A Study of Drought Management for Ben Tre Province in the Mekong Delta, Vietnam

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Abstract

The Mekong Delta (MKD) spreads over 3.9 million ha that is the home to over 17.5 million people. The main economic activity is agriculture with 1.5 million ha of paddy and 0.39 million ha of fruits which mainly use surface water through a highly dense canal system. In the dry season (December to April), the enhanced penetration of salinity has occurred, possibly because of the sea-level rise and low stream level due to droughts, affected to surface water and groundwater, and caused a water shortage for 1.4 million ha of the coastal zone of the MKD. Recently, the delta has faced with climate change (CC) and sea level rise (SLR) and has struggled with hydropower development and water extraction and diversion. In this context, the occurrence of drought has happened more frequently and severely since 1998, especially in 2004, 2010, and 2013. Specifically, in 2016, the most severe drought in the last 90 years was recorded in Vietnam. Many projects have been initiated in the Mekong Delta to tackle with the negative impacts of CC and SLR, and saline intrusion. However, drought study was just recommended to further studying.

The objective of this study is to seek for the holistic and appropriate approach to drought management, and, more specifically, to figure out the suitable drought index and/or multi-index for drought monitoring in Ben Tre, the MKD.

Currently, there are in the order of 50 popular drought indicators and indices worldwide based on such approaches as the standardized deviation, regression analysis, remote sensing, and hydraulic simulation. In this study, the standardized drought index based on the standardized deviation (Z-score): $Z = (x - \bar{x})/s$; for a variable x and its mean $\bar{x}$ and standard deviation s for a given period was examined because it is widely applied and easy to obtain. The variable x was rainfall amount for the Standardized Precipitation Index (SPI), discharge for the Streamflow Drought Index (SDI) and the difference between rainfall and evapotranspiration for the Standardized Precipitation Evapotranspiration Index (SPEI). These indices were calculated for different overlapping time periods of one month, three months, six months, nine months, and twelve months. To figure out the promising indices, the correlation analysis was conducted between the calculated indices with the statistics on drought damage, and with recorded salinity data.

The results indicated that SDI for six months from January to June (SDI-6), two months from January to February (SDI-2) and one month of April (SDI-1) were best matched up with historical droughts years such as 1998, 2005, and 2010. Moreover, the coefficient of determination R^2 between SDI-6 and the affected areas was the highest with R^2=0.48. In the case of SDI-1 (April) and SDI-2 (Jan.-Feb.) R^2 were 0.34 and 0.37. The R^2 for other time periods of SDI-3 (Jan.-Mar.), SDI-9 (Jan.-Sep.) and SDI-12 (Jan.-Dec.) were 0.40, 0.28, and 0.19, respectively. The results for SPI and SPEI were not as promising. Only SPI-6 (Jan.-Jun.) had a good responded pattern to severe droughts and the highest R^2 value was as low as 0.26

(with the affected areas) and 0.16 (with the number of affected households). The comparison of SPEI with the affected areas showed that the highest R^2 value was only 0.14 for SPEI-6 (Jan.-Jun.) while for the others time periods the R^2 values were as low as 0.02 for SPEI-3 (Feb.-Mar.); 0.11 for SPEI-9 (Jan.-Sep.); and 0.01 for SPEI-12 (Jan.-Dec.).

It is noteworthy that the number of hours recording saline concentration ≥4 ppt (Salinity Index) in March to April clearly showed the evidence of historical drought years. When indices were compared with the Salinity Index at Huong My Station, SDI-2 (Jan.-Feb.) showed a good correlation (R^2=0.75) with Salinity Index as 4 ppt in periods (Mar.-Apr.). To examine thoroughly, this study added Son Doc and Tra Vinh Station located 20-30 km from the sea to the examination. The correlation analysis was conducted between recorded hours with salinity ≥ 4 ppt in (March and April) and those in (January to February) of these stations and SDI in different time periods of the dry season (December to May) of Tan Chau and Chau Doc Station. Similar to Huong My Station, SDI-2 (Jan.-Feb.) resulted in R^2 ranking 0.75 to 0.81 in comparison with both stations. Ideally, SDI-2 (Jan.-Feb.) should be applied for the drought early warning through Salinity Index.

In summary, a hybrid Drought Index as minimum [SDI-6 (Jan.-Jun.), SDI-2 (Jan.-Feb.) and SDI-1 (Apr.)] reproduced all drought events well in Ben Tre. SPI-6 (Jan.-June.) and SPEI-3 (Feb.-Apr.) only responded to severe drought years. Salinity Index (≥4 ppt) in the dry season (Mar.-Apr.) clearly showed evidence of historical drought events. Moreover, SDI-2 (Jan.-Feb.) had a good correlation with recorded hours with salinity index ≥ 4 ppt in (March and April). Thereupon, this study recommends a hybrid index including SDI-6 (Jan.-Jun.), SDI-2 (Jan.-Feb.) and SDI-1 (Apr.) for the drought monitoring and SDI-2 (Jan.-Feb.) for the drought early warning for Ben Tre.

Keywords: Climate change, salinity intrusion; drought monitoring and drought indices.

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1 Introduction

1.1 Drought impacts

Drought is one of the natural disasters which cause severe damage to human beings, and it is one of a mega-crisis. Globally, in the 20th century, many droughts occurred worldwide with the huge casualties; for example, China in 1959-1961, India in 1965-1967 and Africa in 1980 (Helsloot, *et al.*, 2012). The drought has long-lasting effects on large regions (UNISDR, 2009).

In the 21st century, droughts have happened more frequently with the tendency of higher magnitude due to climate change, and some drought events hit historical records such as the Millennium Drought in Australia in 2010 and the worst drought year in California, USA. Table 1 shows the extreme drought events recorded worldwide recently such as Brazil in 2013, China in 2010, and Russia in 2010 and 2011 (Cai, 2014).

Table 1: The summary of historically severe drought events in the world in the 21st century

Locations	Years	Remarks
Brazil	2015	The worst drought in 84 years
California, USA	2014	The worst drought in 1,200 years
Australia	1996-2010	The Millennium Drought
India	2010	670 million people affected
Europe	2003	70,000 casualties and €8.7 billion

In the Mekong Delta in Vietnam, the drought occurred in 1998, 2004-2005, 2010, 2013 and 2016. Especially, the 2016 drought was the most severe in recent 90 years and affected more than 1.5 million people (UN, 2016).

Drought is getting worse, and affecting more people due to climate change and developing issues. Therefore, understanding on drought is necessary to alleviate the consequences of droughts.

1.2 Drought definition and classification

Basically, drought happens when the demands of human activities exceed the water available (Botterill and Fisher, 2003).

There is no single definition of drought for various regions in the world. The concept about drought for a typical region highly depends on distinguished climate, topography, and external aspects. Hereafter, the most popular definitions of drought defined by different organizations were quoted to prove.

- “a sustained, extended deficiency of precipitation” (WMO, 1986)
- “the naturally occurring phenomenon that exists when precipitation has been significantly below normal recorded levels, causing serious hydrological imbalances that adversely affect land resource production system (UN, 1994),
- “the percentage of years when crops fail from the lack of moisture” (FAO, 1993).

To clarify the definition of drought in order to approach drought study, Glantz and Wilhite (1985) classified the drought by four types that have been accepted and followed by researchers around the world. These can be summarized below:

- Meteorological drought happens when the lack of rainfall in a long period, in other words, is rainfall deficit. It also combines changes in seasonal pattern, increased temperature, and evaporation;
- Hydrological drought refers to shortages in both surface and groundwater, including reduction in surface water availability, reservoir drawdown, groundwater levels;
- Agricultural drought is about soil moisture deficit due to meteorological and hydrological droughts and causes impact upon crop production and livestock;
- Socioeconomic drought is associated with an imbalance of water due to the natural phenomenon. It happens when the water demand exceeds the water availability.

1.3 Indices and indicators in drought management

Drought management includes drought assessment, drought monitoring and countermeasures. Among these, drought monitoring is an essential step (Wilhite, 2005; Rossi, 2013). Drought indices are tools to monitor and assess drought timing, severity, and duration and many types of indices have been introduced already.

Some reviews on drought indicators and indices which have contributed the clear views on drought monitoring were made by Mishra and Singh (2010) and Heim (2002). It is noteworthy that the World Meteorology Organization (WMO) published the handbook in 2016 covering 50 popular drought indicators and indices around the world (Svoboda, 2016) with suggested references. Moreover, indices were grouped, discussed and each analyzed including advantages and disadvantages. The information mainly extracted from the handbook of WMO above. The WMO (2016) defined drought indicators and indices:

- “Drought indicators are variables as precipitation, temperature, groundwater, soil moisture, reservoir levels, streamflow, and snowpack used to describe drought conditions.”
- “Drought indices are calculated values to describe the severity and qualitative state of droughts for a target period utilizing climatic inputs that including the indicators above. Indices are also technical indicators.”

1.3.1 Single index

In the early days, the indices which cooperated with precipitation such as Munger's Index were introduced in 1916, followed by Kincer's Index in 1919, Marcovitch's Index in 1930, Blumenstock's Index in 1942, and Antecedent Precipitation Index in 1953 (Jr., 2002). In recent years, development of technology and improvement of availability observed data have allowed researchers to develop other indices from variables such as temperature, evaporation, groundwater level, streamflow, and soil moisture.

a) Meteorological drought indices

Various meteorological drought indices have been introduced and applied to different regions. However, this part only discusses and introduce the most typical and widely applied indices. Most of the meteorological drought indices were generated from precipitation, with some indices involving temperature.

➢ Standardized Precipitation Index (SPI)

In terms of meteorology, the precipitation is the most basic variable so that its deficit could affect changes in groundwater, soil moisture, and streamflow. In 1993, American scientists McKee, Doesken and Kleist introduced the Standardized Precipitation Index (SPI). It is based on standardized precipitation that is the difference of precipitation from the mean divided by the standard deviation (McKee et al., 1993). Equation (1) is the definition of SPI.

$$SPI = \frac{(P - \overline{P})}{\sigma_P} \quad (1)$$

of which, P: precipitation; $\overline{P}$: mean precipitation and σ_P: standard deviation.

Table 2: The category of Standardized Precipitation Index

SPI values	Drought category	Time in category
0 to -0.99	Mild drought	24%
-1.00 to -1.49	Moderate drought	9.2%
-1.50 to -1.99	Severe drought	4.4%
≤ -2.00	Extreme drought	2.3%

McKee *et al.*, (1993) noted on SPI that SPI is normally distributed so it can be used to monitor the wet or the dry periods. It could be applied to the other variables of snowpack, reservoir, streamflow, soil moisture, and groundwater. SPI tends to close to zero when the time periods are three or six months, and it has a larger value for longer periods of 12, 24, and 48 months. In what follows SPI for n month is indicated as SPI-n.

It is important to note that the gamma distribution (GAM) was used to fit data in SPI. Then, the fitted data is transformed into standardizing values. Ideally, McKee *et al.*, (1993) suggested the length of data longer than 30 years. Regarding probability distribution, Guttman (1999) made a rigorous analysis for 1,035 sites in the U.S with the averaged record lengths of 85 years (the least length of 65 years). As a result, Guttman (1999) stated that it does not matter which distribution is chosen because of "very little difference in the number, duration, intensity; even so, the 3-parameter Pearson Type III (PE3) is the best choice for probability distributions."

In December 2009, the Interregional Workshop on Indices and Early Warning Systems for Drought was held at the University of Nebraska-Lincoln. This workshop gathered the World Meteorological Organization (WMO) and its partners, including 54 participants representing 22 countries from around the world. This workshop came to a consensus as the Lincoln Declaration on Drought Indices that encourages using SPI for the meteorological drought in the world. In June 2011, the Sixteenth World Meteorological Congress also requested that the SPI manual was published and distributed in all official languages of the United Nations (Svoboda *et al.*, 2012). Mahfouz (2016) recently presented the step by step procedure to obtain SPI.

Based on the premise above, SPI has been applied widely in drought study. Various drought studies have been conducted on this index for different regions and countries such as India (Kumar, 2009), central Poland (Labedzki, 2014), Czech (Dubrovsky, 2009), in the Mekong Delta (Tinh, 2012) and (Ty, 2015). In the EU region, especially in semi-arid region like Greece, the SPI-6 showed good responses to historical drought events (Karavitis *et al.*, 2011) than other time periods. In contrast, Kumar (2009) found that SPI did not respond drought events well in India, and suggested that application of SPI should have a caution in areas having low rainfall and the distinct dry season. Similarly, Homdee (2016) also concluded that SPI alone, even SPI-12 known to be relatively sensitive to drought, was unable to apply in Thailand, and it is better to use it in a set with the other indices. The effect of time scale to SPI was also mentioned by Chhinh (2015) in the case study of Kampong Speu, Cambodia (near the MDK) that SPI-12 value was higher than shorter time SPIs, SPI-3 responded to some drought events, and the recommendation was to collect soils data and added rainfall stations.

SPI is easy to apply and flexible index. Some researchers already have applied SPI to study drought in the context of climate change with projected scenarios. However, it only reflects the change in rainfall and might be suitable for areas depending on precipitation and/or closed watershed. Moreover, the results of SPI depend on the length of data. It is reliable with the 50 years of data (Guttman, 1994). Nonetheless, overall, SPI is suitable to be applied widely and firstly because of its simple input data; and it possibly describes meteorological droughts. The SPI code is available at the website of the National Drought Mitigation Center University (NDMC) of Nebraska-Lincoln [(1)].

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[1] http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx

b) Agricultural drought indices

- Palmer Drought Severity Index (PDSI)

Palmer (1965) introduced, described, and applied Palmer Drought Severity Index (PDSI, and proposed Crop Drought Index (CDI) in (1968) for the drought monitoring in America. Briefly, CDI is based on the difference between actual evapotranspiration under soil water deficit (mm) and potential evapotranspiration (PET) under sufficient soil moisture content (mm). Unfortunately, such indices are difficult to apply in most Asian countries due to the lack of moisture data.

- Standardized Precipitation Evapotranspiration Index (SPEI)

Some indices were employed from the difference between precipitation (*P*) and evapotranspiration; for example, Reconnaissance Drought Index (RDI) that was proposed by Tsakiris and Vengelis (2005). RDI is calculated from a method of dividing potential evapotranspiration by precipitation (the ratio of *P* to *PET*). Similarly, Climatic Water Balance (CWB) has been used in Poland for meteorological drought monitoring. CWB is also obtained from the difference between precipitation and evapotranspiration (Labedzki, 2014).

Herein, SPEI that was proposed by Vicente-Serrano (2010) was discussed because it eliminates the limitation of RDI in the case of *PET*=0. SPEI was calculated from the difference between precipitation (P) and potential evapotranspiration (*PET*). Vicente-Serrano (2010) explained and examined factor analysis. Another advantage is that SPEI code is freely available and the calculations procedure is also described in the literature [(2)].

Firstly, the monthly potential evapotranspiration (*PET*) (mm) is estimated from the Equation (2) (Thornthwaite, 1948):

$$PET = 16K\left(\frac{10T}{I}\right)^{m} \qquad (2)$$

of which, *T* is the monthly mean temperature (^{o}C), *I* is heat index, *m* is coefficient depending on *I*, and *K* is correction coefficient calculating from Equations (3), (4), and (5), respectively.

$$I = \sum_{i=1}^{i=12}\left(\frac{T}{5}\right)^{1.514} \qquad (3)$$

$$m = 6.75\times 10^{-7}I^{3} - 7.71\times 10^{-5}I^{2} + 1.79\times 10^{-2}I + 0.492 \qquad (4)$$

$$K = \left(\frac{N}{12}\right)\left(\frac{NDM}{30}\right) \qquad (5)$$

[2] http://spei.csic.es/home.html#p10

where *NDM* is the number of days of the month and *N* is the maximum number of sun hours, which is obtained from Equation (6).

$$N = \left(\frac{24}{\pi}\right)\bar{\omega}_s = \left(\frac{24}{\pi}\right) \times arccos(-tan\varphi tan\delta) \tag{6}$$

where φ is the latitude in radians and δ is the solar declination in radians that is obtained from Equation (7)

$$\delta = 0.4093sen\left(\frac{2\pi J}{365} - 1.405\right) \tag{7}$$

in which *J* is the average Julian day of the month.

Alternatively, *PET* could be obtained from Equation (8) as the FAO-56 Penman–Monteith equation (Allen *et al.*, 1998).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{8}$$

where, R_n is net radiation at crop surface, *G* is soil heat flux, *T* is mean daily air temperature at 2 m height, U_2 is wind speed at 2 m height, e_s-e_a: saturation vapor pressure deficit, Δ: slope vapour pressure, and γ: psychrometric constant.

Secondly, the difference between *P* and *PET* for target period *i* is calculated from Equation (9).

$$D_i = P_i - PET_i\ (mm) \tag{9}$$

In the next step, *Di* values are fitted by log-logistic distribution, and resulting cumulative probabilities are transformed into a standardized variable similar to SPI, including category (Table 2). The advantage of SPEI compared to SPI is that the temperature and other climatic variables are involved. Because of this, SPEI is suitable to explain drought in the context of climate change (Vicente-Serrano, 2010). Vicente-Serrano (2010) stated that the method of calculation PET and the time scale of SPEI would affect to results of SPEI.

The SPEI was conducted in many types of research for various regions such as China (Wang *et al.*, 2015), Iran (Banimahd and Khalili, 2013), Czech (Potop, 2011), and Vietnam

(Nguyen, 2015). Wang *et al*., (2015) concluded that SPEI-3 and SPEI-6 are accurate indices in drought assessment for the Luanhe River Basin, China, and the limitation of SPEI might be the use of the Thornthwaite to calculate evaporation. In a similar manner, Banimahd and Khalili (2013) pointed out that SPEI-3 and SPEI-6 detected droughts well in Iran. In contrast, Nguyen (2015) stated that SPEI only responded to droughts for the wet periods in the central Vietnam.

In general, SPEI is a good index involving more climatic variables than SPI. Therefore, it is suggested to use SPEI in the context of global warming studies.

c) Hydrological drought indices

For hydrological drought, indices have been used and generated from streamflow, groundwater level, and reservoir storage data. For example, Van (2015) fully described the concept of hydrological drought in the recent research that introduced main indices.

Regarding streamflow index, various approaches have been introduced such as low flow, the Streamflow Drought Index (Nabaltis and Tsakiris, 2009), the Standardized Runoff Index (Shukla and Wood, 2008), the Standardized Streamflow Index (Serrano *et al*., 2012), the daily flow duration curve (exceedance probability) and mean annual flow (Sharma, 2008). These indices employ similarly standard deviation.

