (a) spring paddy and (b) coffee of Gia Lai province. Red color bars indicate negative values and blue color bars are positive values. Red box and orange box indicate severe and moderate drought years (Table 2.1) recorded over Gia Lai province, respectively. ND is no data.

3.3 Relationships of drought indices and crop yield residuals

Figure 3.5 gives the results of a correlation analysis in which the value of R^2 was determined for different pairs of monthly drought index and annual CYR values of coffee and spring paddy for the period 2000-2010. The red color lines indicate critical value of R^2 at the significant value *p-value* = 0.05. The critical values for a two-tailed *t*-test are 0.44 for a series with nine values (coffee) and 0.36 for series with 11 values (spring paddy). It means the correlation is statistically significant if R^2 > critical value. Figure 3.5 also groups the R^2 values into the growth stages which were identified in Table 2.5.

3.3.1 Relationships of drought indices and crop yield residuals of coffee

In general, the correlation of the indices with CYR of coffee is higher than those of spring paddy which is indicated by the R^2 value. All the selected indices show the similar trend. The R^2 value increases from the beginning of growth season until it reaches the highest value in the end of development stage or in the early of mid-season stage (SPIs and SPEIs). Then, the R^2 tends to decrease until the end of the crop season although there are some oscillations for some indices. There were one month lags between the highest value of R^2 identified by SPI6, SPEI6, KBDI and CDI and those defined by SPI3, SPI9, SPEI3, and SPEI9. Due to the appearance of potential evapotranspiration in SPEI's formula, it gave the higher correlation with CYRs than SPIs.

3.3.2 Relationships of drought indices and crop yield residuals of spring paddy

For spring paddy, the tendency of relationships of drought indices and CYRs seen in coffee is not clear for spring paddy. The R^2 values of CDI show the same courses of increasing in the initial and development stage and decreasing in the mid-season and late season stages. The other indices show no trend or one tendency of decreasing from the beginning to end of crop season.

The highest values of SPIs do not show the agreement of timing with coffee. Specifically, the significant values of SPI6 occurred in the initial stage while those of SPI9 appeared in the mid-season stage and those of SPI1 in the late-season stage. This inconsistency also can be seen in the chart of SPEIs. These results show the fact that the impact of a drought on paddy yield based on not only the timing of drought but also its duration. The chart of SPIs shows that the deficit of precipitation in pre-growth season and during transplanting has large effect on spring paddy yield, while a one-month drought at the end of growth season has significant effect.

There is no single time step for calculating SPI and SPEI that is appropriate for both coffee and spring paddy. For example, SPI9 and SPEI9 gave the best value for coffee but SPI1 is more sensitive while SPEIs cannot become significant for rice. Although SPEIs includes evapotranspiration in its calculation, SPEI were not sensitive to monitor impact of drought on spring paddy.

The statistics of R^2 value for all drought indices was determined to compare those indices with each other in term of correlation with CYRs. The results are shown in Table 3.1. The bold numbers indicate the statistically significant value. For both cases of coffee and spring paddy, CDI ranked the first with the highest value of mean, maximum of R^2 and the number of times when the significant value appeared (mean = 0.29, maximum = 0.66, and N = 3). The second rank index is SPEI9 for the max of R^2 (= 0.65). The less correlated indices are SPIs for coffee, SPEIs and KBDI for spring paddy.

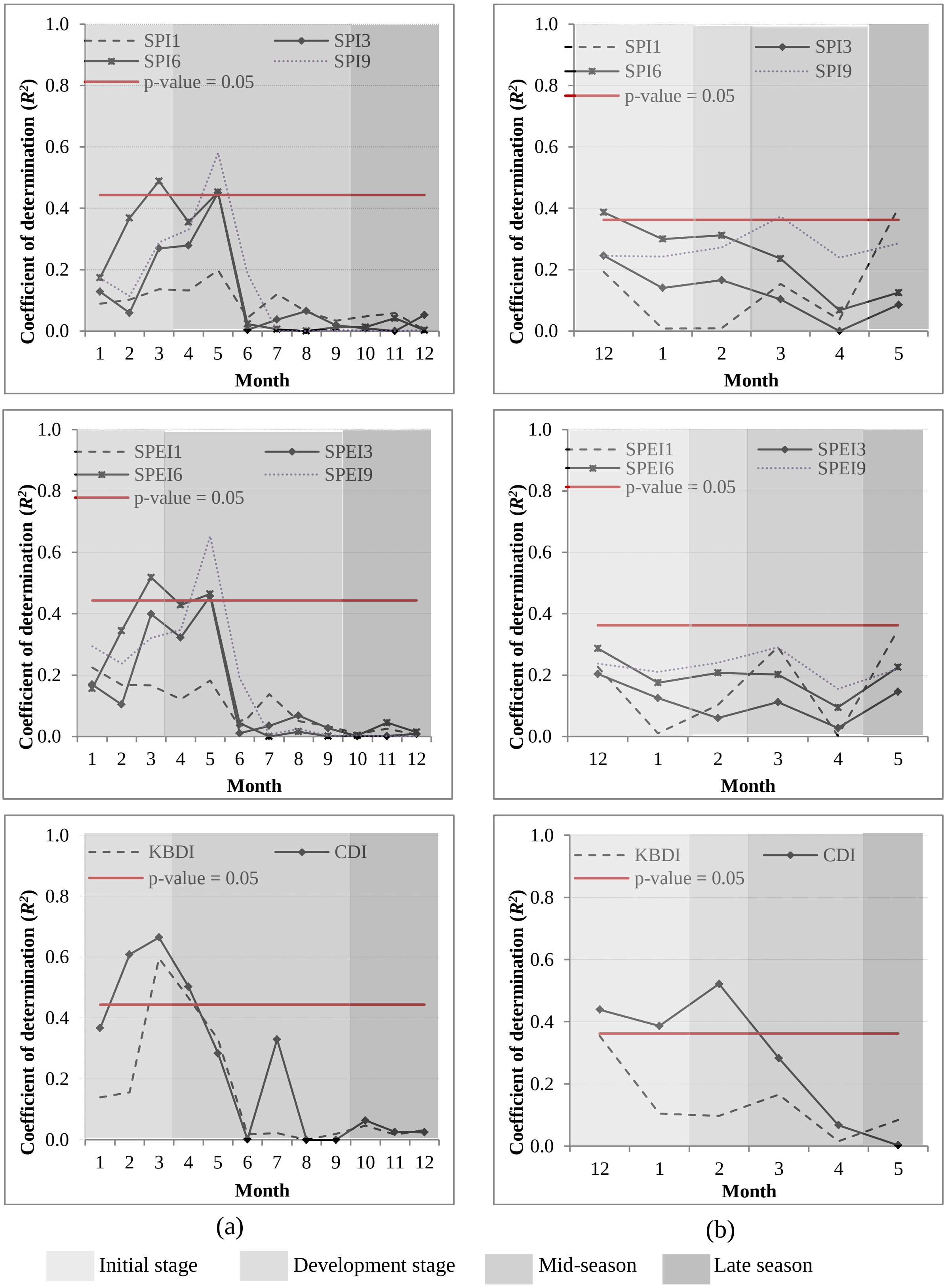


Figure 3.5 The coefficient of determination (R^2) between monthly drought indices values and annual crop yield residuals for (a) coffee and (b) spring paddy in Gia Lai province. The red color lines indicate the value of significance for R^2 (*p-value* = 0.05)

Table 3.1 Statistic of R^2 for all drought indices

Index	Coffee			Spring paddy		
	Mean	Max	N	Mean	Max	N
SPI1	0.09	0.20	0	0.13	**0.40**	1
SPI3	0.11	**0.45**	1	0.12	0.25	0
SPI6	0.16	**0.49**	2	0.24	**0.39**	1
SPI9	0.14	**0.58**	1	0.28	**0.37**	1
SPEI1	0.10	0.22	0	0.16	0.35	0
SPEI3	0.16	**0.46**	1	0.18	0.20	0
SPEI6	0.19	**0.52**	2	0.20	0.29	0
SPEI9	0.20	**0.65**	1	0.23	0.29	0
KBDI	0.15	**0.60**	2	0.14	0.35	0
CDI	0.24	**0.66**	3	0.29	**0.52**	3

Bold fonts: statistically significant.

N is number of significant R^2

3.4 Temporal variability of the indices

Figures 3.6 to 3.13 illustrate the time series of SPIs, SPEIs, KBDI, and CDI at monthly time step for spring paddy (represented by Ayunpa station) and coffee (represented by Pleiku station). According to the classification proposed by each author that is shown in Table 2.6, drought is identified if SPIs or SPEIs are less than −1.0, KBDI is higher than 50.8, and CDI is higher than 0.1. As mentioned in the section 2.1.3 , Gia Lai province suffered from three noticeable droughts in 1998, 2002, 2005 and milder droughts resulting slight yield reduction for rice in 1999, 2003, 2004, 2009, and 2010 and coffee in 2004 and 2007. Therefore, the good drought index should be able to capture all of those drought periods.

The late season stage is maturity and harvest period, and drought has minor impact on crop yield during this stage. In addition, crop yield is sensitive with the drought condition from initial stage to mid-season stage. Therefore, these stages of cropping season are focused.