Cautiously, it is needed to check the consistency of the streamflow data. This situation likely happens in the case of major changes in water use, the method of collecting data, and store (USGS, 1996).

- Streamflow Drought Index (SDI)

Nalbantis and Tsakiris (2009) proposed Streamflow Drought Index (SDI) based on Equation (10) for the drought monitoring.

$$SDI_{i,k} = \frac{V_{i,k} - \bar{V}_k}{S_k} \quad (10)$$

of which, $V_{i,k}$ is the cumulative streamflow of referenced period k of the i-hydrological year, $\overline{V_k}$ and S_k are respectively the mean and the standard deviation of $V_{i,k}$.

One further, Yeh (2015) and Nalbantis (2008) suggested Equations (11) and (12), and the use of natural logarithms of the streamflow, for the estimation of SDI in small basins.

$$SDI_{i,k} = \frac{y_{i,k} - y_k}{s_{y,k}} \; of\ which\ i = 1,2 \ldots; k = 1,2,3,4 \quad (11)$$

$$y_{i,k} = ln(V_{i,k}) \; of\ which\ i = 1,2,\ldots; k = 1,2,3,4 \quad (12)$$

Noticeably, Nalbantis (2008) suggested calculating SDI by the overlapping time periods instead of consecutive months (moving cumulative) as SPI and SPEI.

Table 3: The category of Streamflow Drought Index

SDI values	Drought category	Time in category
0 to -0.99	Mild drought	34.1
-1.00 to -1.49	Moderate drought	9.2
-1.50 to -1.99	Severe drought	4.4
≤ -2.00	Extreme drought	2.3

SDI has also been widely applied in some regions such as in Greece (Nalbantis, 2008), in Taiwan (Yeh, 2015), in Iran (Tabari, 2012), and in China (Hong, 2014). Yeh revealed that the SDI for periods of three months (November to January) and six months (November to April) could be responded to significant droughts in northern Taiwan. Similarly, Nalbantis concluded that SDI could detect the severe drought events in the Evinos and Boeoticos Kephisos basin, Greece. In addition, Nalbantis (2008) noted that SDI requires high quality streamflow data. In Northwestern Iran, the results of Tabari (2012) showed the agreement of SDI for the nine-month and twelve-month period and extreme droughts. Hong (2014) discussed the change in SDI (increase in the occurrence of severe droughts) through different periods in the Yangtze River (the largest river in China) due to the change in land use, climate, and development activities. He determined the SDI is suitable for drought assessment in the Yangtze River basin. In what follows SDI for n month period will be denoted by SDI-n.

d) Socio-economic drought

Socioeconomic drought includes meteorological, hydrological, and agricultural drought. Water demand, land use and water allocation are indices for socioeconomic drought.

In short, studying on drought is a cross-cutting discipline; therefore, it involves various methods and approaches. For a given area, the indices, which are suitable to apply, depend on characteristics of the research areas and researchers' purposes. In the case of the Mekong Delta and Ben Tre Province where the causes of drought are multiple and complex, it is necessary to practice popular and basic indices. It could figure out the variables that are sensitive to droughts in the MDK and Ben Tre.

1.3.2 Multi-indicators

Drought is complex; therefore, a single index may not be able to reflect it. For this reason, many researchers have attempted to find out better approaches for solving it. As a result, multi-indicators and/or integrated drought index have been developed worldwide.

Steinemann (2006) fully explained available approaches to obtain multiple indicators. Some popular methods have been used to obtain a desired multi-indicator is weighted factor analysis (Balint *et al*., 2013), principal components analysis (PCA) (Zoljoodi, 2013; Nguyen, 2015) and regression analysis.

Regarding PCA, Nguyen (2015) examined the Integrated Drought Index (IDI) based on three indices calculated. This index employed three indices of Standard Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and Standardized Soil Moisture Index (SSI). Equations (13), (14) and (15) define IDI.

$$IDI = ay_1 + by_2 \tag{13}$$

$$y_1 = cx_1 + dx_2 + ex_3 \tag{14}$$

$$y_2 = fx_1 + gx_2 + hx_3 \tag{15}$$

of which, SPI, SPEI and SSI corresponded to x_1, x_2, x_3, respectively; y_1; y_2 are the values of the first and second main components; c, d, e and f, g, h are contribution rates.
Then, Equation (16) shows the function to obtain Standardized IDI.

$$SIDI = \frac{(IDI - \overline{IDI})}{\sigma_{IDI}} \tag{16}$$

The determination of IDI is based on the principal components analysis (PCA) introduced by Pearson (1901) and developed by Hotelling (1933). This method was quite good in grouping indices to obtain a better hybrid indicator.

1.3.3 The current situation of drought indices in the Mekong River region

The process of drought in the Lower Mekong Basin (Thailand, Laos, and Cambodia) is similar to the other regions as it occurs when the deficiency of rainfall takes place (GIZ, 2013). On the contrary, the process of drought in the Mekong Delta is more complicated due to the domination of salinity intrusion. It mostly occurs in the dry season from January to June. It starts with the low level of rain in the upstream (Laos and Cambodia) causing the reduction in the water volume flowing into the MKD via Tan Chau and Chau Doc at the end of the flood season (November to December) and/or the dry period (January to April). At the same time, the low water level in the downstream also happens in combination with no rain causing droughts in the MKD. The drought induces the saline intrusion further inland and then salinity intrusion inverts its role to exacerbate the drought situation. This clarification is the most important point to analyze and select the drought indices forwards.

In the Mekong Basin, Terink *et al*. (2011) estimated SPI, NDVI and streamflow and it is one of the rare researches on drought in the Mekong Basin. In this research, the authors also pointed out that the lack of data has imposed a challenge on drought studies in the Mekong Basin. Because of this, this study only used the 11 years data instead of 30 years or 50 years which were recommended by McKee et al., (1993) and Guttman (1999). Additionally, MRC (2005) recommended applying streamflow for the drought study in the Mekong River Basin. Yet, in both cases, there was no examination of the MKD.

In the MDK, there were estimations of the meteorological drought by calculating SPI (Tinh, 2012; Ty *et al*., 2015). Results from these studies showed the high frequency of drought in the Mekong Delta. SPI could not describe drought well, with the reason being that the most agricultural areas are irrigated agriculture while the SPI is more suitable for the rainfed agriculture areas. However, it should be remembered that some areas highly depend on rainfall for domestic use, including three coastal districts of Ben Tre. These areas are far from fresh water sources and lack of groundwater so that rainfall harvesting has played a crucial role in the dry season for domestic use.

Officially, the Decree No. 44/2014/QĐ-TTg issued on 15/8/2014 is the main document related to the classification of drought in Vietnam. In this document, deficiency of the monthly rainfall for periods of three and six months is the main indicator for drought monitoring. The other indicator is the water availability but it is unclear. Furthermore, it mentioned that saline intrusion is an aspect needed to consider for drought monitoring.

The review given above is the basis for the selection of indices calculated in this study. Additional consideration includes the fact that SPI, SDI and SPEI represent different types of the drought and obtained in the same manner based on standard deviation. Ideally, they should be evaluated separately, compared, and combined into a hybrid indicator for drought monitoring in Ben Tre. It is essential to point out that these indices obtained from the monthly input data that could turn to be a disadvantage. This is because drought could occur in the short period or/and in the middle of two consecutive months.

1.4 The purposes of study

The purpose of this study is to gain more knowledge in drought study in order to suggest an appropriate method for drought management and measures to alleviate drought consequences in the Mekong Delta in Vietnam. Through a literature review on drought study, river basin characteristic analysis, and data collection this study aims at the following two specifics purposes:

- To seek the suitable index and/or indicators for ensuring timely and accurate assessment of the impacts of drought;
- To define an inventory of data for Drought Management.

2 Study area

2.1 The Mekong River Basin and Mekong Delta

The Mekong River originates in Tibetan Plateau, China and runs through six countries with the total length of 4,800 km via the Mekong Delta, Vietnam before ending at the East Sea. The total area of the basin is about 795,000 km^2 and is divided into two parts of Upper Mekong Basin (China, Myanmar) and Lower Mekong Basin (LMB) including Laos, Thailand, Cambodia, and Vietnam (MRC, 2009). The character of the Mekong River is that the flood discharge is 30 times higher than that in the dry season.

The Mekong River Committee (MRC) classified Lower Mekong Basin into 10 sub-areas, and the Mekong River Delta, the final part, spreads over 5.850 million ha including 2.334 million ha of Cambodia and 3.515 million ha of Vietnamese part (MRC, 2011).

In the Vietnamese administrative system, the Mekong Delta is located in the southern Vietnam within the total area of 3.9 million ha and its population is about 17.5 million. It has a naturally suitable condition for agricultural cultivation with 1.9 ha of agricultural land; it has contributed up to 50% of paddy production, and 70% of aquacultural production (SIWRP, 2011). For these reasons, the Mekong Delta plays an important role in the agricultural sector and food security of the Vietnam. In addition, it has a distinguished ecosystem of mangrove forests and wetlands.

The Mekong Delta is predicted to be one of the most vulnerable areas to climate change and sea-level rise in the world (IPCC, 2007). One of the reason is that it has a low terrain with nearly 600 km of the seashore and its main source income comes from agricultural activities. Specifically, in the climate change and sea level rise scenarios carried out by Ministry of Natural Resource and Environment (MONRE) stated that 40-50% of the Mekong Delta would be affected by sea water with saline concentration $\geq$ 4 parts per thousand (ppt) and inundation when sea level rise by 12 cm and 30 cm in 2020 and in 2030 respectively (MONRE, 2009).

Ben Tre is a typical case of the Mekong Delta with its large portion of land use used for agricultural activities (80%). Ben Tre is the most vulnerable to climate change and sea level rise among thirteen provinces in the MKD (JICA, 2013). Recently, it has faced water shortage and salinity intrusion more frequently and severely. Historically, the Mekong Delta and Ben Tre Province recorded droughts in 1998, 2004-2005, 2010, 2013, and especially in 2016 when the worst drought event in 90 years occurred. The information about drought in the MKD before 1998 is limited. Some drought events occurred in 1981, 1983, 1984, 1985, 1987, 1992, 1994 and 1998 during summer from April to June (ADPC, 2007). However, it is difficult to find the information related to the statistical damages.

To date, Ben Tre has received efforts from various projects and studies in order to deal with climate change and sea-level rise and water management issues. However, drought is only recommend for further study. There are various reasons for the difficulty in studying drought in the Mekong Delta and Ben Tre, and the complexly hydrological regime is one of the reasons.

In the short term, the embankments and sluice gates that are under construction could control saline intrusion. Nevertheless, the water shortage in the prolonged dry season is the main challenge. There seems to be a consensus that drought will happen in the Mekong Delta more frequently and severely due to climate change and development activities.

2.2 Ben Tre Province

2.2.1 Location

Ben Tre is a coastal province among 13 provinces in the Mekong Delta. It spreads from 9 degrees, 47 minutes to 10 degrees, 20 minutes in the north latitude; and from 105 degrees, 55 minutes to 106 degrees, and 47 minutes in the east longitude. It is located in the south Ho Chi Minh City, and it takes 2 hours from Ho Chi Minh City by bus (Figure 1).

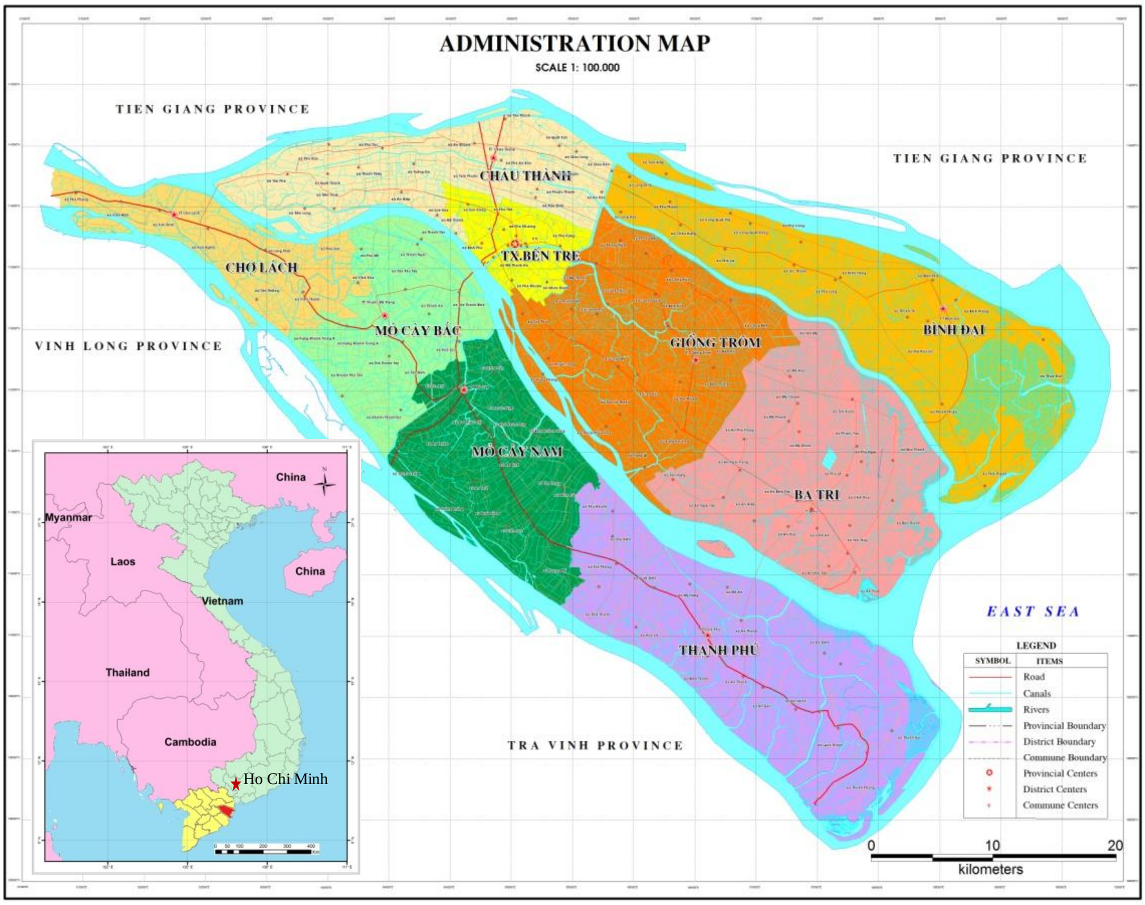

Figure 1: Administrative map of Ben Tre Province (modified from SIWRP, 2016)

2.2.2 Area, population, and administrative units

The area of Ben Tre is 235,983 ha and it has a high density of large rivers and canals. Administratively, Ben Tre is divided into one City (Ben Tre City) and eight districts, under of which there are 10 towns and 164 communes. This system is similar to all of other provinces in the MKD. In terms of geography, Ben Tre includes two islands, namely North Ben Tre (Ben Tre City, Chau Thanh, Binh Dai, Ba Tri and Giong Trom) and South Ben Tre (remaining 4 districts in the south).

The total population is 1,262,205 in 2014. Like other provinces in the Mekong Delta, most of the residents live in the rural area (the rural residents account for nearly 90%) and their incomes mainly depend on agricultural activities. Because of this, their livelihood is exposed to the negative impacts of drought and climate change.

The water resource is a factor that affected to population density; the upstream districts have a higher density population than that of the three coastal districts. In the upstream districts, where fresh water dominated, the population density ranges from 653 to 729 persons/km^2 (Cho Lach, Chau Thanh) while this number in the coastal districts, which is dominated by saline water, varies between 302 and 311 (Binh Dai, Thanh Phu). The sensity of the whole MKD and that of the country is 430 and 263 persons/km^2, respectively and are shown in Table 4 (SIWRP, 2016).

Table 4: The area and population of districts in Ben Tre Province

District/City	Area	Population	Density	Of which	
	(ha)	(person)	(person/ km^2)	Urban (person)	Rural (person)
Total	235,983	1,262,205	535	129,179	1,133,026
Bến Tre City	7,112	120,749	1,698	65,826	54,923
Châu Thành	22,507	164,037	729	3,894	160,143
Chợ Lách	16,763	109,387	653	7,665	101,722
Mỏ Cày Bắc	22,208	145,966	657	11,781	134,185
Mỏ Cày Nam	15,818	109,151	690		109,151
Giồng Trôm	31,316	167,203	534	10,021	157,182
Bình Đại	42,151	130,998	311	10,029	120,969
Ba Tri	35,838	187,161	522	10,562	176,599
Thạnh Phú	42,270	127,553	302	9,401	118,152
The MKD	4,057,600	17,506,774	430	4,307,971	13,198,803

2.3 Natural conditions

2.3.1 Climate

➢ Temperature

The climate in the Mekong Delta, also Ben Tre, is the humid tropic and dominated by the Asian monsoons. Its mean temperature is stable through the year from 24 to 29°C and it is not different in the mean temperature between the hottest month in April (29.6°C) and the coldest month in January (24.4°C). In a year, the highest temperature is about 36.3°C and the lowest is in the order of 18.0°C. The sunshine hour is about 2.650 hours/year.

Figure 2 shows the monthly mean temperature data of Ben Tre Hydro-Meteorological Center (BTHMC) for the last three years.

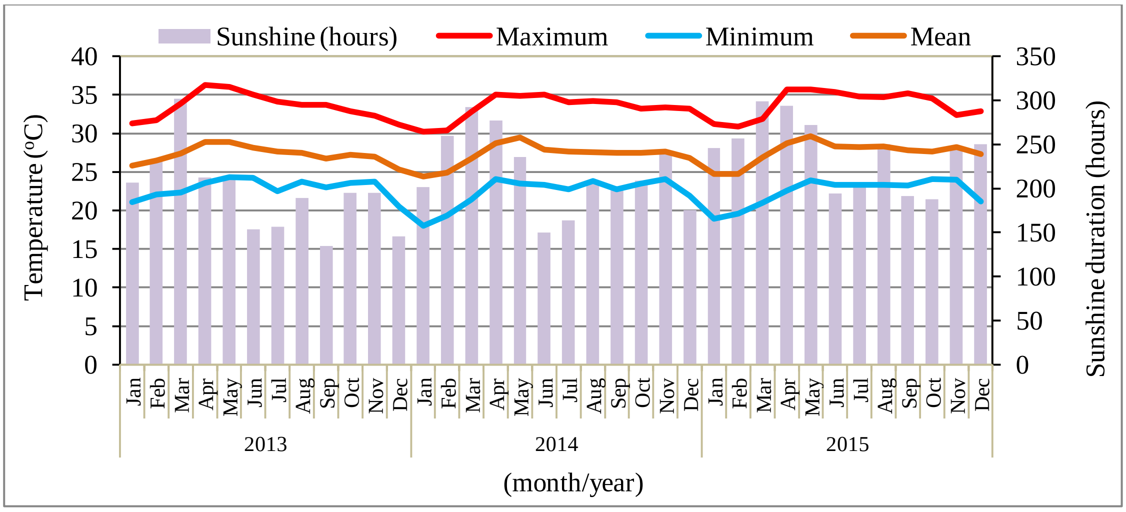

Figure 2: Monthly mean temperature and the sunshine duration in Ben Tre from 2013 to 2015

➢ Rainfall

The annual rainfall is in the order of 1,000 to 2,300 mm depending on years (Figure 3). Meteorologically, the wet season from May to November accounts for 85 to 90% of the annual total rainfall, with remaining 10 to 15% for the dry season from December to April. In some years, there is no rain from January to March causing water shortage and salinity intrusion (World Bank, 2016). The potential evaporation in the dry season is in the range from 4 to 6 mm per day while in the dry season it ranges from 2.5 to 3.5 mm per day.

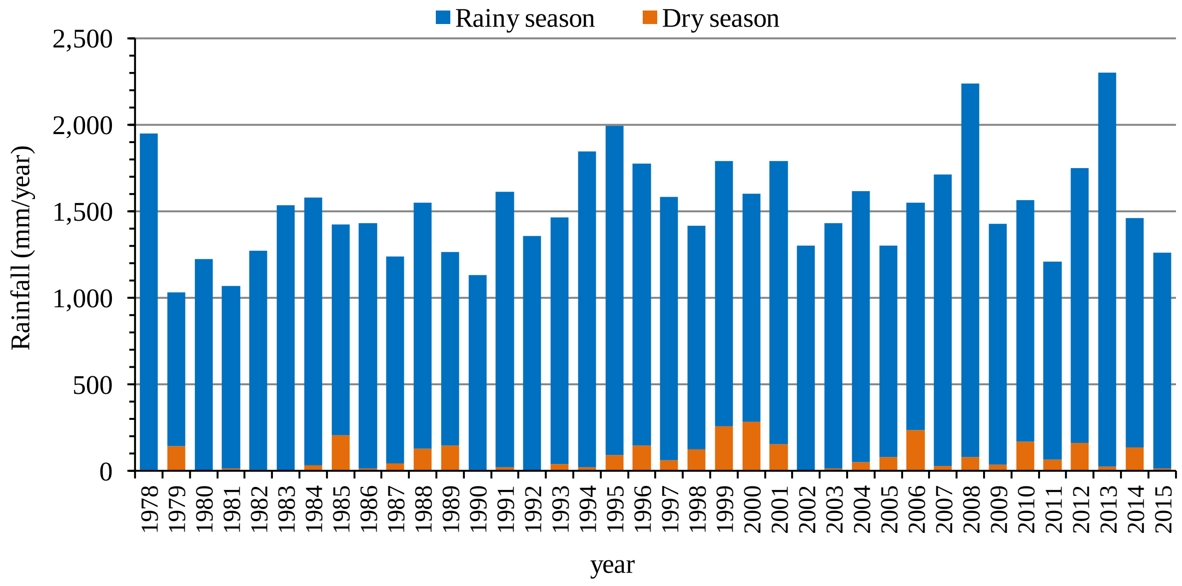

Figure 3: Annual rainfall in Ben Tre from 1978 to 2015 (Ben Tre Hydro-Meteorological Center)

➢ Humidity

The humidity is relatively high and the monthly average ranges from 76 to 86%. Figure 4 illustrates the monthly data from 2012 to 2014 measured at BTHMC. It also changes seasonally. In the rainy season, humidity is higher than in the dry season by about 15%.

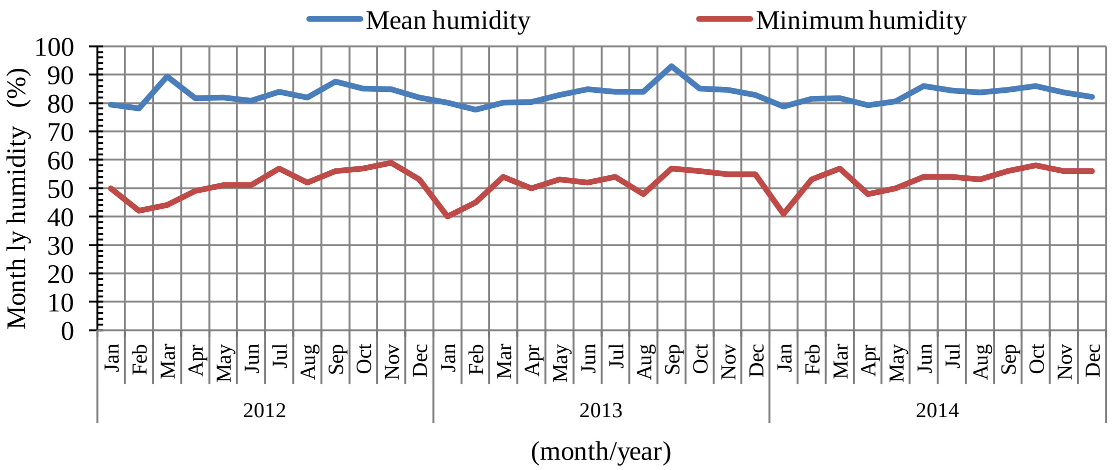

Figure 4: Humidity data in Ben Tre from 2012 to 2014

➢ Winds

The wind intensity and direction play an important role in the Ben Tre. They affect to rainfall and especially tide regime. In the rainy season (from May to September), the westerly and the south-westerly winds dominate with daily maximum wind speed about 6 to 7 m/s in July to September. In the dry season (December to April), the north-easterly and the east winds are prominent with near-constant wind speeds in the order of 4 to 6 m/s (Figure 5).

The dry season wind direction is onshore. Therefore, winds exacerbate the penetration of seawater into the MKD as one of the causes of drought phenomenon in Ben Tre and the MDK, especially in combination with spring tides.

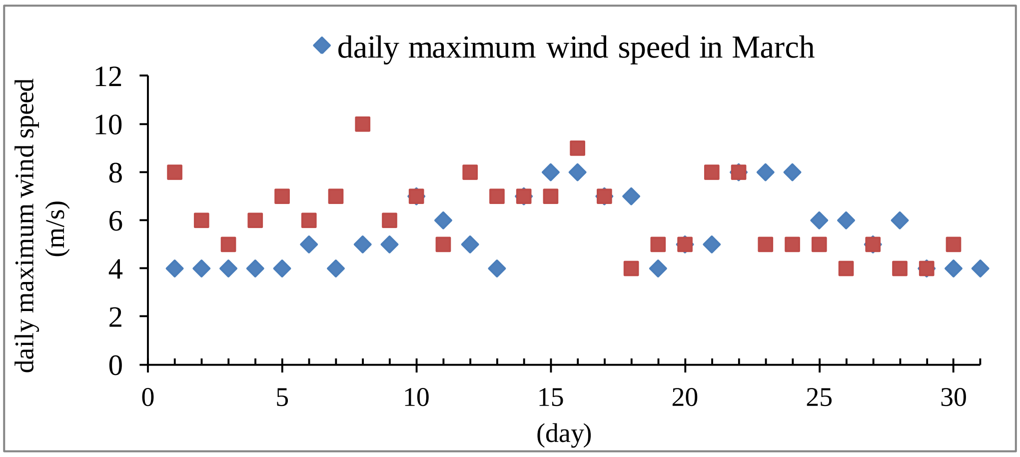

Figure 5: Daily maximum wind speed in the dry season in Ben Tre in 2011

2.3.2 Topography

Ben Tre is a coastal province; therefore, its terrain is low-lying and flat. Most of the area of Ben Tre (69.83%) is lower than 1 m above sea level (SIWRP, 2011). The upstream of the province has a higher elevation than other parts ranging from 1.8 to 2 m above sea level. However, sand dunes in the coastal zone have the highest elevation in the order of 3 to 5 m above sea level (Figure 6). The presence of sand dunes has created many low-lying areas in the center which are prone to inundation or backwater.

Ben Tre accounts for 50% of the total eight estuaries of the MKD, that explain why its landform has changed significantly year by year due to erosion and accretion.

Table 5: Altitude distribution of Ben Tre Province

Elevation (m)	Areas (ha)	Proportion (%)
less than 1	161,661	69.83
1 to 2	40,660	17.56
more than 2	1,336	0.58
rivers	27,845	12.03
Total	231,502	100.00

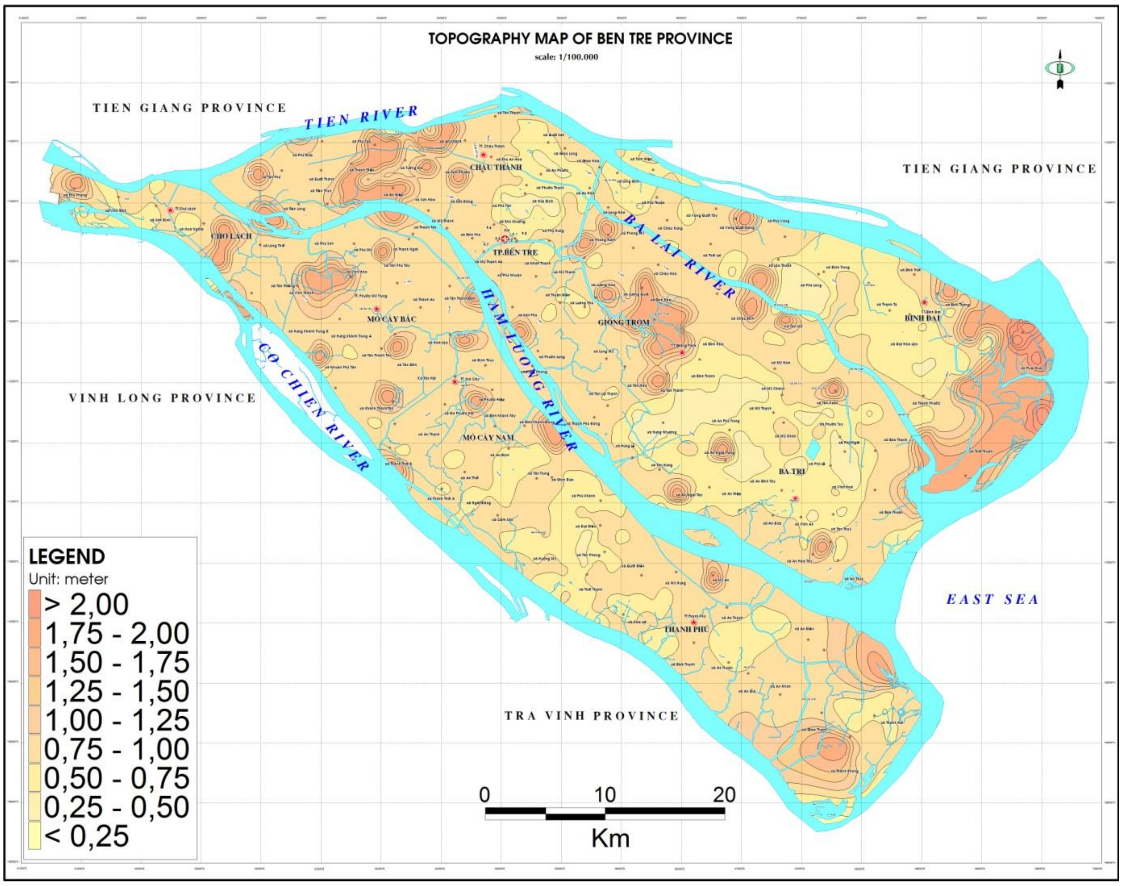

Figure 6: Topography map of Ben Tre Province (modified from SIWRP, 2016)

2.4 Agricultural sector and land use

Ben Tre is similar to the whole of MKD as the agriculture is the main economic activity. According to the statistical yearbook of Ben Tre published in 2015, the agricultural sector in Ben Tre contributed to 44% of the gross domestic production (GDP).

Of 235,983 ha of the province, 179,696 ha (75%) is used for the agricultural sector. The main cultivations are paddy fields, orchards, and brackish aquaculture (Table 6).

Table 6: Statistic on land use in Ben Tre in 2015

Agricultural land	Areas (ha)	Proportion (%)
Paddy	38,269	21%
Fruits	33,497	19%
Coconut	61,460	34%
Forests	7,055	4%
Aqua-land	26,648	15%
Other	12,767	7%
Total	179,696	100%

The variety of fruits with the total area of 33,497 ha are distributed in the north of the province where fresh water is abundant. Of 26,684 ha of aquaculture, 80% is used for brackish aquaculture in the coastal area, mainly shrimp cultivation. The total area of paddy is 38,269 ha, including 19,280 triple crops and 14,212 double crops, planted in the central area (Figure 7). Therefore, these numbers reveal that a large amount of water has been used for irrigation.

It is necessary to emphasize that triple paddy is a challenge to water management in the context of drought. This rotational paddy not only degrades soil quality but also generates pressure on water management in the dry season. The reason is that the triple paddy includes one main season in the cropped calendar (Winter-Spring) from December-January to March-April that has faced the threat of water shortages and salinity intrusion every year.

One of the individually agricultural characteristics of Ben Tre is that the coconut tree is widely planted in a large area of 61,460 ha. This is because coconut is more tolerant to higher saline concentration than other crops. Coconut production will be affected if the salinity level is above 4.0 ppt (JICA, 2016).

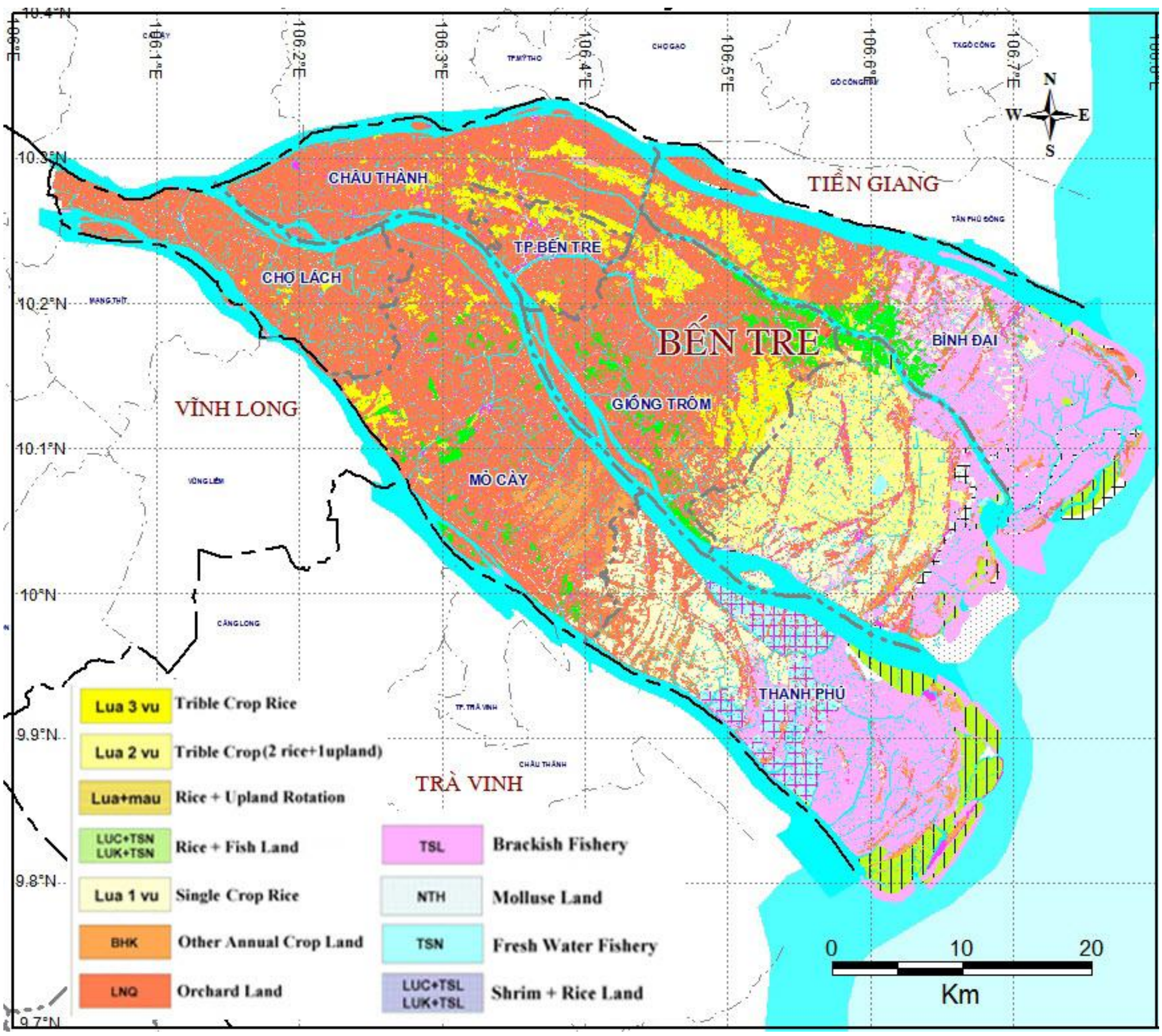

Figure 7: The map of land use of Ben Tre **(**modified from SIWRP, 2016)

2.5 Water use and water management

2.5.1 Water use

➢ Domestic use

Ben Tre Water Supply One-member Limited Liability Company (Btre Waco) carries out water supply in the urban area. This company is running four plants with the total capacity is 52,800 m^3/day and it is exploited about 49,300 m^3/day. The number of customers has doubled from 22,015 in 2005 to 59,684 in 2015, of which 40,000 customers living in Ben Tre City (JICA, 2016). Table 7 reveals the information regarding water supply for Ben Tre City. A small proportion of people who are living in the rural areas use tap water supplied by private sectors or the Center for Rural Water and Environmental Sanitation under DARD. Remaining use water directly from rivers and canals; therefore, it is difficult to identify water amount used for domestic in the rural area.