3.4.1 Comparison with drought events for spring paddy

a) Standardized Precipitation Index

Figure 3.6 shows the time series of SPIs in comparison with drought events. SPIs could not fully describe drought events. SPI3 is the better indices than other SPIs but it could capture only 4/8 drought. SPI3 failed to detect drought in the severe year 2002 during cropping season, instead of that, SPI3 indicated the drought condition before cropping season in 2002. SPI6 was successful to figure out the severe droughts. SPI1 is the less effective than other SPIs since it could detect droughts for only two years, 2003 and 2004. SPI1 also failed to detect droughts in severe years. However, Figure 3.6 reveals that SPI1 often indicated drought conditions several months earlier than other SPIs with longer time scale. For example, SPI1 shows that the drought in 2002 stemmed from the lack of precipitation since September in 2001. Similarly, the drought in 2005 was indicated by SPI1 since November in 2004. Therefore, SPI1 has an advantage of predicting drought condition for crops. However, in 1998, due to accumulated small rainfall deficit in many months, SPI1 did not promote this strength.

SPIs were unsuccessful in explaining droughts in 1999, 2009 and 2010. In addition, the magnitude of SPIs also did not reflect correctly the severity of drought events, except SPIs in 2005. SPI3 indicated drought event in 1998 (the severe drought year), but the magnitude of SPI3 in 1998 was much lower than it in 2003 and 2004 (the moderate drought years). Likewise, the magnitude of SPI6 in 1998 also was lower than it in 2007 (the non-drought year).

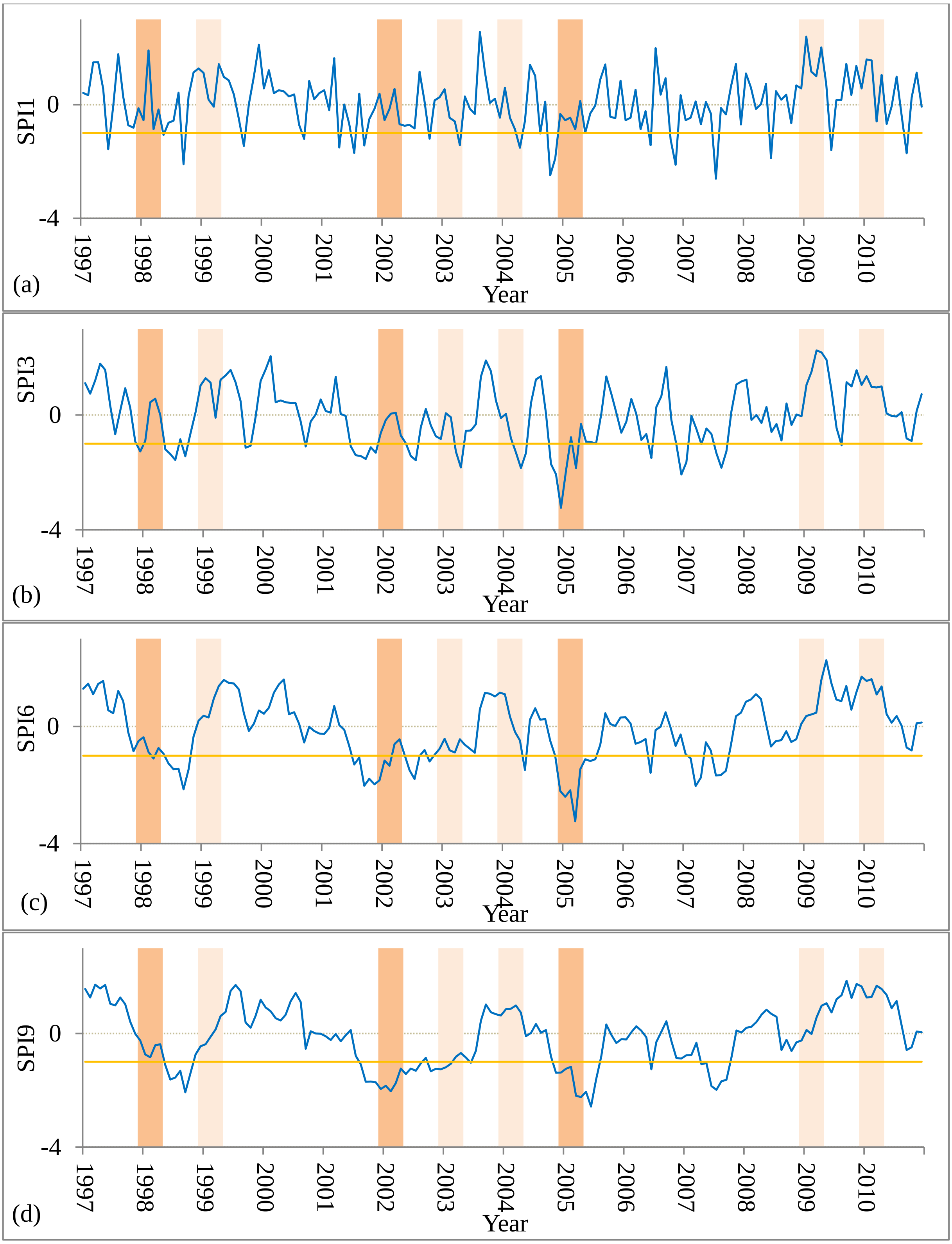


Figure 3.6 Monthly change in SPIs for (a) 1-month, (b) 3-month, (c) 6-month, (d) 9-month scales at Ayunpa station. The orange lines indicate drought threshold. Dark and light shaded bars show the historical severe and moderate drought events, respectively. *x*-axis tick marks indicate January 1st of each year.

b) Standardized Precipitation Evapotranspiration Index

The results of SPEIs are shown in Figure 3.7. Similar to SPIs, SPEIs could not respond all drought conditions. However, SPEIs perform better than SPIs as SPEIs identified more drought events, in general. SPEI1 shows a different picture from SPI1 since SPEI1 explained 5/8 drought events, including severe droughts. SPEIs could describe droughts in severe years, except that SPEI3 failed to detect severe drought in 2002. Especially, SPEI6 was fruitful to identify all severe droughts but failed to describe moderate drought events.

The time lags between different time scales of SPEIs were also found, similar to SPIs. Therefore, SPEI1 is more effective than other SPEIs and SPIs to declare drought conditions. However, the magnitude of SPEIs also did not reflect the severity of drought conditions. For example, the value of SPEI1 in 2002 indicated a moderate drought, not a severe drought (according to the drought classification in Table 2.6). Similarly, the magnitude of SPEI3, SPEI6 and SPEI9 in 1998 did not explain severe drought condition. SPEIs also failed to respond to droughts in 1999, 2009, 2010.

c) Keetch-Byram Drought Index

Figure 3.8 presents the result of KBDI. It is obviously seen that KBDI responded to all drought conditions for spring paddy. However, the magnitude of KBDI is not effective to identify the level of drought conditions. The value of KBDI almost reached its maximum value during the dry season.

d) Crop Drought Index

The time series of CDI are shown in Figure 3.9. The results reveal that CDI is good for explaining drought conditions for spring paddy. In the severe drought years, CDI always maintained at a high value during cropping season. Meanwhile, in the milder drought years, the values of CDI were lower than in severe drought years and did not last as long as in severe drought years. Moreover, Figure 3.5 also proved that CDI from December to February was more effective to identify the impact of drought on the yield of spring paddy. On the other hand, drought in other months has less effect on the yield of spring paddy as is clear in 2003 and 2004 when CDI presented the high value in April but not result in high yield reduction.

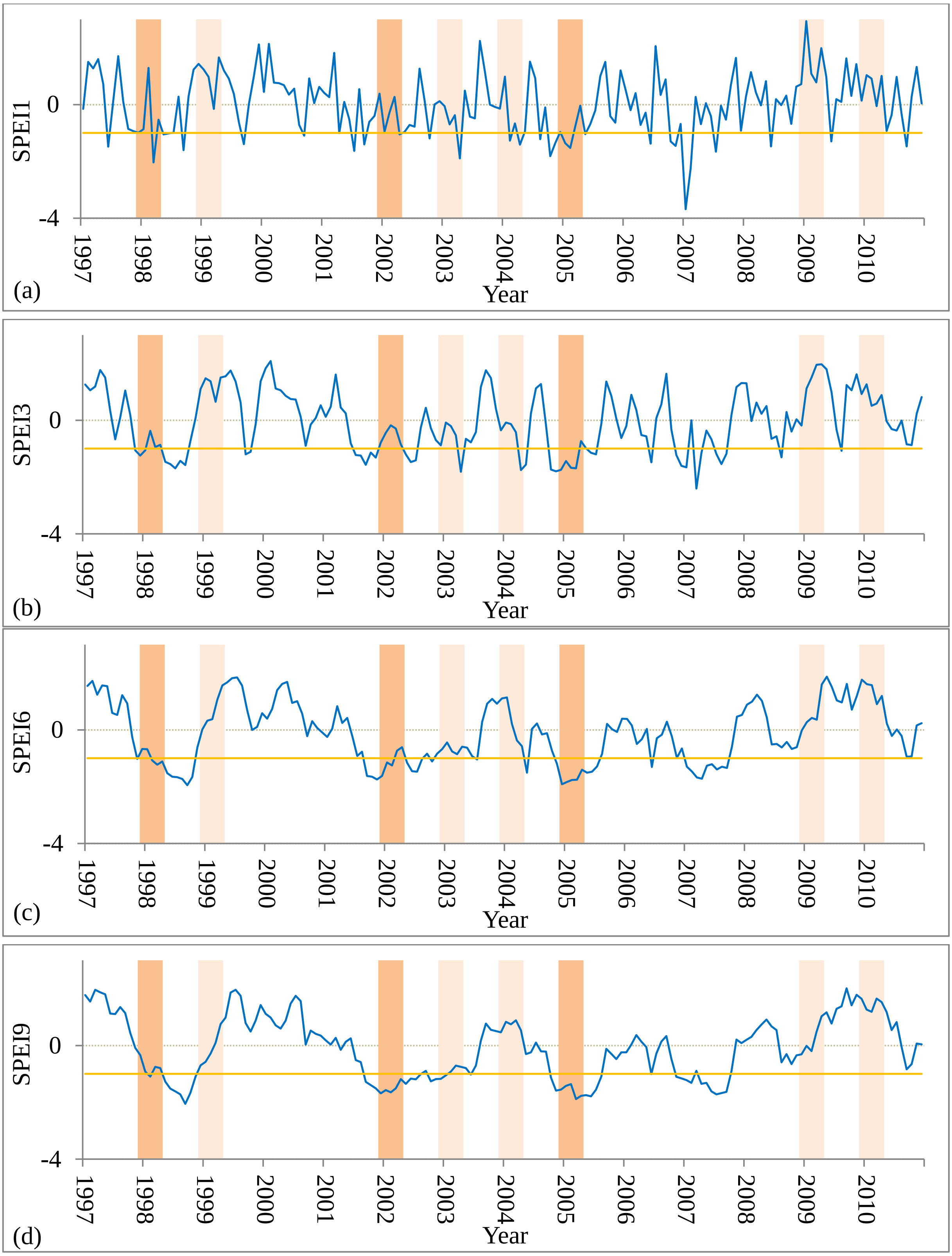


Figure 3.7 Monthly change in SPEIs for (a) 1-month, (b) 3-month, (c) 6-month, (d) 9-month scales at Ayunpa station. The orange lines indicate drought threshold. Dark and light shaded bars show the historical severe and moderate drought events, respectively. *x*-axis tick marks indicate January 1st of each year.

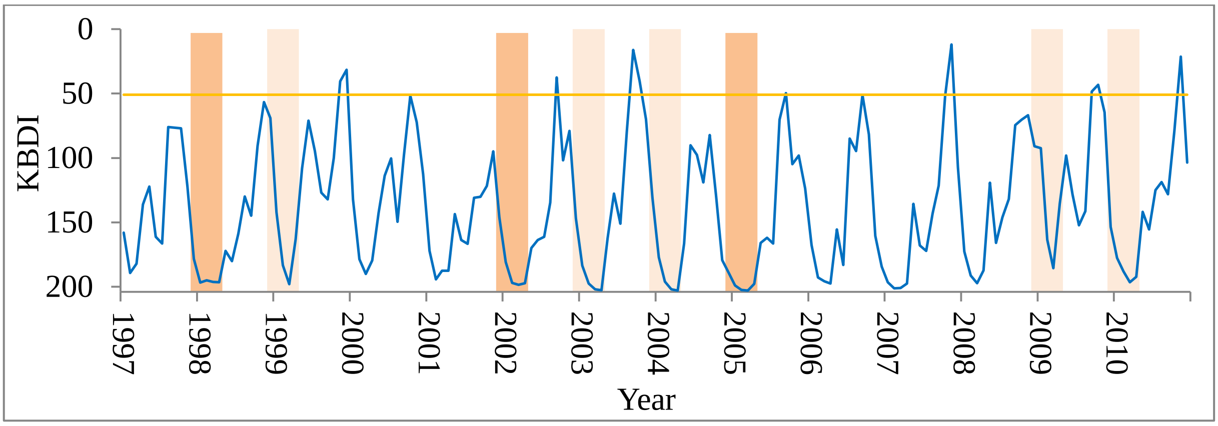


Figure 3.8 Monthly change in KBDI at Ayunpa station. The orange lines indicate drought threshold. Dark and light shaded bars show the historical severe and moderate drought events, respectively. *x*-axis tick marks indicate January 1st of each year.

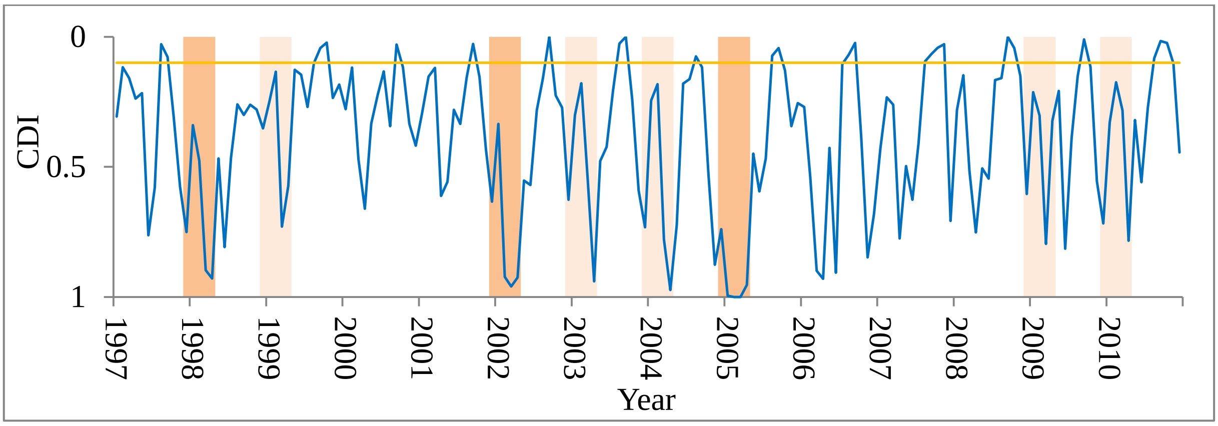


Figure 3.9 Monthly change in CDI at Ayunpa station. The orange lines indicate drought threshold. Dark and light shaded bars show the historical severe and moderate drought events, respectively. *x*-axis tick marks indicate January 1st of each year.

3.4.2 Comparison with drought events for coffee

a) Standardized Precipitation Index

For coffee, Figure 3.10 shows that SPIs are good for reflecting severe drought events since all SPIs showed the value below than -1 in the severe years 1998, 2002, 2005. SPI3 was found better than other SPIs because it could capture 5/5 drought events for coffee while SPI1 and SPI9 only responded to severe drought conditions and failed to describe droughts in moderate years. SPI6 identified 4/5 drought events and was unsuccessful to detect drought in 2004. The time lags between the SPIs for different time scales were also found in SPIs for coffee.

There was a different picture of SPIs for coffee from those for spring paddy. The magnitude of SPIs reflected the impact of drought on yield reduction of coffee better than those for spring paddy. That resulted in the stronger correlation between SPIs and CYRs of coffee in the comparison with spring paddy.

b) Standardized Precipitation Evapotranspiration Index

The results of SPEIs are quite similar as those of SPIs (Figure 3.11). All SPEIs were successful in indicating droughts in severe years. Only SPEI3 could identify the year 2004 as drought year while other SPEIs failed to identify drought in this year. That made SPEI3 becomes the effective index to detect drought conditions for coffee. SPEI1 and SPEI6 identified 4/5 drought events. SPEI9 is the worst index since it could detect only three drought events. The time lags between the SPEIs for different time scales were also found in SPEIs for coffee.