To estimate water uses in such cases, the Vietnamese standard has been applied. As an example, the standard named TCXDVN 33:2006 is shown in Table 8.

Table 7: The capacity of main water supply plants in Ben Tre

Water plant (renovated year)	Source of Water	Capacity (m^3/day)		Affected by salinity
		Designed	Operating	
Son Dong (2011)	Surface water of Thanh Binh canal, Ma River, Ham Luong River, 50 km from the sea.	31,900	38,000	March to May
Huu Dinh (2011)	Ground water of boreholes at depth of 300-320 m	10,500	3,500	when exploited > 6.000 m^3/day and night
Cho Lach (2014)	Surface water on Tien River 80 km from the ocean	4,400	2,400	No
Luong Quoi (2014)	Surface water of Vong canal-Chet Say canal (from Tien river to Ham Luong River), 35 km from the sea.	6,000	5,400	February to July
Total		52,800	49,300	

Table 8: Domestic water demand according to the Standard TCXDVN 33:2006

No	Water using subject and water supply components	Stage	
		2010	2020
I.	Urban area level II, level III		
	a) Domestic use water		
	- Water supplying standard (l/person/day): + Urban	120	150
	+ Rural	80	100
	- Proportion of the having access to water supply (%):		
	+ Urban	85	99
	+ Rurual	75	90
	b) Public service water (watering, street cleaning, fire); in % of (a)	10	10
	c) Industrial urban services water; in % of (a)	10	10
	d) Industrial zone water (m^3/ha/day)	22- 45	22- 45
	e) Leaking water; in % of (a+b)	< 25	< 20
II.	Urban area level IV, level V, Rural residential area		
	a) Domestic use water		
	- Water supplying standard (l/person/day):	60	100
	- The proportion of the having access to water supply (%):	75	90
	b) Services water; in % of (a)	10	10
	c) Leaking water; in % of (a+b)	< 20	< 15

➢ Industrial use

In Ben Tre, seven industrial zones have been set up; however, only three zones, An Hiep, Giao Hoa and Giao Long zones in the Chau Thanh District, nearly Ben Tre City are in operation. Table 9 illustrates the areas of each zone. In fact, the industry in the Ben Tre slowly develops and mainly connects with the agricultural sector. The industry sector consumes the smaller amount water in comparison with the other sectors.

Table 9: The scale of industrial zones in Ben Tre by 2016

Name	Address	Area (ha)	Products
An Hiep Industrial Zone	An Hiep Commune, Chau Thanh District	72/120	Agricultural products, construction products,
Giao Long Industrial Zone	An Phuoc Commune, Chau Thanh District	100	Agricultural products, computer products, ceramics products
Giao Hoa Industrial Zone	Giao Hoa Commune, Chau Thanh District	270	Agricultural products, mechanical products

Source: Ben Tre Industrial Zone Authority

In An Hiep Industrial Zone includes nine companies using 47,000 m^3/day in total. There are still vacant lots in this zone and the areas used are 72 of the 120 ha total area.

The Giao Long Industrial Zone has 22 companies that using more than 103,000 m^3/ day in total (JICA, 2016). Giao Long zone does not have data so its water use could be estimated by means of the standard in Table 3.2. However, the number used from statistics above is 8 to 14 times higher than the standard.

➢ Agricultural use

In the MDK and Ben Tre, there is no data on the amount of water used by the agricultural sector, including irrigation for paddy fields, orchards, livestock, and fresh aquaculture. The main reason is that water is free to all the people excluding tap water. Farmers who use surface water directly from rivers, canals and groundwater are not being charged any fee. For livestock, Table 10 shows the Vietnamese standard 14 TCN-87 for the estimation of water demand for livestock.

Table 10: Livestock water demand according to the Standard 14 TCN-87

Items	Basic demand (litre per day)
Buffalo-Ox	60
Pig	15
Goat	10
Poultry	1

To identify the water used by paddy fields and upland crops, the water use calculation method has been applied based on land use, cropped stages, cropped calendar and technical standards (a part of agricultural extension). The result from SIWRP (2009) in Table 11 based on this method could be used as a reference. Table 11 partially describes the challenge of the water supply system in Ben Tre, as it shows that the water demand in the dry season is significantly high compared to other periods. It means that the cropped patterns and cropped calendar play a certain role to aggravate the drought situation.

Table 11: The estimation of water uses for paddy and upland crops in Ben Tre in 2015

Months	(m^3/s)	Months	(m^3/s)	Months	(m^3/s)
January	34.99	May	12.29	September	8.18
February	44.01	June	14.52	October	1.89
March	33.40	July	12.12	November	13.25
April	23.18	August	1.87	December	28.43

2.5.2 Surface water

Regarding hydrology, the hydrological season for the Lower Mekong Basin is determined based on the discharge at Kratie Station, and the dry season lasts from late November to late May while flood season is from the end of June to early November. There are two transitional seasons alternate between these periods (Beilfuss and Triet, 2014). However, the hydrological season in the Mekong Delta is still a matter of argument.

It is similar to the Mekong Delta; Ben Tre has a high density of rivers, canals because of their advantages in surface water availability. In the MKD, the Mekong River splits into and generates eight estuaries at the end points (in the past it was nine as Nine Dragons in Vietnamese). Four in eight estuaries are in Ben Tre Province, which are My Tho (Tien), Co Chien, Ham Luong, and Ba Lai River. Additionally, there are many main, secondary, and interior field canals (Mekong Delta canal classification) connecting with these rivers to create the complicated channel network. This system allows surface water to reach to fields easily; however, it also brings salinity into agricultural lands in the dry season.

Table 12: Dimension of main rivers in Ben Tre Province

Rivers	Length (km)	Width (m)	Deep (m)
My Tho	90	1,500 ÷ 2,000	
Co Chien	80		
Ham Luong	70	1,200 ÷ 3,000	12 ÷ 15
Ba Lai	55	200 ÷ 300	3 ÷ 5

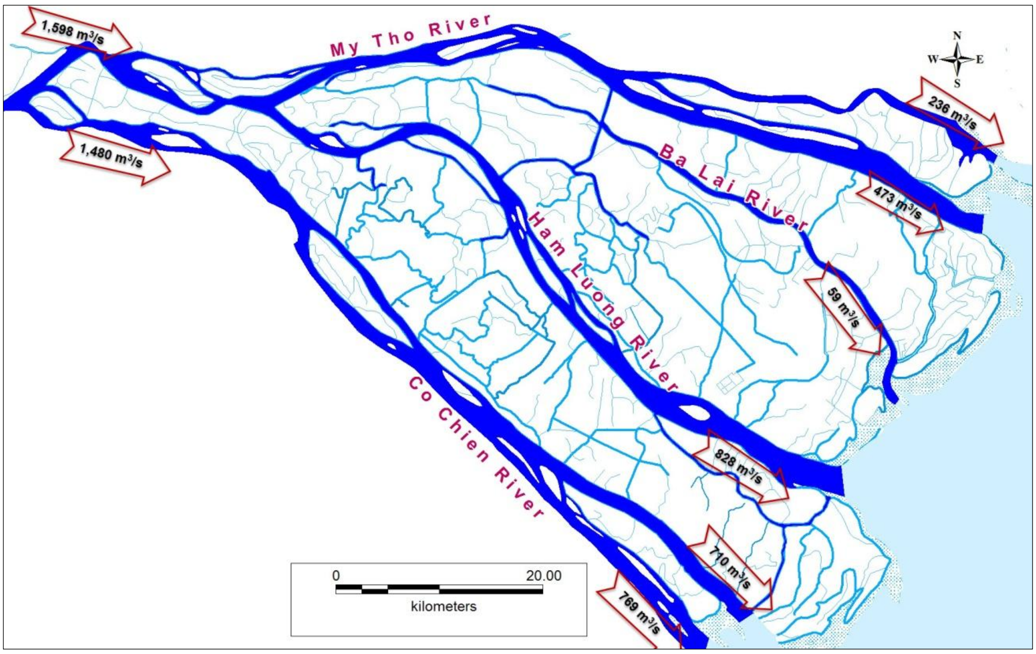

Figure 8: The map of rivers and main canals in Ben Tre (modified from SIWRP, 2016)

In the dry season (December to April), the discharge of Mekong River flows to Ben Tre via My Tho River and Co Chien River are 1,598 m^3/s and 1,480 m^3/s, respectively (Figure 8). This amount of water would exceed the water demand. However, the combination of incoming spring tide and strong onshore winds could dominate and generate the inverse flows that bring salinity to inland. Consequently, in the dry season (especially March and/or April) 90% of the areas of Ben Tre is surrounded by saline water with a concentration above 1 ppt. In flood seasons (May to November), the discharge of My Tho River and Co Chien River are 6,840 and 6,000 m^3/s. This surplus of water puts salinity back to sea so that ends salinity intrusion and the dry periods.

2.5.3 Groundwater

In Ben Tre, groundwater can be found in seven aquifers distributing from 0 to 700 m beneath the land surface (MONRE, 2016) as listed in Table 13.

Table 13: The list and thickness of aquifers in Ben Tre

Aquifers (abbreviation)	Thickness of aquifers (m)		Average deep (m)
Holocene (qh)	Minimum	2.0	17.2
	Maximum	35.0	
	Average	17.2	
Upper Pleistocene (qp_3)	Minimum	22.5	64.0
	Maximum	75.0	
	Average	46.8	
Upper-Middle Pleistocene (qp_{2-3})	Minimum	20.0	109.5
	Maximum	73.0	
	Average	45.5	
Lower Pleistocene (qp_1)	Minimum	7.0	146.0
	Maximum	86.0	
	Average	36.5	
Middle Pliocene (n_2^2)	Minimum	32.0	206.3
	Maximum	125.0	
	Average	60.3	
Lower Pliocene (n_2^1)	Minimum	40.0	285.0
	Maximum	131.0	
	Average	78.7	
Upper Miocene (n_1^3)	Minimum	39.0	377.7
	Maximum	200.1	
	Average	92.7	

The potential exploitation reserves are 213,727 m^3/day (fresh groundwater) and 5,511,282 m^3/day (brackish groundwater). The potential exploitation reserves of fresh groundwater in Ben Tre is limited in compared to other provinces; for example, Long An is adjacent to Ben Tre with 3,165,175 m^3/day.

The total number of wells in Ben Tre is 2,653 with total exploitation amount is 17,987 m^3/day (10-15% of its adjacent provinces) (Table 14). This number increased slowly compared to data in 2007 (DONRE, 2009), as the total number of wells was 2,063 with the total exploitation rate was 6,683 m^3/day. The number of wells with exploited discharge over 200 m^3/day is 2,637. Most of the wells have extracted water from shallow aquifers at a depth of 0 to 200 m beneath the land surface (MONRE, 2016).

Table 14: The number of wells dividing by aquifers in Ben Tre

The number of total wells	Divided by purposes		The number of wells divided by aquifers				
	Domestic and agriculture	Industry	qh	qp_3	qp_{2-3}	n_2^1	n_1^3
2,653	2,634	19	1,873	548	204	23	5

Table 15 shows the result of the groundwater balance estimation by MONRE (2016).

Table 15: The groundwater balance estimation in 2010 for Ben Tre

Aquifers	qp_3	qp_{2-3}	qp_1	n_2^2	n_2^1	n_1^3	Sum
Q-1	20.545	398	3.214	6.960	83.137	99.472	213.727
Q-2	4.109	80	643	1.392	16.627	19.894	42.745
Q-3	1.926	541	0	0	10.161	3.300	15.928
Q-4	2.183	-461	643	1.392	6.466	16.594	26.817

Note: Q-1 is the potential exploitation reserves (m^3/day), Q-2 is the safety exploitation rate (m^3/day) = 20% Q-1, Q-3 is the current exploitation rate (m^3/day), and Q-4 is the safety exploitation rate in the future (m^3/day).

Table 16: Groundwater quality in Ben Tre from 2005 to 2014

Name of wells	Depth (m)	Water level (m)	Salinity 2005 (mg/l)	Salinity 2010 (mg/l)	Salinity 2014 (mg/l)
G1	458.0	3.0	152	260	270
G3	315.0	3.15	95	160	380
G5	307.0	2.0	89	180	220
G7	316.0	3.0	101	300	500
G8	320.0	3.0	214	400	420
G9	316.0	2.3	174	340	400
G10	310.0	2.5	131	270	290
G11	318.0	3.0	202	600	630

This estimation partially reveals the limitation of groundwater in the Ben Tre Province. Additionally, salinity intrusion has intruded into groundwater, as the groundwater quality data (Table 16) from Ben Tre Water Supply One-member Limited Liability Company for wells located in Ben Tre City and Chau Thanh District (adjacent Ben Tre City) showed that most of the wells have a concentration of salinity exceeded Vietnamese Standards as 300 mg/l.

2.6 Future projection

2.6.1 The socio-economic development plan-a vision towards 2020

In Vietnam, each province has the social and economic development plan at the provincial level and the sector development plan; for example, agricultural development plan, for a period of five years is important to economic development. In such documents, the economic objectives and targets of the province are presented, including projected data on population and land use. For Ben Tre, these documents were published in 2011 and 2015, and they can be referenced from the governmental document named Decision No. 83/QD-TTg on the socio-economic development plan for Ben Tre Province towards 2020. The information extracted from these documents were mentioned below.

- Population

The total population of Ben Tre is predicted to be about 1,550,500 in 2020 (Table 17). The urban residents are expected to increase due to urbanization while the rural residents are projected to reduce by 125,526 people (SIUP, 2012).

Table 17: The total population predicted in Ben Tre by 2020

Years	Total	Urban	Rural
	(person)	(person)	(person)
2020 (predicted)	1,550,000	542,500	1,007,500
2014	1,262,205	129,179	1,133,026
2020-2014	287,795	413,321	-125,526

Note: (-) reduction

➢ Land use

Agricultural land predicted in 2020 would slightly change in comparison to 2014 (Table 18). Paddy areas and coconut are expected to be reduced while the area of aquaculture is planned to increase by 18,352 ha. It could be an adaptive solution to climate change and sea level rise, and saline intrusion.

Table 18: The land use projected in Ben Tre by 2020

Agricultural land	Areas (ha)	Proportion (%)	Compare to 2014
paddy	33,000	19%	-5,269
- triple crops	18,000		-1,280
- double crops	11,217		-2,995
- single crop	3,783		-994
fruits	30,000	17%	-3,497
coconut	51,400	30%	-10,060
forests	7,833	5%	778
aqua-land	45,000	26%	18,352
other	6,420	4%	-6,347
Total	173,653	100%	-6,043

Note: (-) reduction

The areas of industrial zones are expected to increase to 1,600 ha by 2020.

Base on this projection, water demand for agricultural sector would be decreased while water use of industry and urban areas would be increased in 2020.

2.6.2 Climate change projection

MONRE (2009) carried and published climate change projection for the MKD in 2009. Table 19 (temperature) and Table 20 (rainfall) illustrate the projected change for the selected scenario B2 (IPCC, 2007).

Table 19: Change in average temperature (^oC) in the MKD in scenarios B2

Variables	Times	
	Month	2020
Temperature changes (^oC)	December-February	0.3
	March-May	0.4
	June-August	0.5
	September-November	0.5

Table 20: Change in rainfall (%) in the MDK in scenarios B2

Variable	Times	
	Month	2020
Rainfall changes (%)	December-February	-3
	March-May	-2.8
	June-August	0.3
	September-November	2.6

Note: (-) reduction

By 2050, 4 ppt salinity range would affect/surround the entire province in 45 to 60 days annually and Ben Tre is one of three provinces which would be most affected by drought and water shortage (WB, 2016). Thus, the combination with the limitation of groundwater will lead to an emergency of water stress in the whole province.

3 Datasets and methods

3.1 Data collection and datasets

In Ben Tre Province, the organization which has the official mandate to hydro-meteorological observation and forecast information is the Ben Tre Hydro-Meteorological Center (BTHMC)[3]. This centre is a branch of the Southern Regional Hydro-Meteorological Center (SRHMC)[4], under Ministry of Natural Resources and Environment (MONRE). The SRHMC oversees hydro-meteorological observation and forecast in the South Vietnam, including 13 provinces in the MKD. In principle, data are collected by BTHMC and then reported to SRHMC and stakeholders daily, and they can be accessed via the website of the Department of Agriculture and Rural Development (DARD)[5].

In line with these organizations, Ministry of Agriculture and Rural Development also has some regional and provincial branches that have duties to gather hydro-meteorological data in the MKD. In the regional scale, Southern Institute for Water Resources Planning (SIWRP) and Southern Institute of Water Resources Research (SIWRR) are assigned to report on flood and salinity issues in the MKD to MARD weekly, and such information has been published on their websites[6]. In the provincial level, Ben Tre Irrigation Works Exploitation One-Member Limited Liability Company (IWEC)[7] under DARD has collected salinity data to operate and manage the waterworks in the whole province, and the salinity data can be approached from its website correspondingly; and the Irrigation and Drainage Division (IDD) has duty to reckon up the people affected and the financial loss caused by droughts and other natural disasters. The data used were gathered and referenced from the above-mentioned organizations, and Figure 9 illustrates the relation and levels of them.

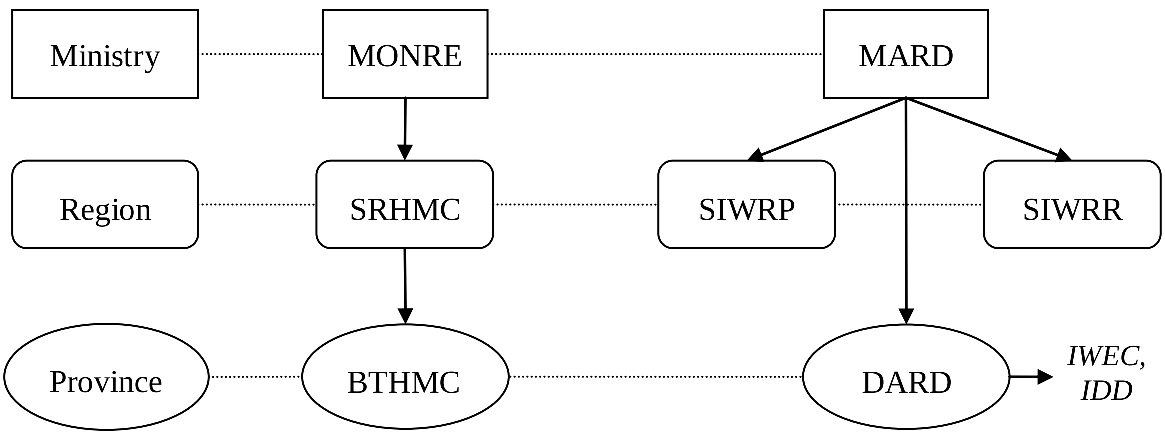

Figure 9: The institutions related to the water sector in Ben Tre and the MKD

[3] Trung tâm Khí tượng-Thủy văn tỉnh Bến Tre; Address: 131 Đoàn Hoàng Minh, Phường 6, Tp. Bến Tre.
[4] Đài Khí tượng-Thủy văn khu vực Nam Bộ; Website: http://kttvnb.vn
[5] Sở Nông Nghiệp tỉnh Bến Tre; Website: http://www.snnptnt.bentre.gov.vn
[6] Viện Quy hoạch Thủy lợi miền Nam (http://www.siwrp.org.vn); Viện Khoa học Thủy lợi miền Nam (http://www.siwrr.org.vn).
[7] Công ty TNHH MTV Khai thác công trình thủy lợi Bến Tre; Website: http://ctythuyloibentre.com

Regarding data, the meteorological data are collected at BTHMC that is located in the Ben Tre City. This centre has been invested on equipment to collect data automatically.