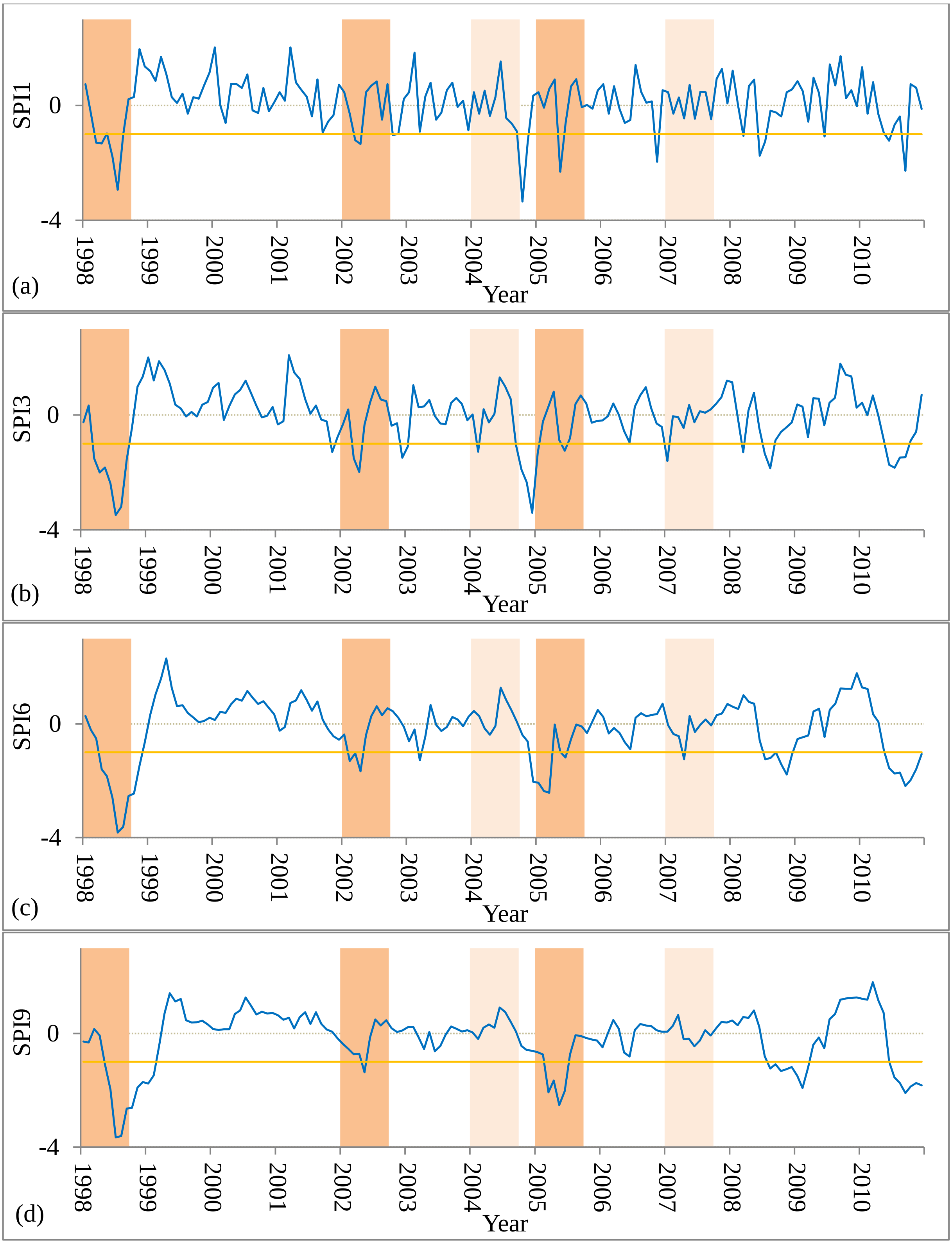


Figure 3.10 Monthly change in SPIs for (a) 1-month, (b) 3-month, (c) 6-month, (d) 9-month scales at Pleiku station. The orange lines indicate drought threshold. Dark and light shaded bars show the historical severe and moderate drought events, respectively. *x*-axis tick marks indicate January 1st of each year.

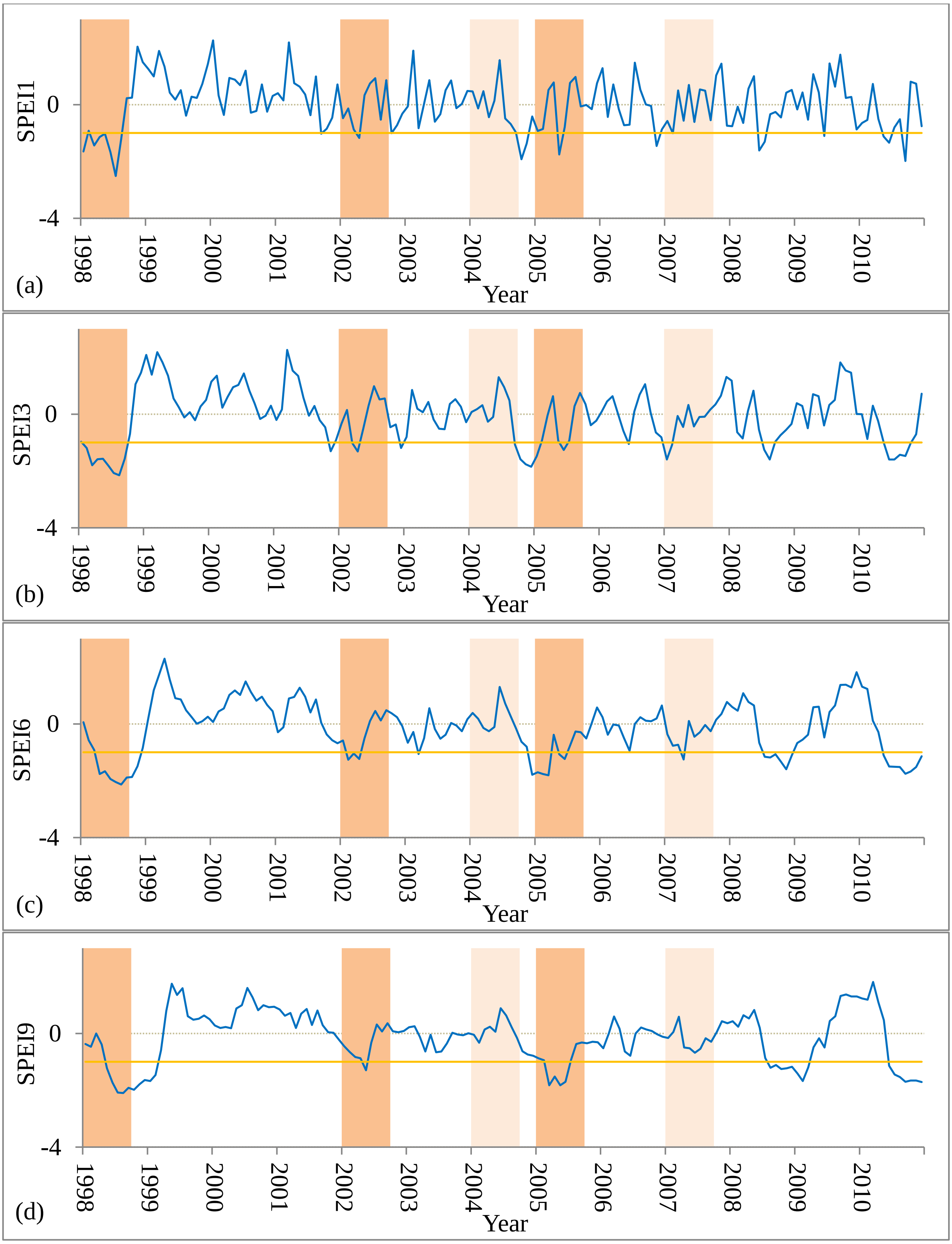


Figure 3.11 Monthly change in SPEIs for (a) 1-month, (b) 3-month, (c) 6-month, (d) 9-month scales at Pleiku station. The orange lines indicate drought threshold. Dark and light shaded bars show the historical severe and moderate drought events, respectively. *x*-axis tick marks indicate January 1st of each year.

c) Keetch-Byram Drought Index

Similarly to KBDI for spring paddy, Figure 3.12 shows that KBDI also captured all drought events for coffee. There was also no significant difference in magnitude of KBDI in severe and moderate drought years, even in non-drought years.

d) Crop Drought Index

The results of CDI are presented in Figure 3.13. CDI was found more effective than other indices to describe drought conditions. Obviously, severe droughts in 1998, 2002, 2005 were identified by high value of CDI as well as the period of time that high values sustained during the development stage (flowering stage). In the milder drought years (2004 and 2007), CDI showed the lower value than in severe drought years.

In 2009 and 2010, there was no yield reduction in coffee but most drought indices indicated drought for coffee. This situation is also shown in time series of CDI although CDI considered the supplement of irrigation to crop water demand deficit. One possible reason is the irrigation rate in this study was assumed from surface water. However, Dang (2008) reported that the amount of groundwater exploitation for irrigation was significant in the Central Highlands, especially for coffee and pepper. This might mitigate the drought stress for coffee in these years.

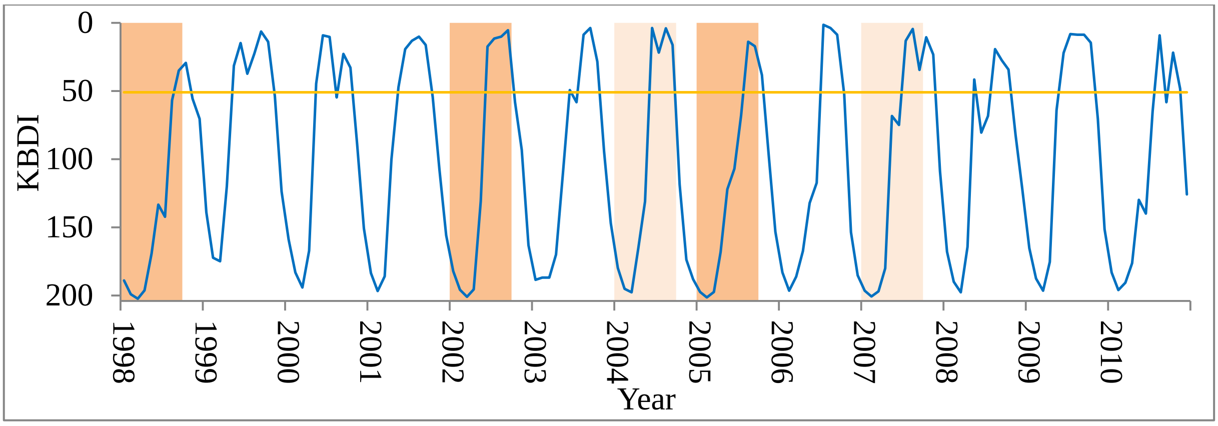


Figure 3.12 Monthly change in KBDI at Pleiku station. The orange lines indicate drought threshold. Dark and light shaded bars show the historical severe and moderate drought events, respectively. *x*-axis tick marks indicate January 1st of each year.