Table 21: The data availability used to apply for Ben Tre

Stations	Sources	Variables	Periodic	Coverage
Ben Tre	BTHMC	Meteorological data	Daily	1978 to 2016
Tan Chau	SRHMC, SIWRP	Streamflow	Hourly	1998 to 2015
Chau Doc	SRHMC, SIWRP	Streamflow	Hourly	1998 to 2015
Huong My	SRHMC, SIWRR	Salinity (30km from sea)	Hourly	1998 to 2016

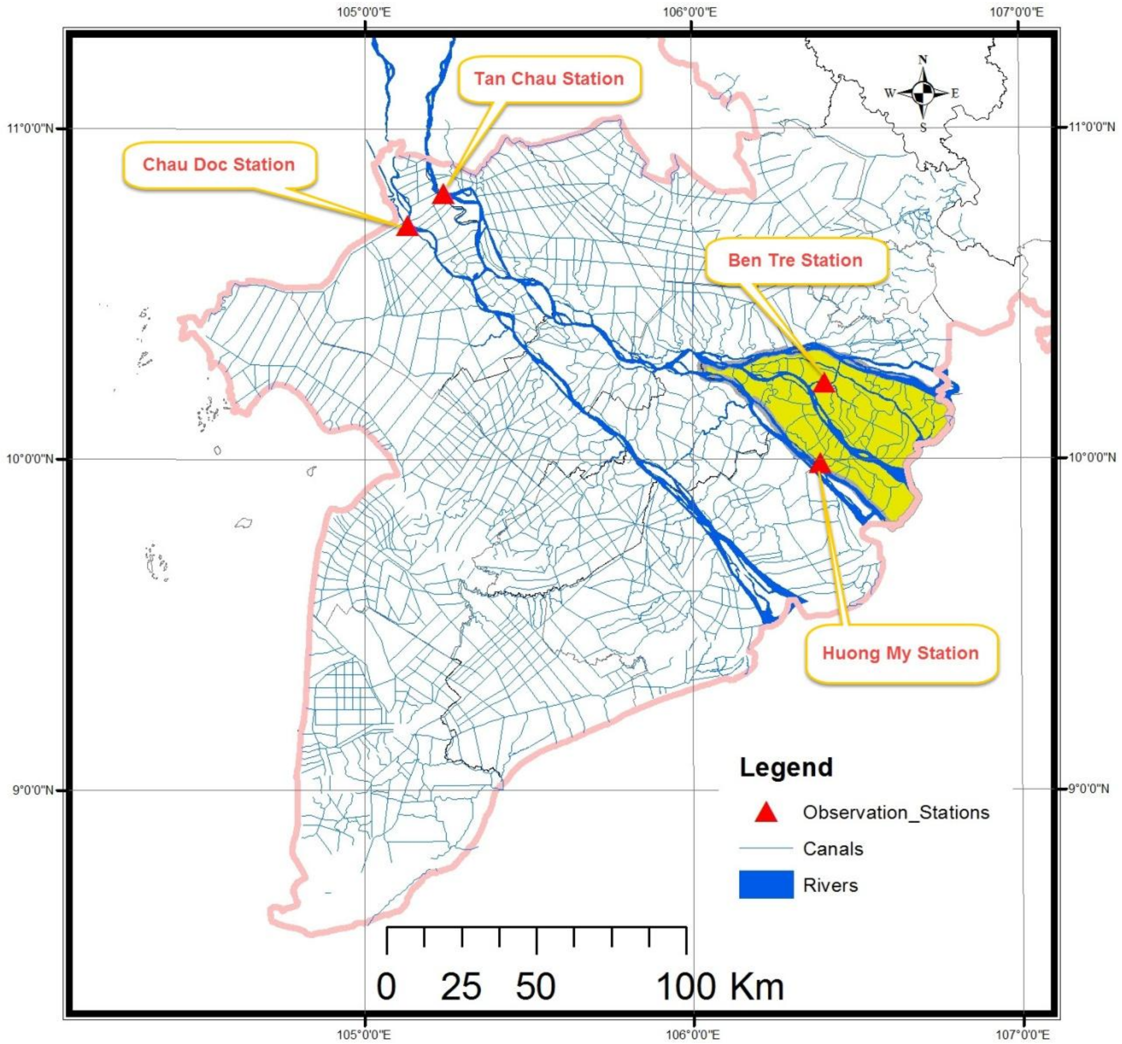

Figure 10: The location of observation stations

Hydrological data at Tan Chau and Chau Doc also have been measured automatically (hourly). Salinity has been measured three or four times per month in the dry season based on the lunar calendar during a certain spring tide. It also has been obtained at three layers; surface, middle and riverbed; however, it is not much different due to characteristics of the MKD. Salinity data have been recorded hourly since 2004.

The data on the impacts of droughts are still inadequate and mainly related to the agricultural and water supply sectors while other sectors have been neglected. Statistics of drought damages could be seen in some documents (Oxfarm, 2008; WWF, 2012; WWF, 2013; GIZ, 2013; Renaud, 2015; Le, 2016; Nguyen, 2017). Alternatively, the other source to obtain data related to impacts of droughts, especially the 2016 drought event, in the Mekong Delta is the UN in Vietnam[8]. However, the challenge is the differences between data on impacts, duration, and intensity of droughts from various sources. To fill this gap, the data from Irrigation and Drainage Division, DARD, Ben Tre that has a governmental duty to evaluate and report on the natural disaster damages, including drought and saline intrusion were used to classify the intensity of drought forwards. In theory, drought indices have been developed to describe the areal extent of droughts so that this study utilized the statistics on the affected areas. In the Ben Tre and the MKD, there is no a clear classification standard of drought; thus, the determination of severe and mild drought is based on affected areas (Table 22) and references. Hereafter, in this document, the historical severe drought years referred to 1998, 1999, 2005, 2010 and 2016; and the mild drought years referred to 2002, 2004, 2007, 2011 and 2013 (Table 22).

Table 22*:* Historically recorded data in drought damages in Ben Tre

Year	Affected Area (ha)	Damage Cost (VND billion)	Water shortage (household)
1998	33,613	119	
1999	40,669	67	
2002	20,292	20	50,000
2004	9,671	12	16,131
2005	53,395	570	112,093
2006		0.08	4,000
2007	450		
2010	33,924	197	
2011	10,063	560	
2013	13,078	80	84,900
2016[9]	29,000	1,500	83,000

[8] http://www.un.org.vn
[9] Data in 2016 was estimated at March 2016

3.2 Methods

The statistical Z-score (standardized deviation) (Equation 17) associated with the standard normal distribution was selected for the estimation of drought indices. This method is suitable for the short record and missing data, easily obtained without fitting data, and widely applied for most of the drought indices. In other words, because the data length is short (17 years of streamflow data and 12 years of salinity data), an assumption is that data follow a normal distribution. Also, the results from this method is similar (linear coefficients R^2 ranking 0.965 to 0.996 depending period of 1 month, 6 months, 9 months, or 12 months) to other standardized indices with gamma fitting data (Wu, 2001). Guttman (1999) recommended this approach as a basic step of calculating indices. Briefly, the variables were used to calculate Z-score of the cumulative streamflow, rainfall, and evapotranspiration for the target periods. Afterwards, indices are obtained based on the standard normal distribution (Van, 2015). In fact, this is the same as Equation (1) for SPI and Equation (10) for SDI.

$$Z_i = \frac{X_i - \bar{X}}{s}; of\ which: \bar{X} = \sum_{i=1}^{n} \frac{X_i}{n}\ and\ s = \sqrt{\sum_{i=1}^{n} \frac{(X_i - \bar{X})^2}{n-1}} \qquad (17)$$

The disadvantage of this method has been reported to underestimate the severity of drought in some periods. The advantage is that the comparison of different variables would be accurate and not be affected by the length of data unlike other standardized indices with gamma fitting data such as SPI and SPEI (Wu, 2001). This is because, the change in the lengths of the record leads to variance in the shape and scale parameters of the gamma distribution in the case of SPI (Mishra, 2010). Furthermore, this method is proposed to maintain the statistical consistency of variable examined in order to develop a hybrid indicator forwards that was pointed out by Steinemann (2006).

The process of calculation includes four steps. First, the indices were obtained from Equation (17). The next step was the qualitative analysis in which the indices calculated for the different periods were compared with the timing of historical years. Then the promising indices were selected and used to conduct the correlation analysis with affected areas by droughts in Ben Tre. The final step was to recommend the suitable index for drought management in Ben Tre from promising results.

Based on this concept and input data, the indices selected for this study followed Standardized Precipitation Index (SPI), Streamflow Drought Index (SDI), and Standardized Precipitation Evapotranspiration Index (SPEI). For SPI, the rainfall is X in Equation (17). For SDI calculation, the cumulative of streamflow is X in Equation (17). For SPEI, the difference (Di=P-E) between rainfall (P) and evapotranspiration (E) is X in Equation (17). Evapotranspiration (E) was obtained from Equation (8). The detailed steps to obtain these indices were respectively explained in the articles (Kumar *et al.*, 2009; Serrano *et al.*, 2012; and Serrano *et al.*, 2010). Herein, these indices were calculated for overlapping time periods of one month, three months, six months, nine months, and twelve months. To figure out the promising indices, the correlation analysis was conducted between the results of indices calculated with the historical drought impacts as areas affected, financial loss, the number of households suffered from water shortage, and salinity data recorded in Table 22.

Figure 11 illustrates the process of calculation.

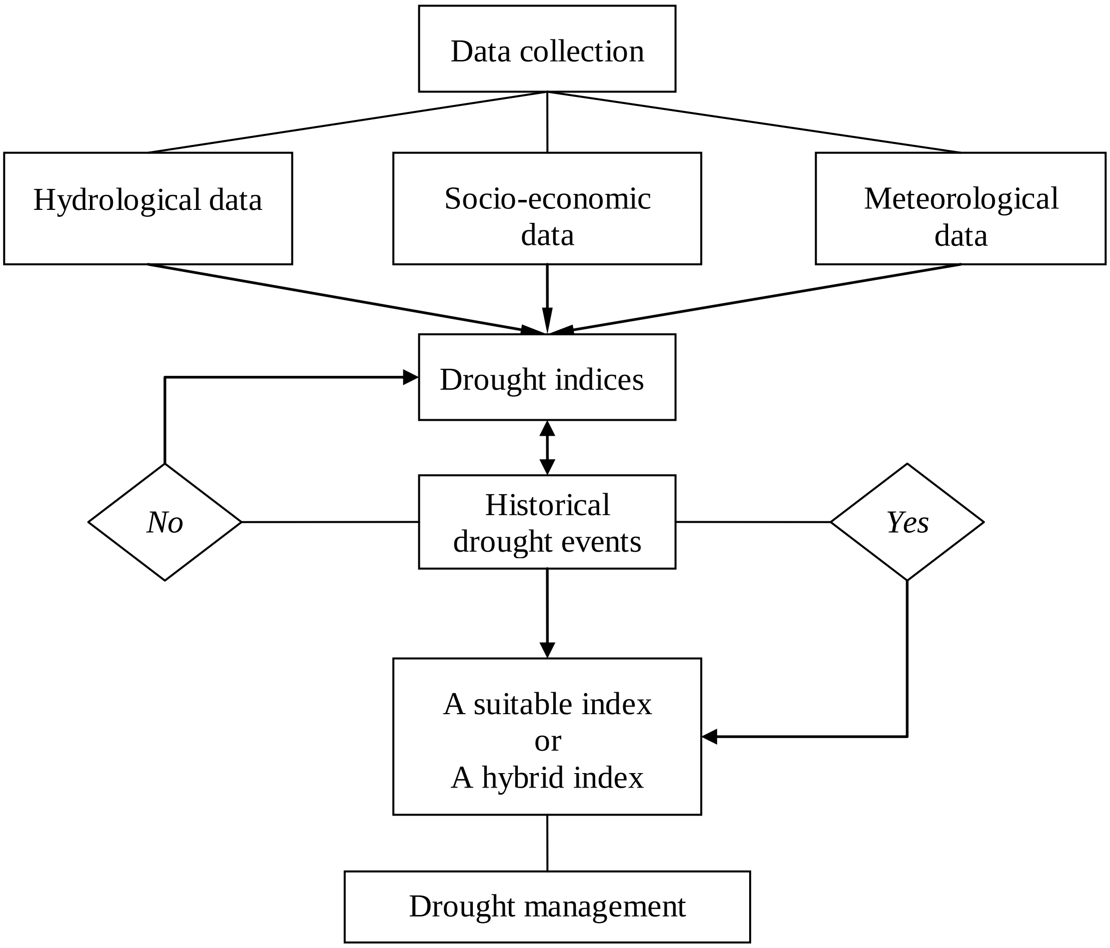

Figure 11: The flow chart of the study

4 Results and discussion

4.1 Standardized Precipitation Index

4.1.1 Results of SPI for different periods time

➢ One-month period for Ben Tre Station

From January to March, SPI-1 did not reproduce droughts well; there is not much difference between normal years and drought years (blue arrows[10]) (Figure 12). In other periods only SPI-1 (May) and SPI-1 (June) showed the good responded patterns to severe historical droughts in 1998, 1999, 2005 and 2010 (Figure 13). These results are similar to the previous study (Tinh, 2012) that is the meteorological droughts in the MKD are often seen at the end of dry season. It revealed that the extended dry seasons would have aggravated the severe historical droughts.

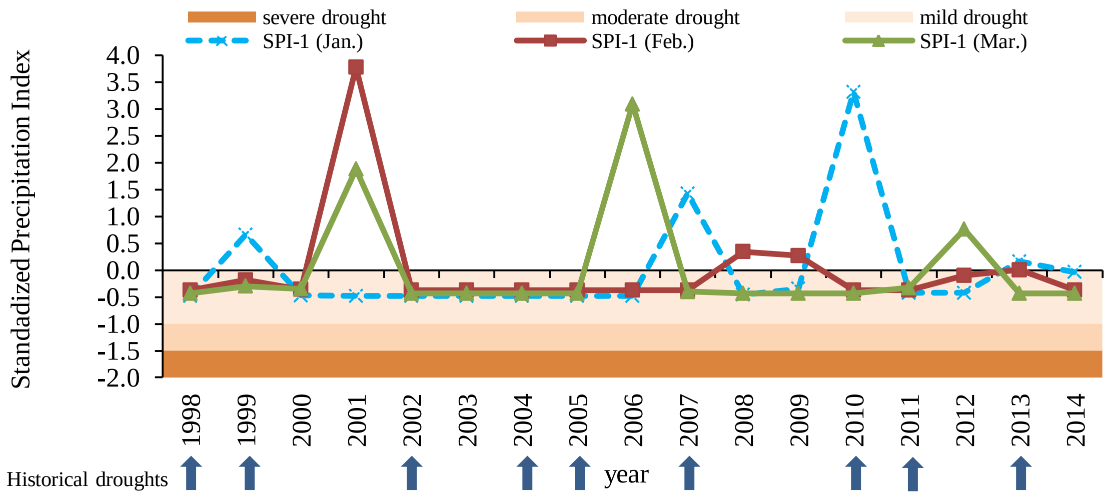

Figure 12: The SPI for one-month period during January to March of Ben Tre Station

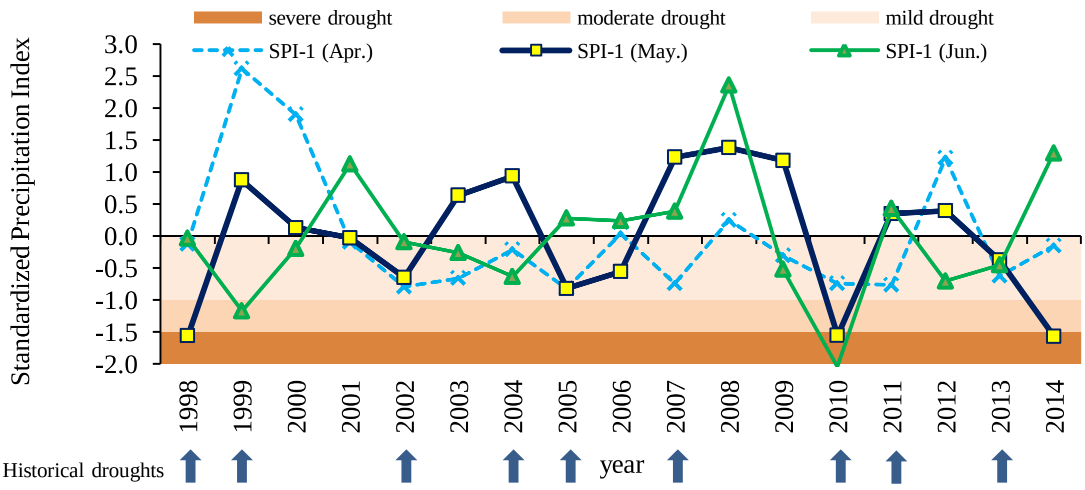

Figure 13: The SPI for one-month period during April to June of Ben Tre Station

[10] In the Section 4, the blue vertical arrows illustrate the historical droughts in figures.

➢ Three-month period for Ben Tre Station

Tinh (2012) also conducted a research on three-month period to evaluate SPI in the Mekong Delta. SPI-3 (Apr.-Jun.) showed the most severe drought that was also found in this study (Figures 14 and 15). SPI-3 also reproduced the severe droughts at the end of dry season, specifically for the period from March to June. Specifically, SPI-3 (Mar.-May.) presented the severe drought in 2010 while showed the moderate droughts in 1998 and 2005; and the mild droughts in 2002, 2011 and 2013. Unfortunately, it failed to describe the 1999 and 2007 droughts and the normal year of 2014 (Figure 14). The situation here is similar to one-month period because three-month period will be more sensitive to drought for a period from April to June that is the end of dry season.

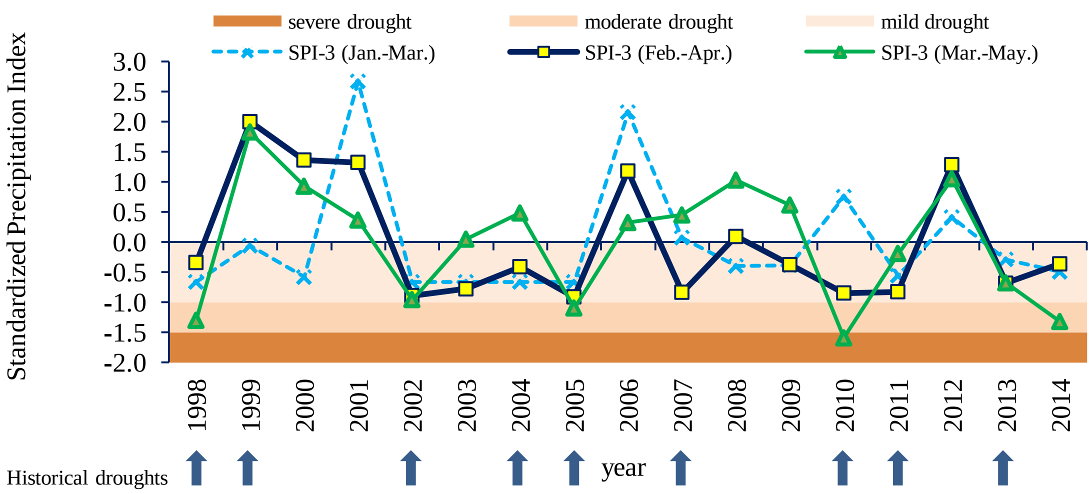

Figure 14: The SPI for three-month period during January to May of Ben Tre Station

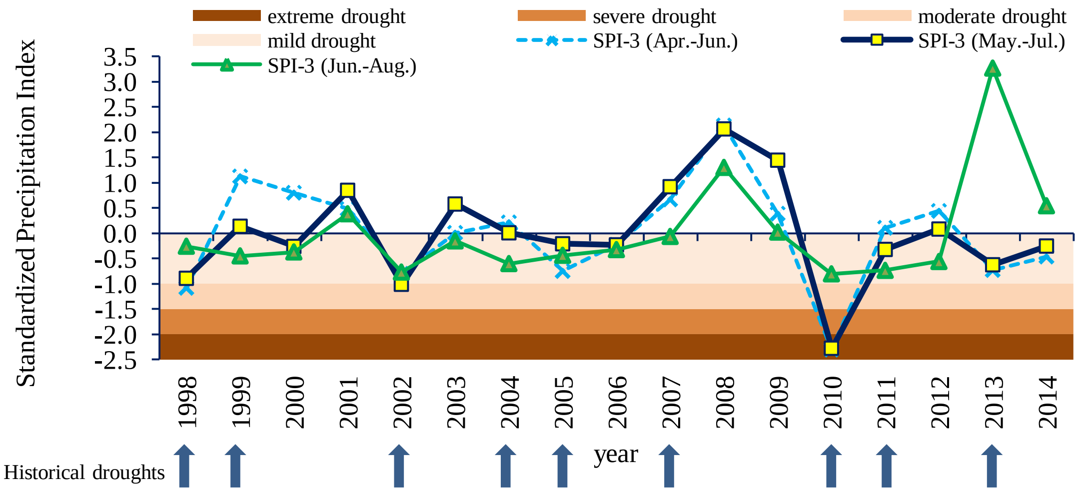

Figure 15: The SPI for three-month period during April to August of Ben Tre Station

➢ Six-month, nine-month and twelve-month period for Ben Tre Station

The results from SPI-6 showed the severe and extreme droughts for periods from January to August. For example, SDI-6 (Jan.-Jun.) reproduced mild droughts in 2002, 2005, 2013 and 2014; moderate drought in 1998; and severe drought in 2010 (Figure 16). SPI-9 did not depict droughts well; it showed droughts in the normal years of 2000, 2009 and 2014 (Figure 17). Similarly, SPI-9, SPI-12 (Jan.-Dec.) could not detect droughts in 1999, 2004, 2007 and 2013. Moreover, it presented a discrepancy as the drought signals were obtained in the normal years such as 2003 and 2009 (Figure 18). Overall, SPI-6 is the best matched up with historical droughts and results from previous studies. In overall, SPI-1 (Jun.), SPI-3 (May.-Jul.), SPI-6 (Jan.-Jun.) and (Feb.-Jul.) reproduced well the severe drought and responds the drought situation in the MKD. In order words, the levels of rain from January to June are an important and main factor determining the meteorological drought in the Ben Tre and the MKD, especially in May and June.

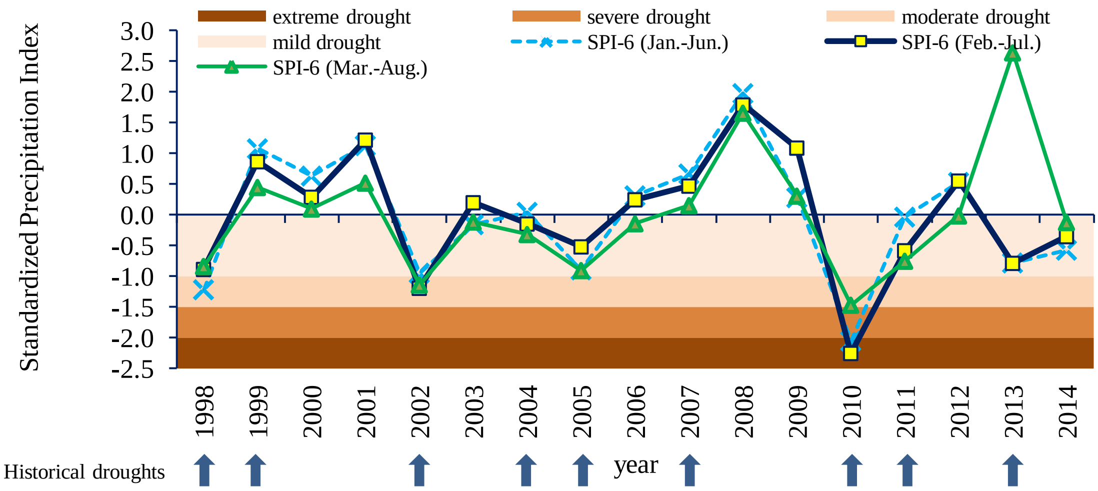

Figure 16: The SPI for six-month period during January to August of Ben Tre Station

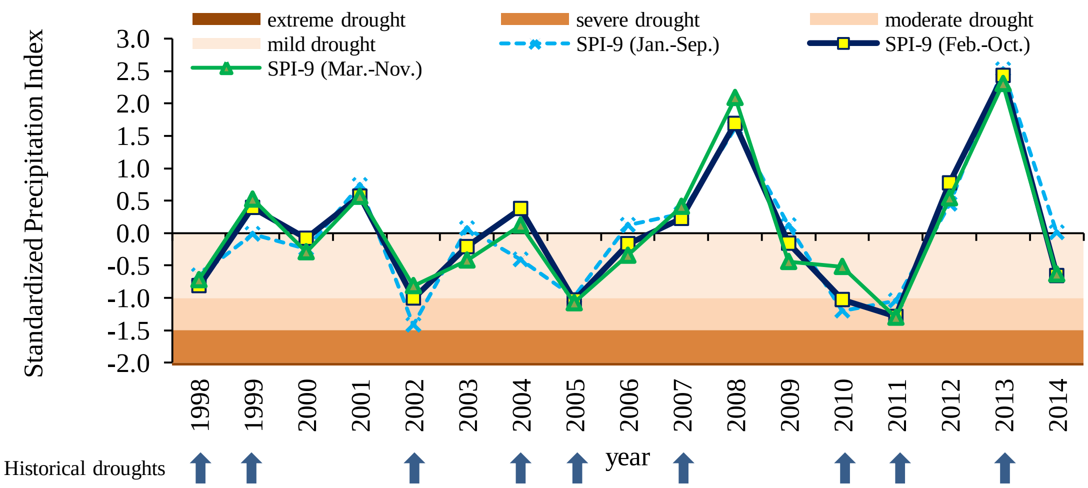

Figure 17: The SPI for nine-month period during January to November

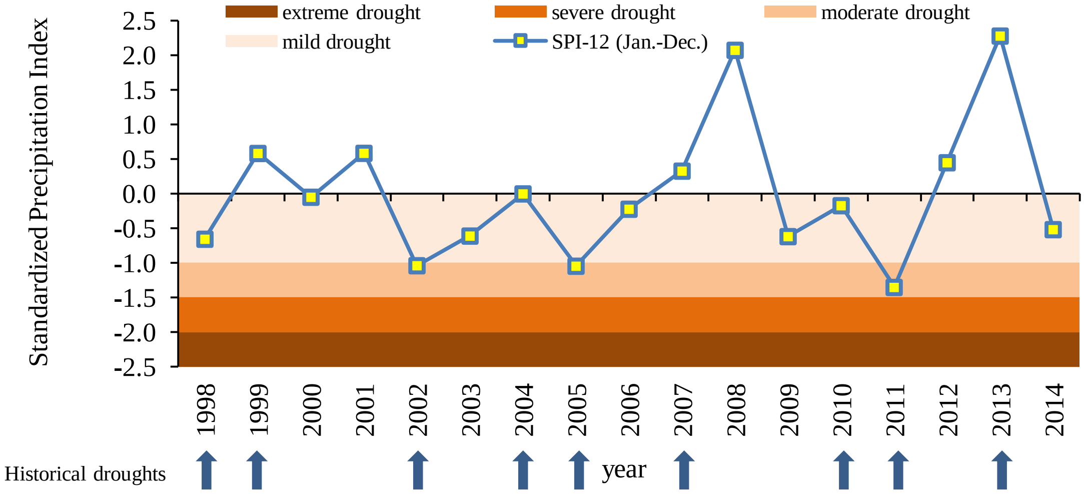

Figure 18: The SPI for twelve-month period from January to December

4.1.2 The correlation analysis between SPI and statistical drought damage

Due to the analysis above, the promising results of SPI calculation were used to conduct the correlation analysis with the statistic on areas affected by droughts. The SPI-6 (Jan.-Jun.) showed the highest R^2=0.265 (Figure 19c). It also agreed with the analysis above. There is a slight difference in comparison with other periods; especially SPI-3 (Mar.-May.), SPI-3 (Apr.-Jun.) and SPI-9 (Jan.-Sep.) displayed R^2=0.147, 0.222, 0.211, respectively (Figures 19a, 19b and 19d). It is reasonable because the MKD is not a closed watershed and most of the agricultural land is irrigated. Nonetheless, SPI-6 plays a certain role in the severe drought years.

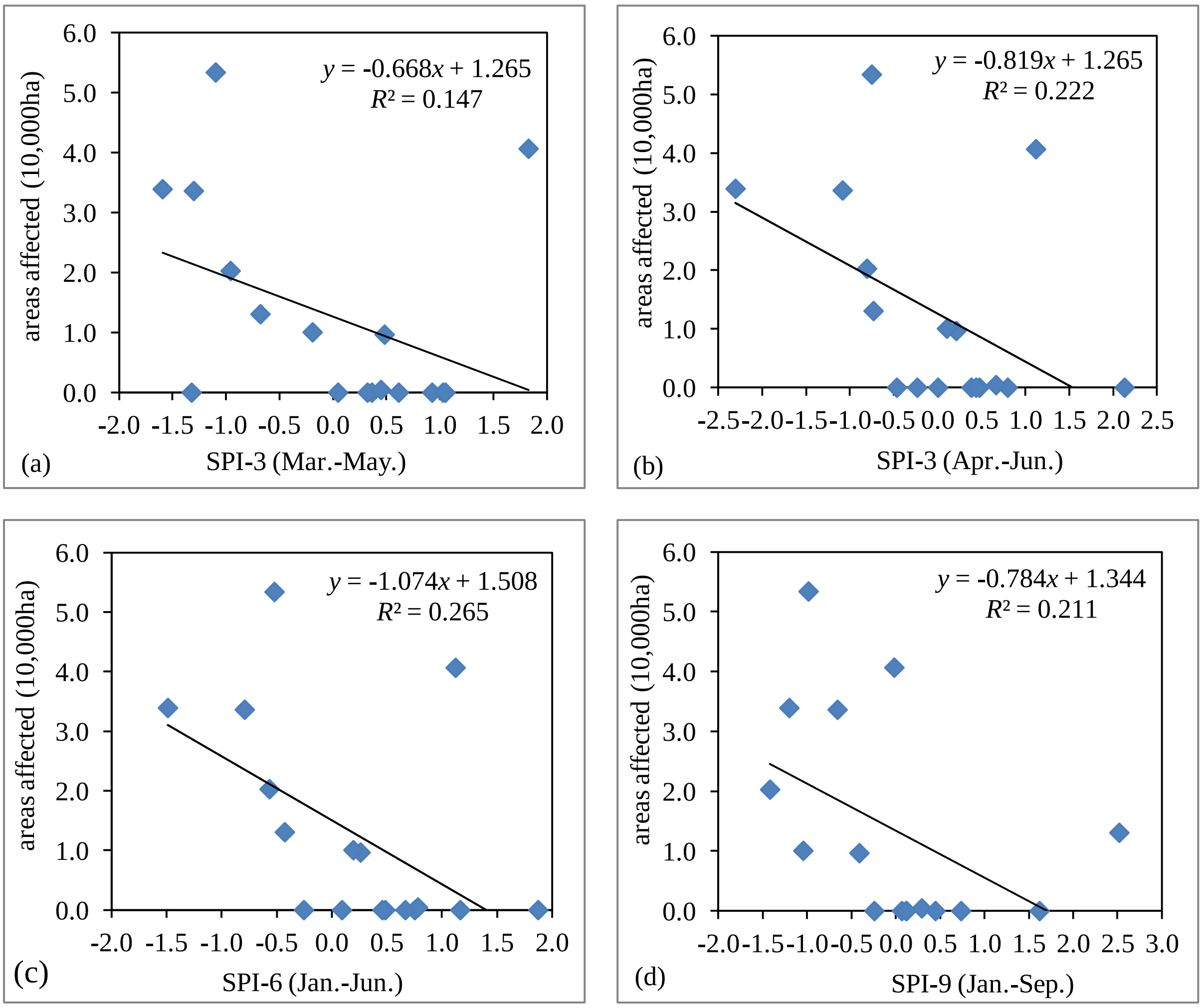

Figure 19: The correlation analysis between SPI for Ben Tre Station and areas affected

(a) SPI-3 (from March to May), (b) SPI-3 (from April to June), (c) SPI-6 (from January to June), and SPI-9 (January to September).

4.2 Streamflow Drought Index

4.2.1 Results of Streamflow Drought Index for Tan Chau Station

The results showed that the SDI-1 for the periods of January and February matched up with historical drought years, except for 2002 (Figure 20). SDI-1 (Jan.) unveiled the severe drought in 1999, moderate droughts in 2004, 2005 and 2013 and mild droughts in 1998, 2007, 2010, 2011. The SDI-1 (Mar.) could not state the 2013 drought and this failure could be found in SDI-1 for April and May. SDI-1 (Jun.) seemed to demonstrate drought signals better other periods; however, it could not describe droughts in 1999 and 2004 (Figure 21).

For the period from October to December, all SDI-1 did not correctly respond to droughts in 2013, 2011 and 2007. They also underestimated the intensity of the drought in 2005 and 2010, only showing the mild drought in these years instead of severe drought as they were (Figure 22). The result showed that hydrological drought could occur in any month of the year. However, it seems to be more severe than in the end of flood season (October to December) or in the early of the dry season (January to March).