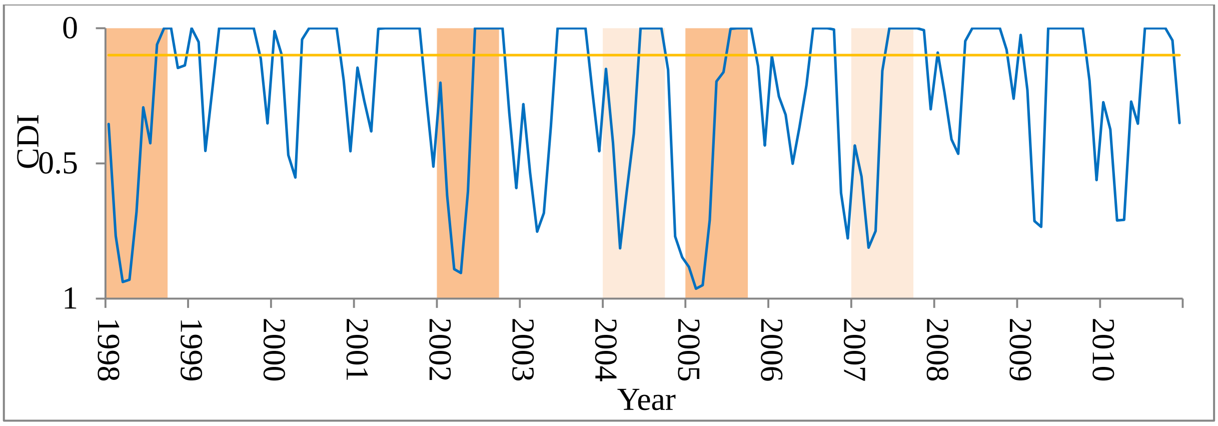


Figure 3.13 Monthly change in CDI at Pleiku station. The orange lines indicate drought threshold. Dark and light shaded bars show the historical severe and moderate drought events, respectively. *x*-axis tick marks indicate January 1st of each year.

3.5 Evaluation of selected drought indices

Figure 3.14 visualizes the qualification analysis for selecting the suitable index for agricultural drought monitoring in Gia Lai province. The relationship between the indices and CYR was quantified by the value of R^2 which is shown in *y*-axis. The ability of the indices to capture drought events was identified by the number of drought years indicated by the indices which is presented by *x*-axis. The most effective index is the index which has significant value of R^2 (located above the line of *p-value* = 0.05) and describes more drought events. Accordingly, for spring paddy, only CDI met the criterion because all other indices could not give significant relationship with CYR of spring paddy. For coffee, CDI was again found the most effective and followed by SPEI9 and KBDI. SPI1 is the les effective index due to the weak relationship with CYRs (R^2 = 0.2 for spring paddy and coffee) and the low number of droughts events identified by SPI1 (2/8 events for spring paddy and 3/5 drought events for coffee).

Figure 3.14 illustrates that SPIs and SPEIs have the weak correlation with CYRs, especial in case of spring paddy. The reason may be that SPIs and SPEIs are solely based on meteorological data. Therefore, the next section will evaluate the modified index of SPIs and SPEIs by considering the irrigation data.

3.6 Improved SPI and SPEI with irrigation data

As mentioned in section 2.1.2 , water demand of paddy and coffee is fulfilled by irrigation systems. Therefore, irrigation practice plays an importance role in identifying the water condition of crop. The indices based on only meteorological data cannot describe fully drought condition of these crops which can be seen in the results of SPI and SPEI. The improved SPI and SPEI will be included irrigation data. The calculation process of improve SPI and SPEI is same as described in Figure 2.8 but the X in equations (2.4) and (2.5) is rewritten as follows:

$$\text{For SPI,} \quad X = P + Ir \tag{3.1}$$

$$\text{For SPEI,} \quad X = P + Ir - ETc \tag{3.2}$$

where Ir is irrigation depth (mm) identified in calculation of CDI.

Figure 3.15 shows the final results of improved SPI and SPEI. Interestingly, relationship between improved SPI and SPEI and CYRs becomes significant for both case of coffee and spring paddy. Especially, the value of R^2 of improved SPI3, SPI6, and SPEI3 for spring paddy and SPI1, SPI3, SPEI1, and SPEI3 for coffee are higher than CDI. The noticeable improvement of number of identified drought events was found in improved SPI1, SPEI1 for coffee and improved SPI1 and SP9 for rice.

3.7 Possible modifications to improve performance of drought indices

The first possible modification is the adjustment of classification scheme of drought in Table 2.6. It can be seen that the drought threshold for CDI which proposed by the author is not appropriate for the study area. Based on proposed threshold, CDI always indicated drought conditions for non-drought years. Very few months had CDI < 0.1 (which indicate normal condition), even in the rainy season (from May to October). Therefore, to improve the performance of CDI in determining normal conditions, the drought threshold should be adjusted to a value > 0.1. Adjustment of drought classification can also be made for SPI and SPEI to improve their ability to indicate drought conditions. Because the values of SPI and SPEI of the study area are relatively high, SPI or SPEI = −1 could not describe drought conditions in the study area (*e.g.* droughts in 1999, 2009, 2010 for spring paddy or in 2004, 2007 for coffee). Accordingly, drought threshold of SPI or SPEI should be > −1. However, this adjustment is not consistent with KBDI because KBDI always indicated severe droughts not only in the drought years but also in all dry seasons.

The second modification may be the parameters in KBDI. The reason for the over estimation of KBDI may be the assumptions which Keetch and Byram (1968) based on. The assumption which has the significant effect on the results of KBDI is the fixed field capacity with a water depth equivalent of 8 inches (= 203.2 mm). In fact, the average field capacity within a 1-m depth soil column in Gia Lai province is 390 mm for Ferralsols and 372 mm for Fluvisols (Table 2.3). The assumption of the maximum soil moisture of KBDI calculation equals to 52% and 54% of the actual field capacity. As a consequence, this assumption reduces the water storage capacity of the soil, leading to the insufficient water during the dry seasons. Thus, KBDI always gives the highest values during dry seasons. Therefore, using local field capacity would improve the performance of KBDI.

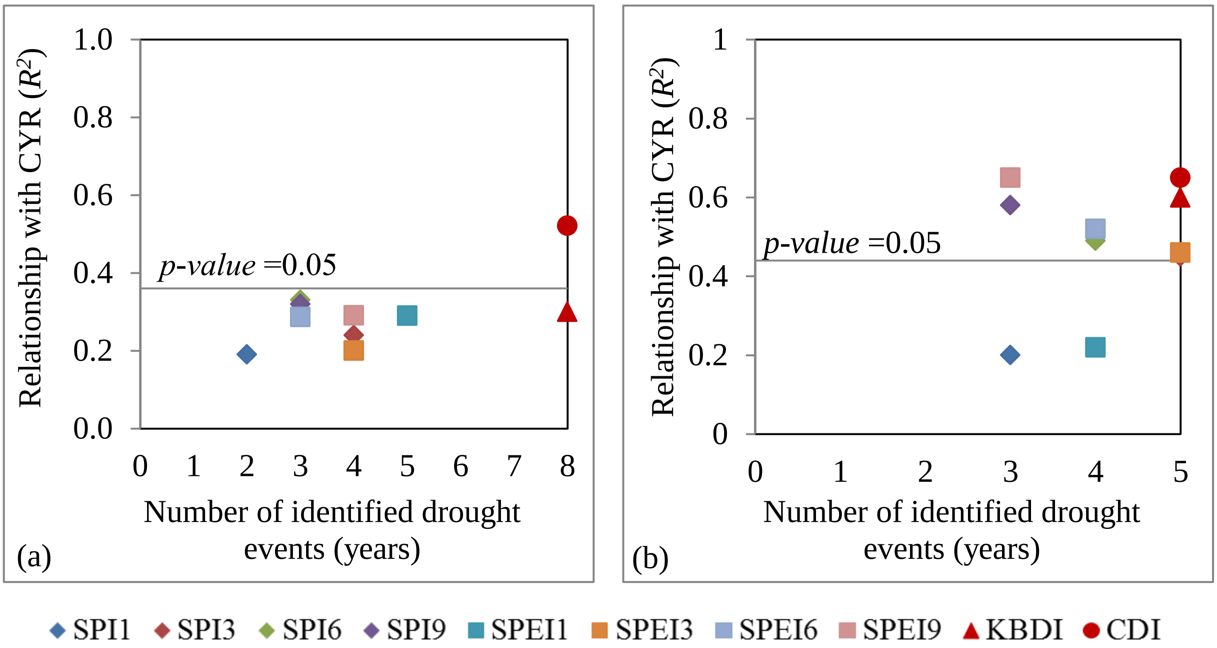


Figure 3.14 The scatter plot between R^2 and number of drought events identified by different indices for (a) spring paddy and (b) coffee