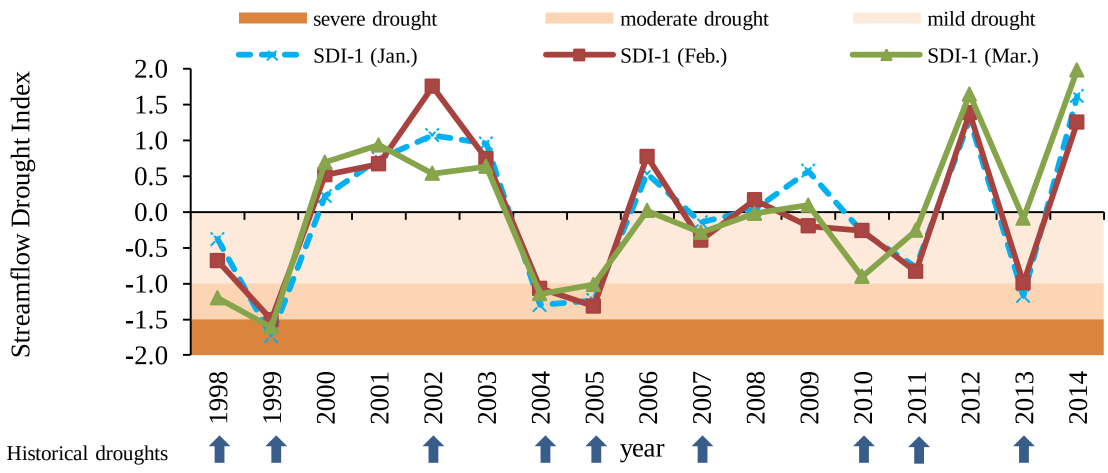

Figure 20: The SDI for one-month period during January to March of Tan Chau Station

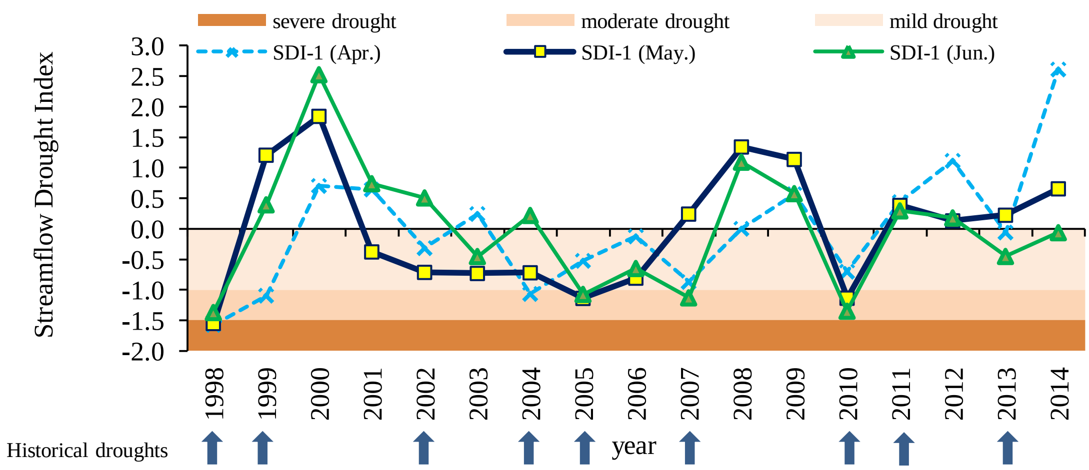

Figure 21: The SDI for one-month period during April to June of Tan Chau Station

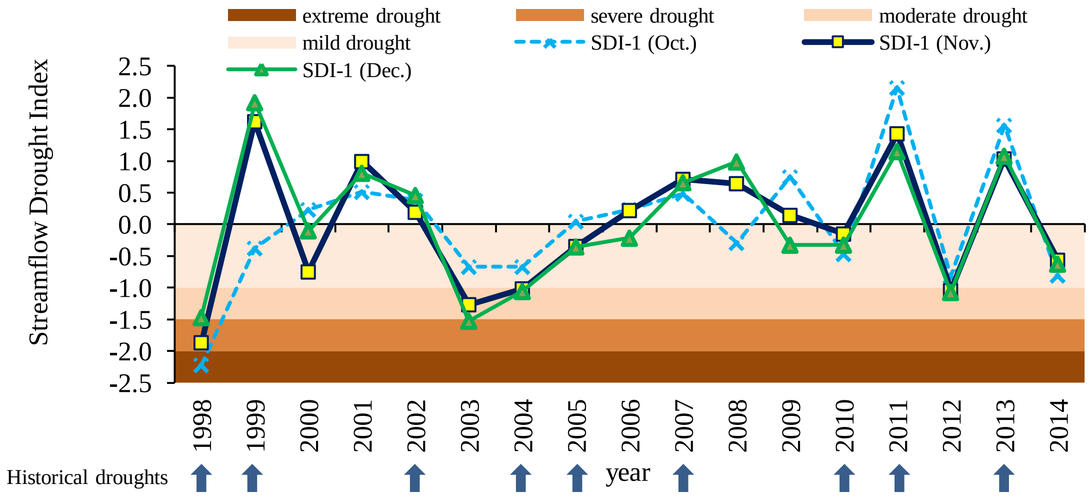

Figure 22: The SDI for one-month period during October to December of Tan Chau Station

➢ Three-month period for Tan Chau Station

From January to May (Figure 23), the results showed that SDI-3 (Feb.-Apr.) and SDI (Jan.-Mar.) were good in describing historical drought events. SDI-3 (Feb.-Apr.) showed the severe drought in 1999, moderate droughts in 1998, 2004 and 2005, and mild droughts in 2007, 2010, 2011 and 2013. However, it could not explain the 2002 drought. Similarly, SDI-1 (Jan.-Mar.) and (Mar.-May.) showed a good responded patterns in drought events such as 1998, 1999, 2004, 2005 and 2010, but they still failed in drought events of 2002 or 2013.

From April to August (Figure 24), the results were not good because of these values failed to describe drought events of 1999, 2002 and 2011. Additionally, they underestimated the 2004 and 2013 droughts with slightly moderate droughts. There is no three-month period SDI showing the best agreement with of historical droughts; however, most of the results show clear evidence of drought in severe droughts of 1998-1999, 2005 and 2010.

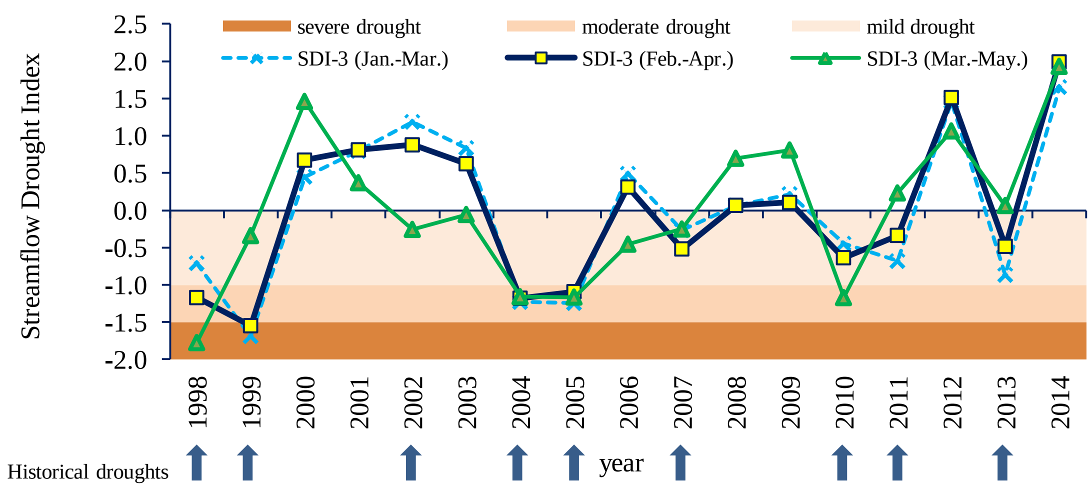

Figure 23: The SDI for three-month period during January to May of Tan Chau Station

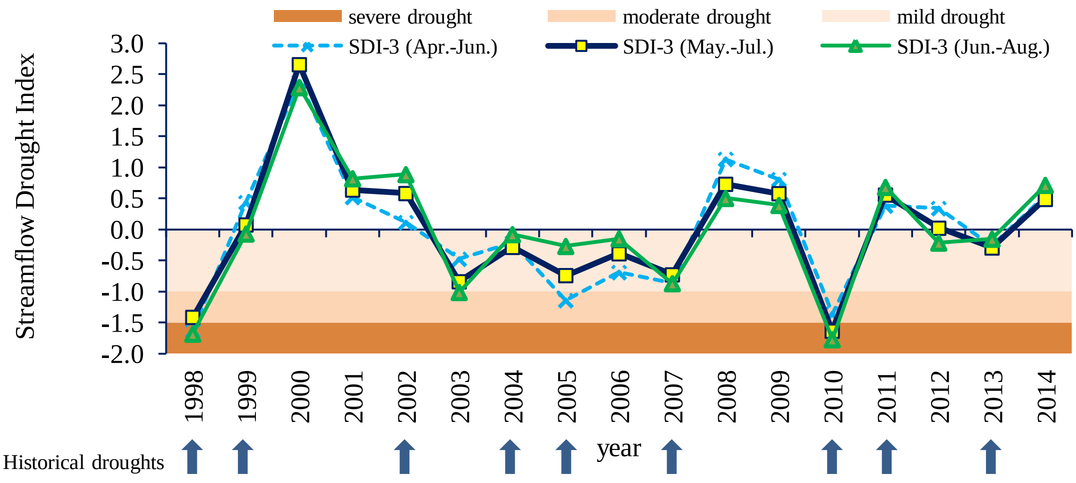

Figure 24: The SDI for three-month period during April to August of Tan Chau Station

➢ Six-month, nine-month and twelve-month periods for Tan Chau Station

From January to August, SDI-6 (Jan.-Jun.) showed the best matched up with historical drought events, only with an exception occurred in 2002. SDI-6 (Feb.-Jul.) and (Mar.-Aug.) also matched with most of the historical years; however, the failures neither occurred in 2002 nor appeared in 2003 (Figure 25).

In the results from April to November, SDI-6 showed the similar patterns and these all reproduced severe or extreme droughts in 1998 and 2010. However, the underestimations were found in 2004 and 2005, and failures were found in 2002, 2003 and 2012 (Figure 26).

The SDI for a time period of nine months and twelves-months showed the similar patterns. The results defined extreme drought in 1998 and severe drought in 2010. Unfortunately, these results also presented incorrect drought signals in the normal year of 2003 and 2012. Furthermore, the intensity and signal of drought in 2004-2005 and 2013 were underestimated and not defined (Figures 27 and 28).

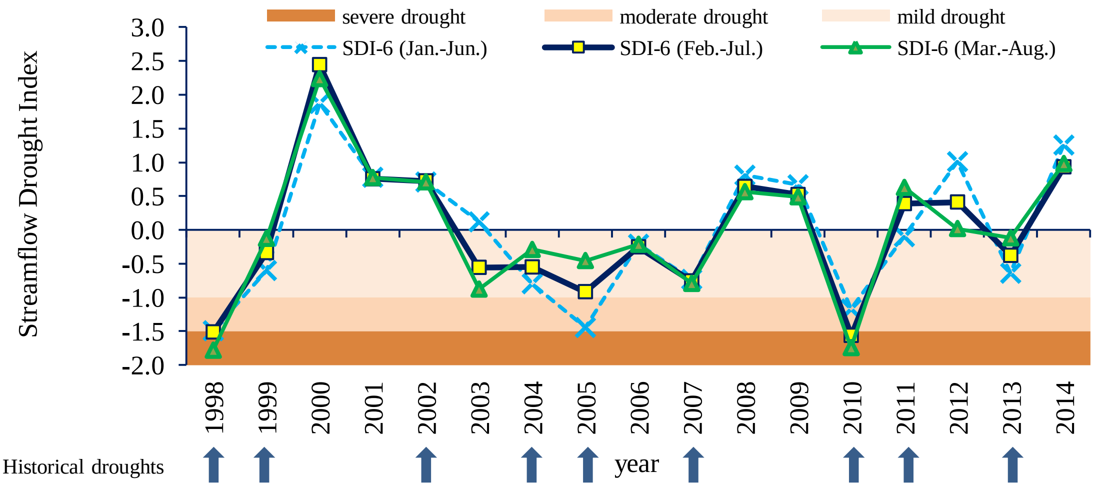

Figure 25: The SDI for six-month period during January to August of Tan Chau Station

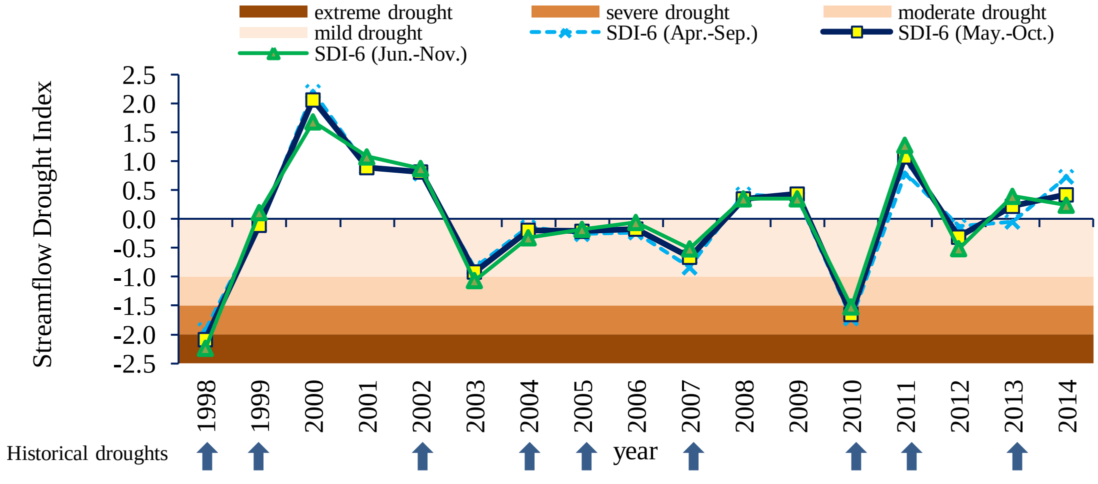

Figure 26: The SDI for six-month period during April to November of Tan Chau Station

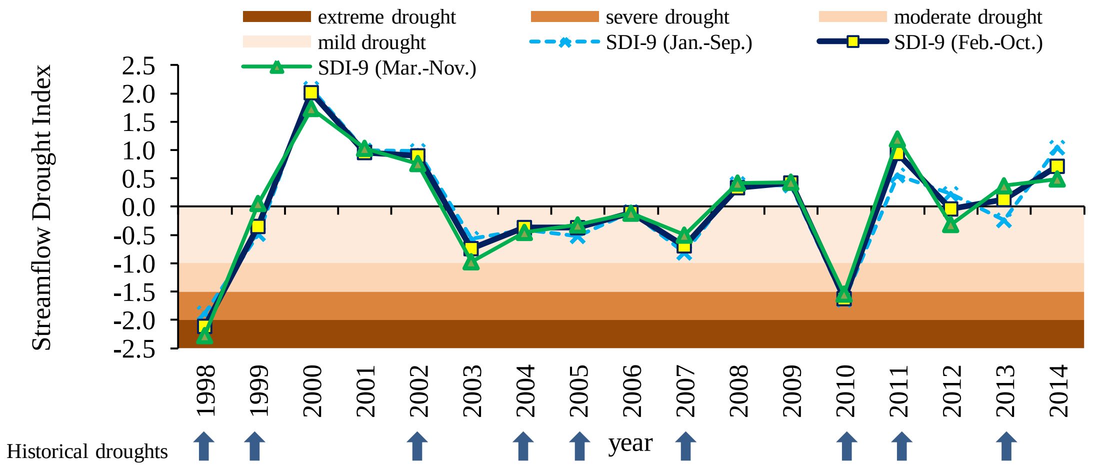

Figure 27: The SDI for nine-month period during January to December of Tan Chau Station

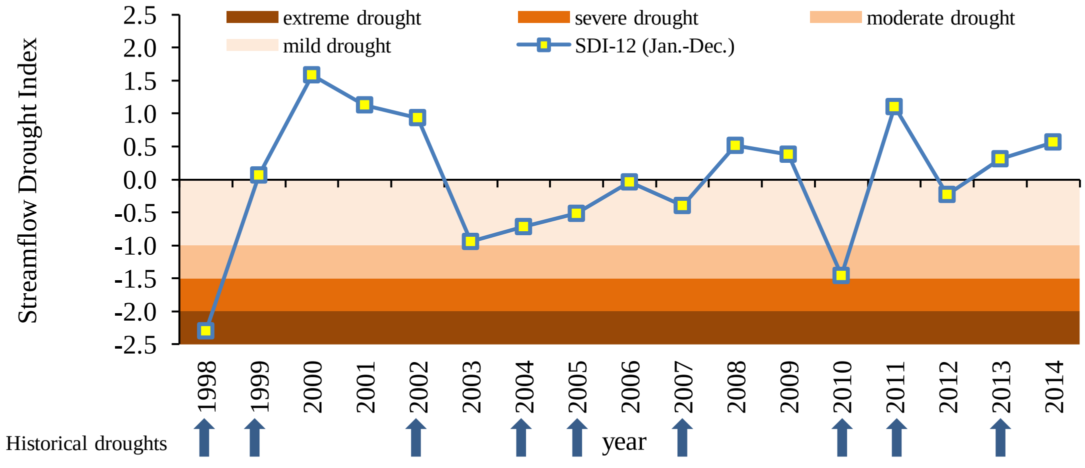

Figure 28: The SDI for Twelve-month period from January to December of Tan Chau Station

4.2.2 The results of Streamflow Drought Index for Chau Doc Station

➢ One-month period for Chau Doc Station

The results of SDI for one-month period at Chau Doc Station only showed a quite good responded pattern from January to March (Figure 29). Especially, SDI-1 (Jan.) revealed the moderate droughts in 2004 and 2005, mild droughts in 1998, 1999, 2007, 2010, 2011 and 2013. The failures found in 2002, 2006 and 2008, as it did not define drought signal in 2002 while showed drought signal in the normal year of 2008. There are no marked differences between results of SDI-1 (Feb.), SDI-1 (Mar.) and SDI-1 (Jan.), with only small the difference being the intensity in 2010 and 2011. In contrast to this, the results of other months were not good as it indicated the drought signals in the normal years of 2001 and 2002 (Figure 30) or 2008, 2009 and 2012 (Figures 31, 32).