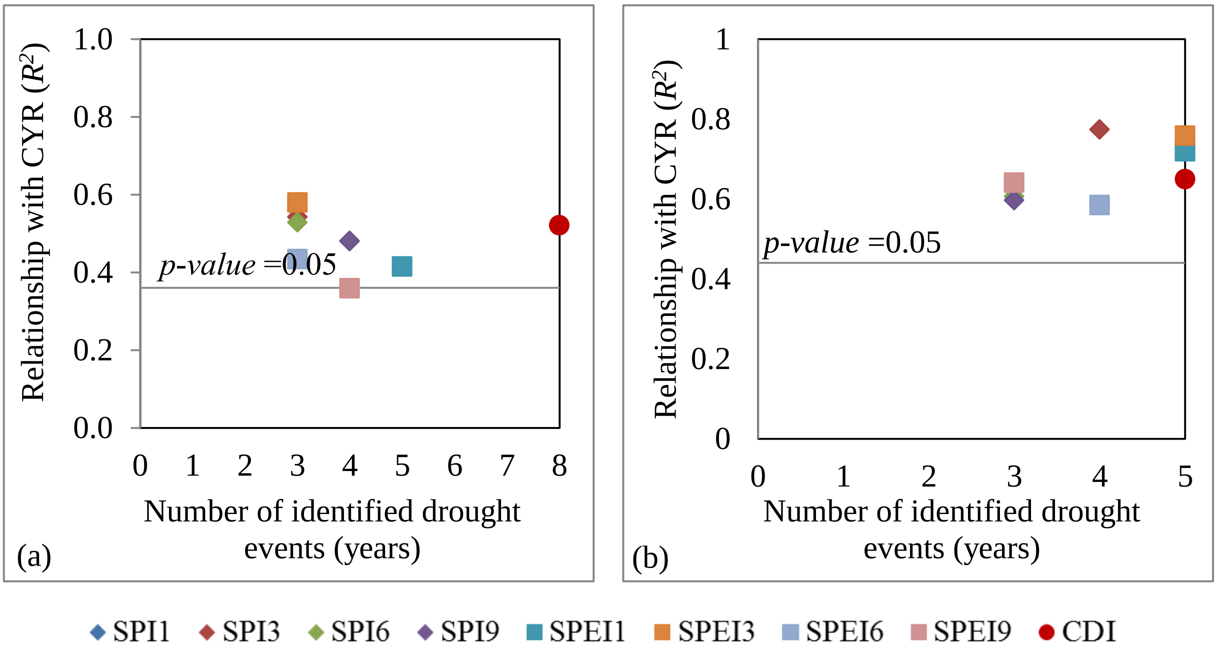


Figure 3.15 The scatter plot between R^2 and number of drought events identified by improved SPI and SPEI for (a) spring paddy and (b) coffee

Chapter 4 Conclusions and recommendation

Agricultural drought has a direct effect on agricultural production as well as food security and other social issues in Gia Lai province. This study, therefore, attempted to find an appropriate tool for monitoring agricultural droughts in the study area, which provides reliable information to warning system and decision makers. Through a review of drought indices and previous studies conducted for Vietnam, four indices have been considered. They are SPIs, SPEIs, KBDI and CDI. The steps of indices calculation and data requirements have been clarified. The selected indices were calculated for two cultivation areas in Gia Lai province. One is the coffee planting area (presented by the Pleiku station) and the other is rice cultivation area (presented by Ayunpa station). This study found that the negative CYRs matched drought occurrences in Gia Lai province, obviously, in severe drought years 1998, 2002 and 2005. Accordingly, CYRs were used as an indicator to identify drought years. Hence, the performance of the selected indices in the relationship with CYRs of two main crops in Gia Lai province was discussed. Furthermore, the ability of four selected drought indices to capture drought/non-drought events was also analyzed.

SPI and SPEI did not fully identify drought conditions. This conclusion is same as Nguyen (2005) since he investigated SPI time series for displaying drought events in the Central Highlands. SPI3, SPI6, SPI9, SPEI3, SPEI6 and SPEI9 are effective for drought monitoring for coffee. None of SPIs and SPEIs was found significant for monitoring drought in spring paddy area. The reason is that agricultural droughts in Gia Lai is not only affected by the climatic condition but also depends on the irrigation practice. Therefore, the meteorological indices do not fully reflect the drought condition of crops. However, due to the limited data requirement and simplicity of calculation, SPIs should be considered for identifying potentiality of drought, especially SPI1 and SPI6. SPI1 indicated drought several months earlier than other SPIs at long time scales and SPI6 can be used for agricultural drought impact assessment. In addition, the improvement of SPI and SPEI by replaceing input of rainfall with rainfall and irrigation enhanced the results of SPIs and SPEIs. Especially, improved SPI1, SPEI1 and SPEI3 were more effective than CDI for monitoring drought impact on coffee.

KBDI should not be recommended for agricultural drought monitoring in Gia Lai province since it declared extreme drought conditions for all dry season in study period. This problem stems from the assumption in KBDI calculation which was not suitable for the study area. Therefore, in order to improve the indices, a further study should be conducted to revise the KBDI assumption.

CDI should be recommended for agricultural drought monitoring in Gia Lai province, based on the followings reasons: (1) CDI is most closely related to CYRs (R^2 = 0.52 for rice and 0.66 for coffee). (2) CDI detected drought events better than other selected indices. And (3) CDI is a good indicator for water management and irrigation schedule because CDI is calculated based on the evapotranspiration deficit which is the water demand for irrigating crops.

The first finding of this thesis is that crop yield can be used to evaluate drought indices in term of agricultural drought monitoring for regions where crop yield reduction is closely related to drought condition. In addition, this analysis also shows that droughts in development stages are more harmful than that in other growth stages. The second finding indicates that meteorological drought indices are not suitable for monitoring impact of drought on crop yield reduction in the irrigated crop as spring paddy and coffee in the study area. That is why drought indices which considered irrigation practice such as CDI and improved SPI and SPEI were found more effective.

However, CDI has limitation of large data requirement and complicated calculation steps. Moreover, CDI still need to be improved. Regarding to the above discussion, CDI indicated drought condition in some non-drought years due to the lack information of irrigation from groundwater. Therefore, in the future work, this information needs to be investigated. In addition, CDI was calculated at a point scale that did not consider the spatial variations of the drought index. The development of remote sensing technology in monitoring evapotranspiration (Mu *et al*., 2007; Mu *et al*., 2013) can improve CDI in drought monitoring at the regional scale with high spatial resolutions.

Furthermore, the use of provincial crop yields to evaluate point scale index may have reduced the result of correlation analysis. As see in Figure 2.1, topography of Gia Lai province is very complex so that meteorological data observed at the two meteorological stations does not represent the climatic conditions for the whole province. In addition, provincial crop yield residual could not indicate drought condition if droughts occurred in small scale as noticed for the year 2003. Yet, it is necessary to investigate the crop yield at smaller scale.

References

Abramowitz, M., & Stegun, I. (1965). *Handbook of Mathematical Functions, with Formulas, Graphs, and Mathematical Tables.* Dover Publications. 1046p.

AIT (2017). *Rice Monitoring with KBDI*. Asian Institute of Technology Webite, Retrieved from http://www.geoinfo.ait.asia/index.php/data-archives/kbdi (Viewed on June 25, 2017).

Allen, R., Pereira, L., Raes, D., & Smith, M. (1998). *Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements - FAO Irrigation and Drainage Paper 56.* Rome: FAO. 333p.

Angelidis, P., Maris, F., Kotsovinos, N., & Hrissanthou, V. (2012). Computation of drought index SPI with alternative distribution functions. *Water Resources Management*, 26(9), 2453-2473.

Arpaci, A., Eastaugh, C., & Vacik, H. (2013). Selecting the best performing fire weather indices for Austrian ecoregions. *Theoretical and Applied Climatology*, 114(3-4), 393-406.

Borg, H., & Grimes, D. (1986). Depth development of roots with time: an empirical description. *Transactions of the ASAE*, 29(1), 194-197.

Brunini, O., Dias, P., Grimm, A., Assad, E., & Boken, V. (2005). Agricultural drought phenomenon in Latin America with focus on Brazil. (pp. 156-168). In V. Boken, A. Crakenell, & R. Heatcote, *Monitoring and Predicting Agricultural Drought: A Global Study*. New York: Oxford University Press. 496p.

CGIAR (2016). *The Drought Crisis in the Central Highlands of Vietnam.* Kon Tum, Gia Lai, Dak Lak: Assessment Report. 36p.

Changnon, S., & Easterling, W. (1989). Measuring drought impacts: the Illinois case. *JAWRA Journal of the American Water Resources Asociation,* 25(1), 27-42.

Chhinh, N., & Millington, A. (2015). Drought Monitoring for Rice Production in Cambodia. *Climate*, 3(4), 792-811.

Dang, P. D. (2008). *General on Groundwater Resources.* Hanoi: Water Sector Review Project, ADB-TA-4903 VIE. 96p.

Dao, Q. T. (2005). *Characteristics of Meteorological and Hydrological Drought in the Central Highlands.* Hanoi : Ins. of Meteorology Hydrology and Environment. 94p. (in Vietnamese).

DoNRE. (2013). *Report of Land-use Planning Toward 2020, Land-use Plan for the 5 years (2011 - 2015) for Gia Lai Province.* Gia Lai: Department of Natural Resources and Environment. 167p.

FAO (2015). *The Impact of Disasters on Agriculture and Food Security.* Retrieved from Food and Agriculture Organization of the United Unions: http://www.fao.org/3/a-i5128e.pdf. 54p. (Viewed on June 29 2017).

FAO (2016). *"El Nino" Event in Viet Nam - Agriculture, Food Security and Livelihood Need Assessment in Response to Drought and Salt Water Intrusion.* Hanoi: Food and Agriculture Organization of the United Unions. 75p.

GHWCo (2016). *Report of Water Exploitation from Chu Prong Reservoir.* Gia Lai: Gia Lai Hydraulic Works Limited Company. 63p.

Gibbs, W., & Maher, J. (1967). *Rainfall Deciles as Drought Indicators.* Melbourne, Australia: Bureau of Meteorology Bulletin No. 48. 37p.

GSO (2012). *Gia Lai Statistical Year Book of Year 2011.* Gia Lai: Statistical Publishing House. 276p.

GSO (2017). *Agriculture, Forestry and Fishing*. General Statistics Office of Vietnam Website. Retrieved from http://www.gso.gov.vn/default_en.aspx?tabid=778 (Viewed on Dec.10, 2016)

Guttman, N. (1999). Accepting the standardized precipitation index: a calculation algorithm. *JAWRA Journal of the American Water Resources Association*, 35(2), 311-322.

Ha, K. V., Nguyen, T. V., Duong, T. V., Luu, H. V., Nguyen, T. D., & Nguyen, T. T. (2008). *Engineering Hydrology.* Hanoi: The Natural Science and Technology Publisher. 580p. (in Vietnamese)

Heim, R. (2002). A review of twentieth-century drought indices used in the United States. *Bulletin of the American Meteorological Society*, 83(8), 1149-1165.

IMHEN (2008). *Mapping Drought and Water Deficient Level in the South Central Coast and the Central Highlands.* Hanoi: Ins. Meteorology Hydrology and Environment. 626p. (in Vietnamese).

Keetch, J., & Byram, G. (1968). A drought index for forest fire control. *USDA Forest Service Research Paper No. SE-38*, 1-32.

Łabędzki, L., & Bąk, B. (2014). Meteorological and agricultural drought indices used in drought monitoring in Poland: a review. *Meteorology Hydrology and Water Management. Research and Operational Applications*, 2(2), 3-13.

Labudová, L., Labuda, M., & Takáč, J. (2017). Comparison of SPI and SPEI applicability for drought impact assessment on crop production in the danubian lowland and the east Slovakian lowland. *Theoretical and Applied Climatology*, 128(1), 491-506.

Lai, Dinh Hoe (2011). *Research on Selecting Rice Varieties and Cultivation Technique for the South Central and the Central Highlands*. Quy Nhon: Agricultural Science Institute for Southern Coastal Central of Vietnam. 82p. (in Vietnamese)

Li, R., Tsunekawa, A., & Tsubo, M. (2014). Index-based assessment of agricultural drought in a semi-arid region of Inner Mongolia. China. *Journal of Arid Land*, 6(1), 3-15.

Lui, X. F., Zhu, X. F., Pan, Y. z., Li, S. S., Liu, Y. X., & Ma, Y. Q. (2016). Agricultural drought monitoring: Progress, challenges, and prospects. *Journal of Geographical Sciences*, 26(6), 750-767.

MARD (2011). *TCVN 8641:2011: Hydraulic Structures - Irrigation and Drainage Techniques for Provisions Crops.* Hanoi: Vietnamese Standards. 31p. (in Vietnamese).

MARD (2012). *QCVN 04-05:2012/BNNPTNT: National Technical Regulation on Hydraulic Structures – The Basic Stipulation for Design*. Hanoi: Ministry of Agriculture and Rural Development. 47p. (in Vietnamese)

MARD, MoH, PACCOM, UN, & INGOs (2016). *Vietnam Drought and Saltwater Intrusion Rapid Assessment Report.* Hanoi: Assessment report. 28p.

MARD (2017). *Cultivation Data*. From Statistics and Food security Information website: http://fsiu.mard.gov.vn/data/trongtrot.htm (Retrieved May 10, 2016) (in Vietnamese)

McKee, T., Doesken, N., & Kleist, J. (1993). The relationship of drought frequency and duration to time scale. *Preprints, 8th Conference On Applied Climatology*, 179-184.

Mishra, A., & Singh, V. (2010). A review of drought concepts. *Journal of Hydrology*, 391(1), 202-216.

Moghaddasi, M., Morid, S., Araghinejad, S., & Agha Alikhani, M. (2010). Assesment of irrigation water allocation based on optimization and equitable water reduction approaches to reduce agricultural drought losses: the 1999 drought in the Zayandeh Rud irrigation system (Iran). *Irrgation and Drainage*, 59, 377-387.

Moorhead, J.E; Gowda, P.H.; Singh, V.P.; Porter, D.O.; Marek, T.H; Howell, T.A; Stewart, B.A. (2015). Identifying and Evaluating a suitalbe index for agricultural drought monitoring in the Texas High Plains. *JAWRA Journal of the American Water Resources Association*, 51, 807-820.

Mu, Q., Heinsch, F., Zhao, M., & Running, S. (2007). Development of a global evapotranspiration algorithm based on MODIS and global meteorology data. *Remote Sensing of Environment*, 111(4), 519-536.

Mu, Q., Zhao, M., & Running, S. (2013). *MODIS Global Terrestrial Evapotranspiration (ET) Product (NASA MOD16A2/A3). Algorithm Theoretical Basis Document, Collection, 5.* Washington DC: National Aeronautics and Space Adminstration. 66p.

Munger, T. T. (1916). Graphic method of representing and comparing drought INTENSITIES. 1. *Monthly Weather Review*, 44(11), 642-643.

Nadir, A. E. (2013). Meteorological Drought and Crop Yield in Sub-Saharan Sudan. *International Journal of Water Resrources and Arid Envionmnets*, 2(3), 164-171.

Narasimhan, B., & Srinivasan, R. (2005). Development and evaluation of Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) for agricultural drought monitoring. *Agricultural and Forest Meteorology*, 133(1), 69-88.

NASA LP DAAC (2011). *ASTER Global Digital Elevation Model Version 2 (GDEM V2).* Retrieved from NASA EOSDIS Land Processes DAAC, USGS Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota (https://lpdaac.usgs.gov): https://gdex.cr.usgs.gov/gdex/ (Viewed on June 11, 2016)

NAWAPI (2015). *Water Resources Planning to 2025 for Gia Lai Province.* Gia Lai: Gia Lai Department for Natural Resourses and Environment. 213p. (in Vietnamese).

Nguyen, K. Q. (2005). *Research Project on Drought Forcast in South Central and the Central Highlands, Constructing Prevent Solution.* Hanoi: National Research Report. 374p. (in Vietnamese).

Nguyen, T. V. (2007). *Research and Develop Technology for Drought Forecasting and Early Warning in Vietnam.* Hanoi: Ins. Meteorology Hydrology and Environment. 192p. (in Vietnamese).

Nguyen, T. V. (2014). *Research on Development of an Drought Forecast and Warming Technology in Vietnam.* Hanoi: Ins. Meteorology Hydrology and Environment. 326p. (in Vietnamese).

Palmer, W.C. (1965). *Meteorological Drought.* Washington, DC, USA: US Department of Commerce, Weather Bureau. 65p.

Palmer, W.C. (1968). Kepping Track of Crop Moisture Conditions, Nationwide: The New Cropo Moisture Index. *Weatherwise*, 21(4), 156-161.

Potopová, V., Boroneanţ, C., & Soukup, J. (2016). Impact of agricultural drought on main crop yields in the Republic of Moldova. *International Journal of Climatology*, 36(4), 2063-2082.

Potopová, V., Stepanek, P., Mozny, M., & Turkott, L. (2015). Performance of the standardised precipitation evapotranspiration index at various lags for agricultural drought risk assessment in the czech republic. *Agricultural and Forest Meteorology*, 202, 26-38.

Quiring, S., & Papakryiakou, T. (2003). An evaluation of agricultural drought indices for the Canadian prairies. *Agricultural and Forest Meteorology*, 118(1), 49-62.

Sivakumar, M., Motha, R., Wilhite, D., & Wood, D. (2010). *Agricultural Drought Indices Proceedings of an Expert Meeting.* Geneva, Switzerland: World Meteorological Organization. 205p.

Stagge, J., Tallaksen, L., & Gudmundsson, L. (2015). Candidate distributions for climatological drought indices (SPI and SPEI). *International Journal of Climatology,* 35(13), 4027-4040.

Takeuchi, W.; Darmawan, S.; Shofiyati, R.; Khiem, M.V.; Oo, K.S.; Pimple, U.; & Heng, S. (2015). Near-real time meteorological drought monitoring and early warning system for croplands in Asia. *In Proceedings of the 36th Asian Conference on Remote Sensing.* Manila, Philippines.

Todisco, F., Vergni, L.; & Mannocchi, F. (2008). An evaluation of some drought indices in the monitoring and prediction of agricultural drought impact in central Italy. In: Santini, A.; Lamaddalena, N.; Severino, G.; & Palladino, M. *Irrigation in Mediterranean Agriculture: Challenges and Innovation for the next Decades*. Bari: CIHEAM. p. 203-211.

Varol, T., & Ertugrul, M. (2016). Analysis of the forest fires in the antalya region of turkey using the Keetch–Byram drought index. *Journal of Forestry Research*, 27(4), 811-819.

Vicente-Serrano, S. (2006). Differences in spatial patterns of drought on different time scales: an analysis of the Iberian Peninsula. *Water Resources Management*, 20(1), 37-60.

Vicente-Serrano, S., Begueria, S., & Lopez-Moreno, J. (2010). A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. *Journal of Climate*, 1696-1718.

Vu-Thanh, H.; Ngo-Duc, T.; & Phan-Van, T. (2014). Evolution of meteorological drought characteristics in Vietnam during the 1961-2007 period. *Theoretical and Applied Climatology*, 118, 367-375.

Vu, M.T., Raghavan, V.S., & Liong S.Y. (2015). Ensemble Climate Projection for Hydro-Meteorological Drought Over a River Basin in Central Highland, Vietnam. *KSCE Journal of Civil Engineering*, 19(2), 427-433.

Wang, H.; Vicente-serrano, S.M.; Tao, F.; Zhang, X.; Wang, P.; Zhang, C.; Chen, Y.; Zhu, D.; & El Kenawy, A. (2016). Monitoring winter wheat drought threat in Northern China using multiple climate-based drought indices and soil moisture during 2000–2013. *Agricultural and Forest Meteorology*, 228, 1-12.

WB (2017) *Fertilizer Consumption.* The World Bank website. Retrieved from http://data.worldbank.org/indicator/AG.CON.FERT.ZS (Viewed on Jun 11, 2017)

Wilhite, D. (2010). Drought as a natural hazard: Concepts and Definitions. In D. Wilhite, *Drought: A Global Assessment* (pp. 3–18). London: Routledge.

Wilhite, D., & Glantz, M. (1985). Understanding the drought phenomenon: The role of definitions. *Water International, 10*, 111-120.

WMO (2014). *Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes 1970–2012.* Geneva, Switzerland: World Meteorological Organization. 48p.

WMO & GWP (2016). *Handbook of Drought Indicators and Indices.* Geneva: Integrate Drought Management Program, 52p.

Wu, H., Hubbard, K. G., & Wilhite, D. A. (2004). An agricultural drought risk-assessment model for corn and soybeans. *International Journal of Climatology*, *24*(6), 723–741.

Zargar, A., Sadig, R., Naser, B., & Khan, F. (2011). A review of drought indices. *Environmental Reviews*, 19, 333-349.

Appendices

Appendix A Meteorological data gap filling

Table A.1 presents the missing situation of climatic data of Pleiku and Ayunap station for the period 1980-2010. The black cells indicate complete data set and the white cells indicate the missing data. Except wind speed data of Ayunpa station is not available, the number of months of missing data range from 1% to 10%. Wind speed of Ayunpa station was imported from Pleiku station as recommended by Allen et al. (1998). The data with missing value less than 10% were gap-filled by linear regression with record from nearby and high correlation as shown in Table A.2.

Table A.1 Missing climatic data of two stations in the study area

Climatic element	Station\year	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	Number of missing month
Rainfall	Pleiku																																9
	Auynpa																																0
Wind speed	Pleiku																																2
	Auynpa																																372
Sun duration	Pleiku																																12
	Auynpa																																18
Mean temperature	Pleiku																																36
	Auynpa																																0
Minimum temperature	Pleiku																																12
	Auynpa																																12
Maximum temperature	Pleiku																																0
	Auynpa																																0

Table A.2 Filling method and statistics description of observation and infilling values

Climatic parameter	Station	Infilling method			Statisitc description of observed data set			Statisitc description data set after infilling		
		Nearby station	R^2	Regression equation	Mean	σ	CV	Mean	σ	CV
Rainfall	Pleiku	Kon Tum	0.18	$y = 0.495x + 7.232$	13.8	19.7	1.43	13.7	19.5	1.4
	Auynpa				9.3	17.3	1.86			
Wind speed	Pleiku	Kon Tum	0.16	-	2.6	1.5	0.57	2.6	1.5	0.6
	Auynpa			-	-	-	-	2.6	1.5	0.6
Sun duration	Pleiku	Kon Tum	0.53	$y = 0.7457x + 1.5101$	6.9	3.1	0.45	6.9	3.0	0.4
	Auynpa	Kon Tum	0.29	$y = 0.5494x + 2.9916$	7.0	3.1	0.45	7.0	3.1	0.4
Mean temperature	Pleiku	Kon Tum	0.79	$y = 0.8622x + 1.4904$	21.9	2.1	0.10	21.9	2.1	0.1
	Auynpa				25.8	2.5	0.10			
Minimum temperature	Pleiku	Kon Tum	0.83	$y = 0.7999x + 2.5452$	18.3	2.7	0.15	18.4	2.7	0.1
	Auynpa	An Khe	0.79	$y = 0.9494x + 2.5005$	22.0	2.7	0.12	22.1	2.7	0.1

σ is standard deviation; CV is coefficient of variation.

Appendix B Calculation of $Q75$ (Ha *et al.*, 2008)

$Q75$ is identified by using flow-duration curve which is built by the following steps:

Step 1: Average discharge Q of dry season for each year is calculated.

Step 2: New time series is created by arranging the record in descending order.

Step 3: Percentage probability of each discharge Q is calculated by using the following equation:

$$P = \frac{m}{n+1} 100\% \tag{B.1}$$

where P is empirical frequency; m is the order number of the discharge; and n is length of record.

Step 4: the discharge Q is plotted against P to get flow-duration curve. Figures B.1 and B.2. show flow duration curves for Kon Tum and Ayunpa stations for the period 1980-2010.

Step 5: $Q75$ is identified by Q at P = 75%.

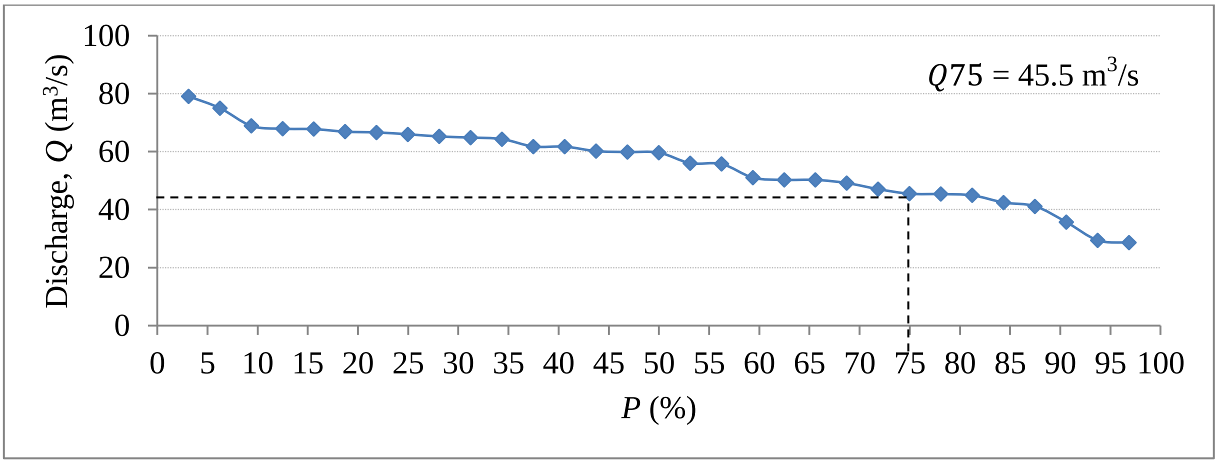


Figure B.1 Flow-duration curve for Kon Tum station

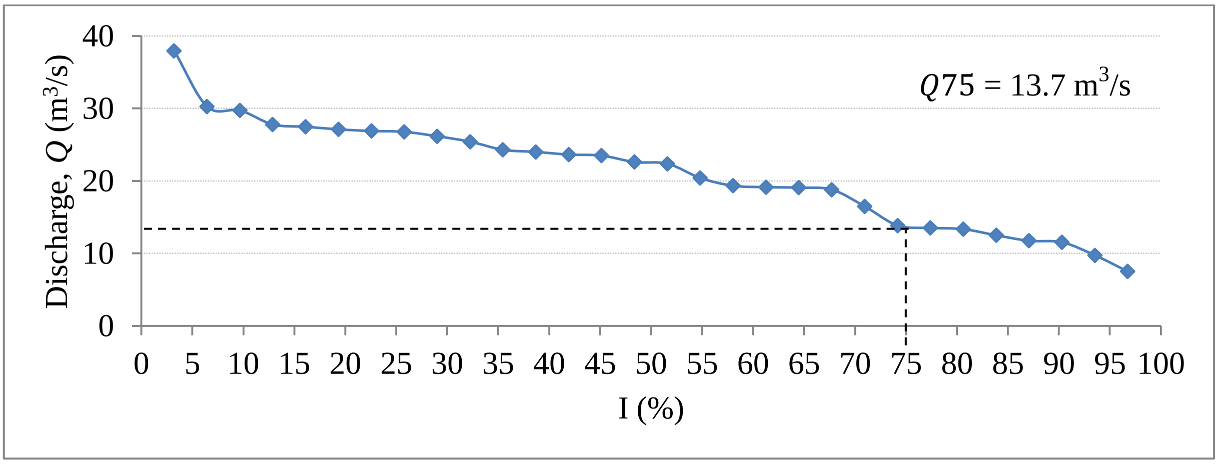


Figure B.2 Flow-duration curve for Ayunpa station