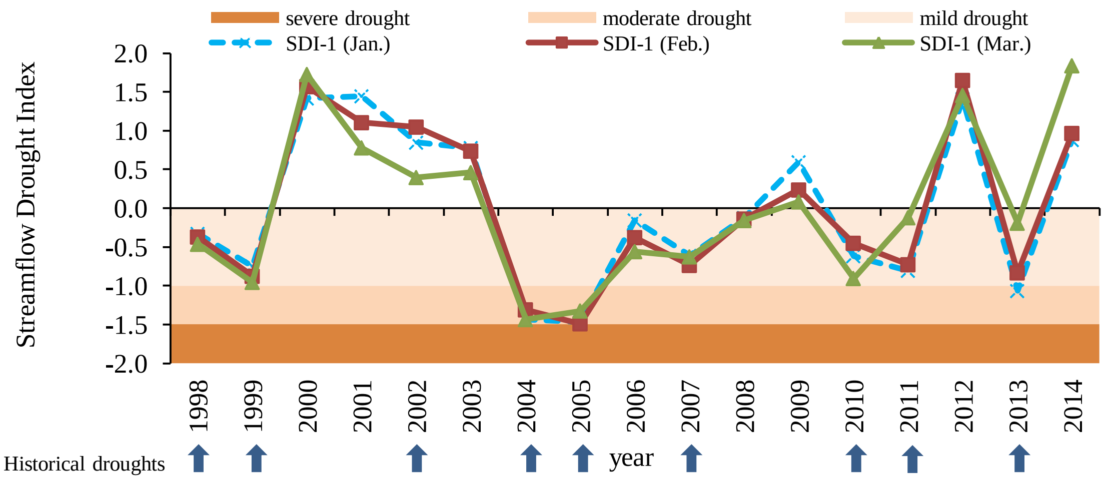

Figure 29: The SDI for one-month period during January to March of Chau Doc Station

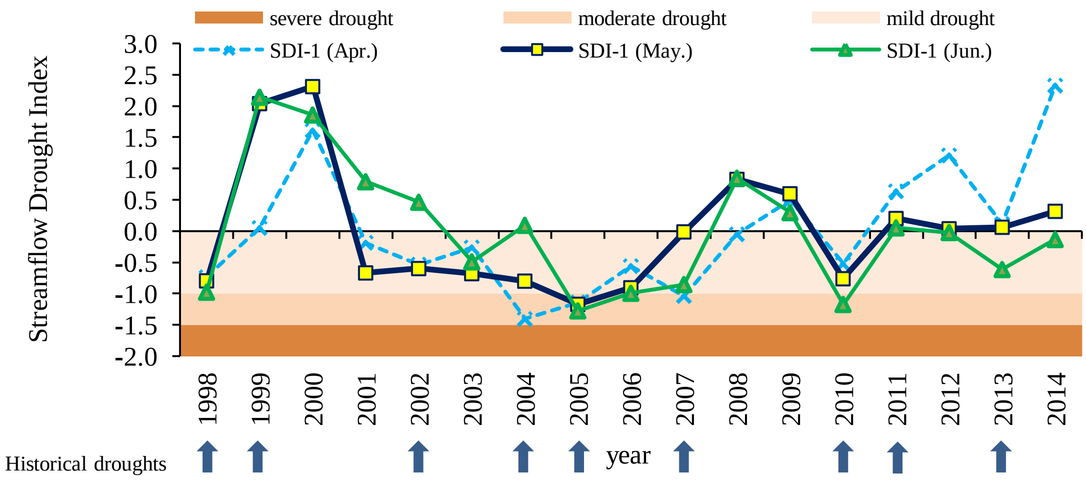

Figure 30: The SDI for one-month period during April to June of Chau Doc Station

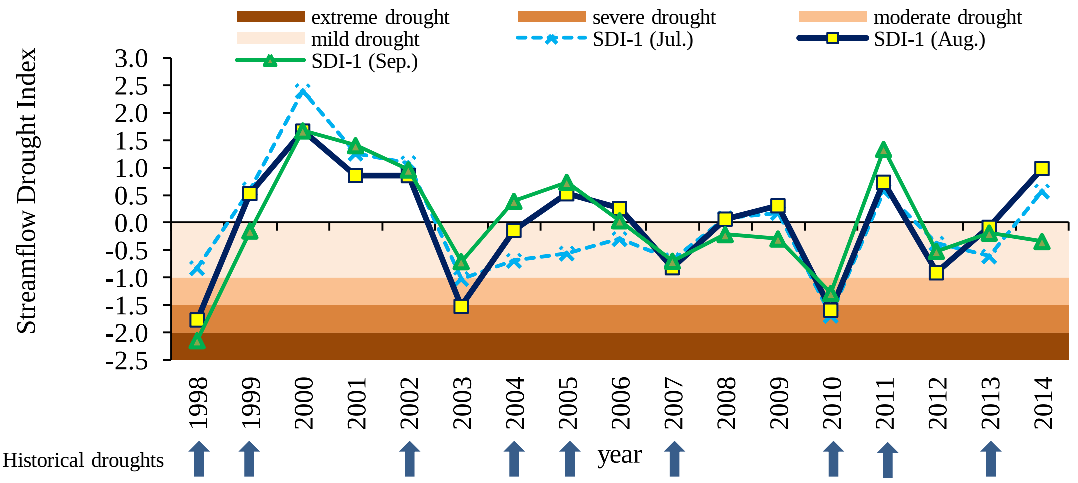

Figure 31: The SDI for one-month period during July to September of Chau Doc Station

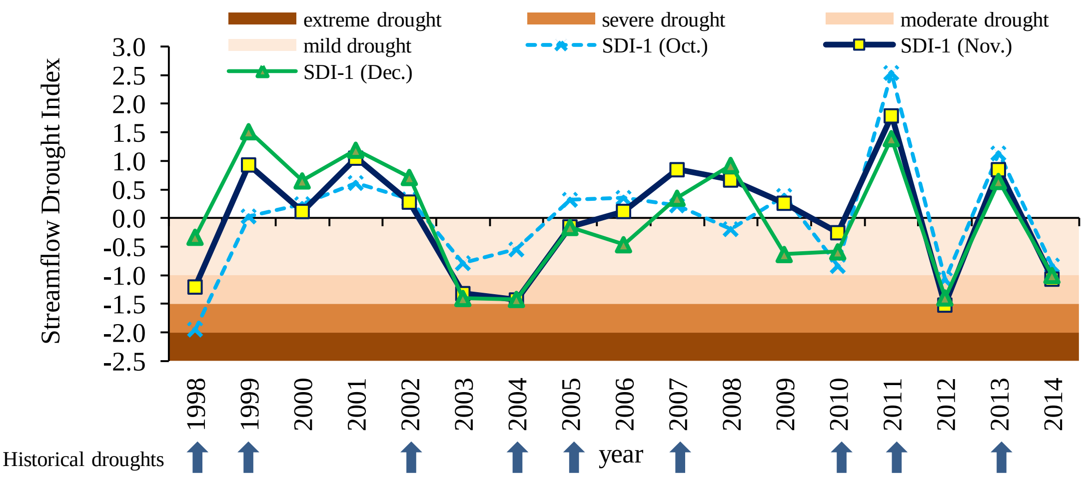

Figure 32: The SDI for one-month period during October to December of Chau Doc Station

➢ Three-month and six-month periods for Chau Doc Station

For the three months periods from January to May (Figure 33), SDI-3 (Jan.-Mar.) and (Feb.-Apr.) had a good response to historical droughts, these indices showed the negative values in drought years except for 2002. It presented moderate droughts in 2004 and 2005; and mild droughts in 1998, 1999, 2006, 2007, 2010, 2011 and 2013. SDI-3 (Mar.-May.) could not define the 2013 drought or showed drought signals in the normal years of 2001 and 2002.

SDI-3 (Apr.-Jun.), (May.-Jul.) and (Jun.-Aug.) neither correctly defined droughts in 2003 and 2012 nor described the drought years of 2002 and 2011 (Figure 34).

In the six-month period, it is similar to Tan Chau Station and SDI-6 (Jan.-Jun.) was the best matched up with historical droughts (Figure 35). It presented the severe drought in 2005, moderate drought in 2010, and mild droughts in 1998, 2004, 2007, 2011 and 2013. However, it could not indicate the 1999 and 2002 droughts. Other periods revealed the moderate and severe historical severe of 1998 and 2005 drought, but they showed the drought signals in the normal years of 2003, 2006 and 2012. In addition, they could not state the historical 1999 and 2002 droughts (Figure 36).

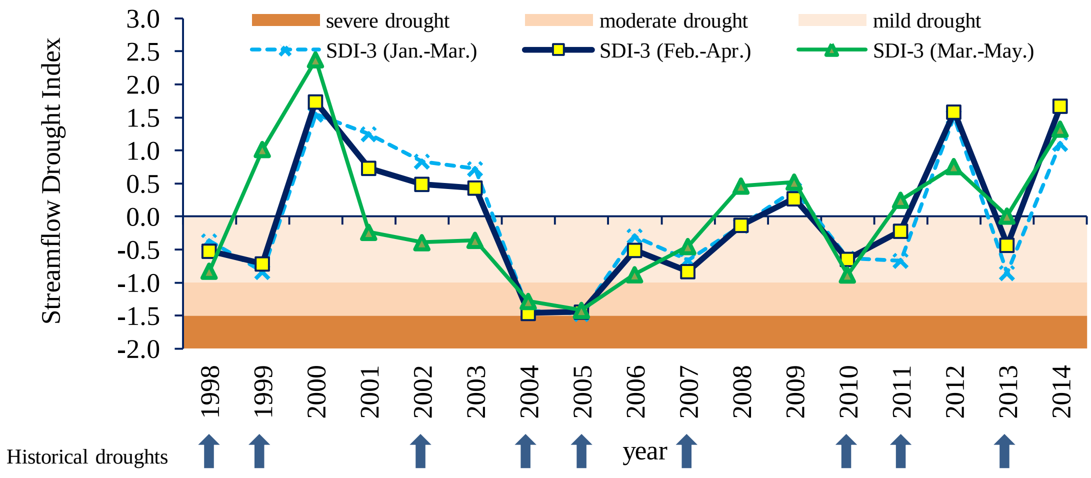

Figure 33: The SDI for three-month period during January to May of Chau Doc Station

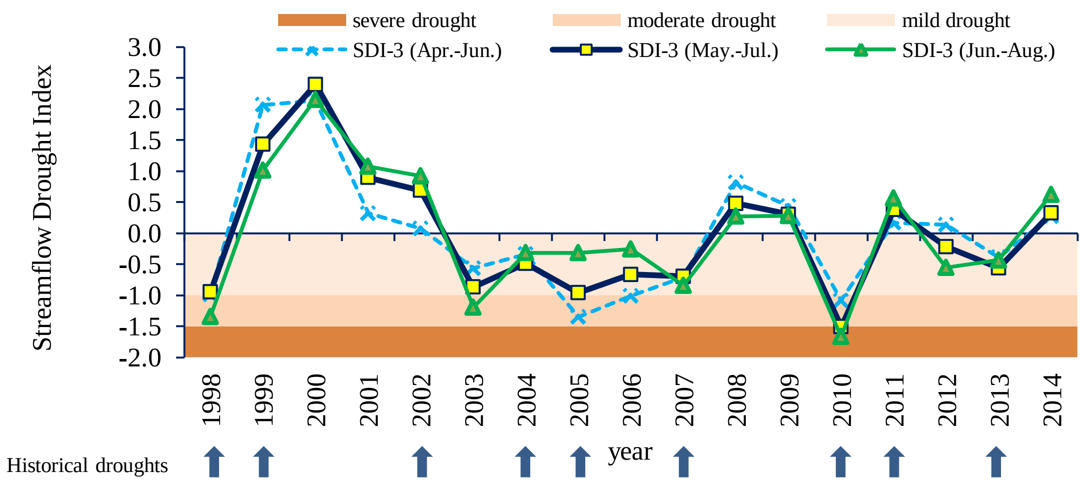

Figure 34: The SDI for three-month period during April to August of Chau Doc Station

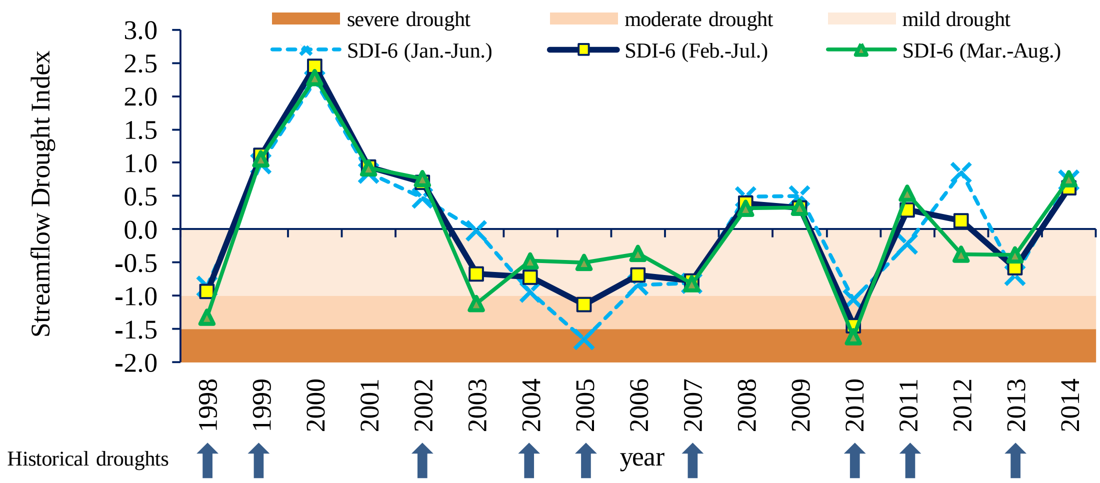

Figure 35: The SDI for six-month period during January to August of Chau Doc Station

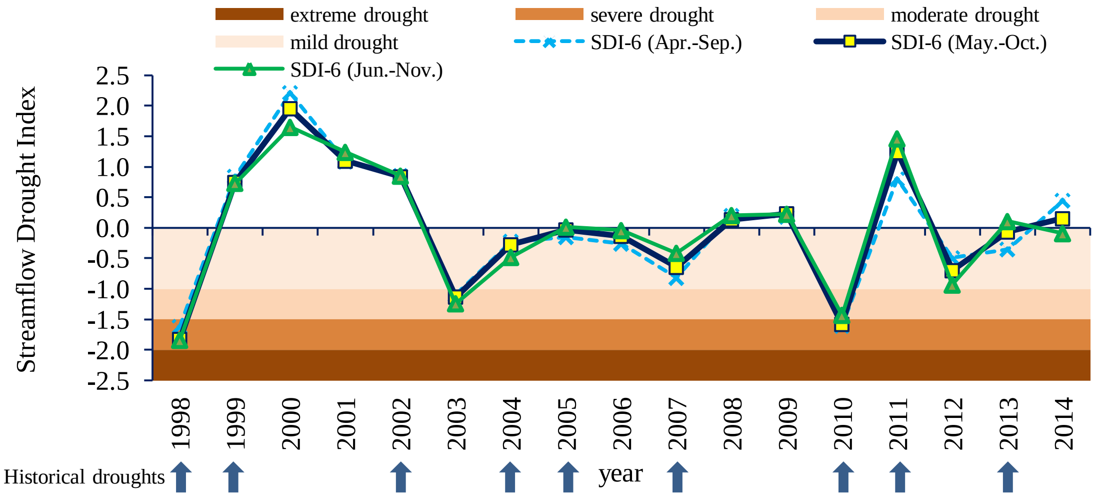

Figure 36: The SDI for six-month period during April to November

➢ Nine-month and twelve-month period for Chau Doc Station

It seemed that there is no difference in the results of the nine-month period. They could not detect the droughts in 1999, 2002, and 2011 and underestimated the historical severe 2005 drought. Despite this, they all reproduced the severe drought signals in the historical severe drought of 1998 and 2010 (Figure 37). Similarly, the twelve-month period presented similar result with that for the nine-month period as it only showed correctly severe drought in 1998 and moderate drought in 2010. However, it failed and underestimated the severe drought 2005. The results for Chau Doc Station were not as good as Tan Chau Station because streamflow at Chau Doc accounting for 20% of river flow into the Mekong Delta.

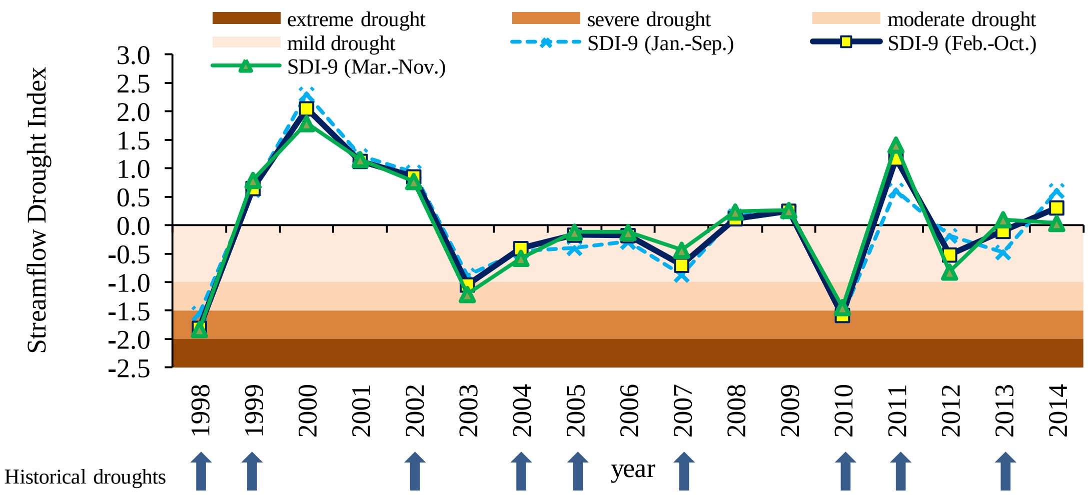

Figure 37: The SDI for nine-month period from January to December

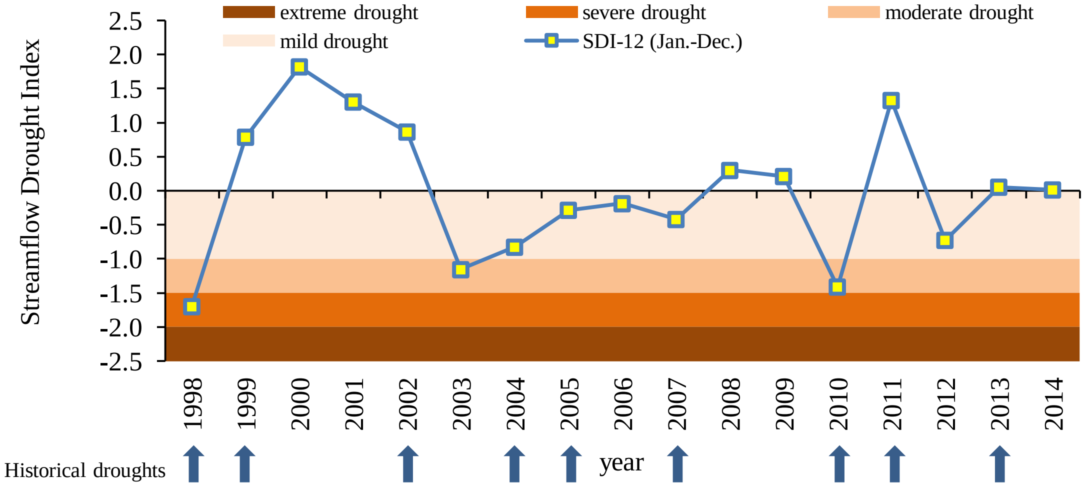

Figure 38: The SDI for twelve-month period of Chau Doc Station

4.2.3 The correlation analysis between SDI and affected areas

➢ Tan Chau Station

The results showed that it was not much different in R^2 between SDI-1 in the dry months and areas affected. It varied in 0.329 (period of January) to 0.489 (period of March) (Figure 39). It had an agreement with the discussion above that there was no SDI-1 that could indicate correctly all historical droughts. Especially, the historical drought as 2002 was the main cause of failures (red dots). In the MKD, from 2000 to 2002 were the historically continuous droughts; therefore, it is necessary to thoroughly examine more for this year.

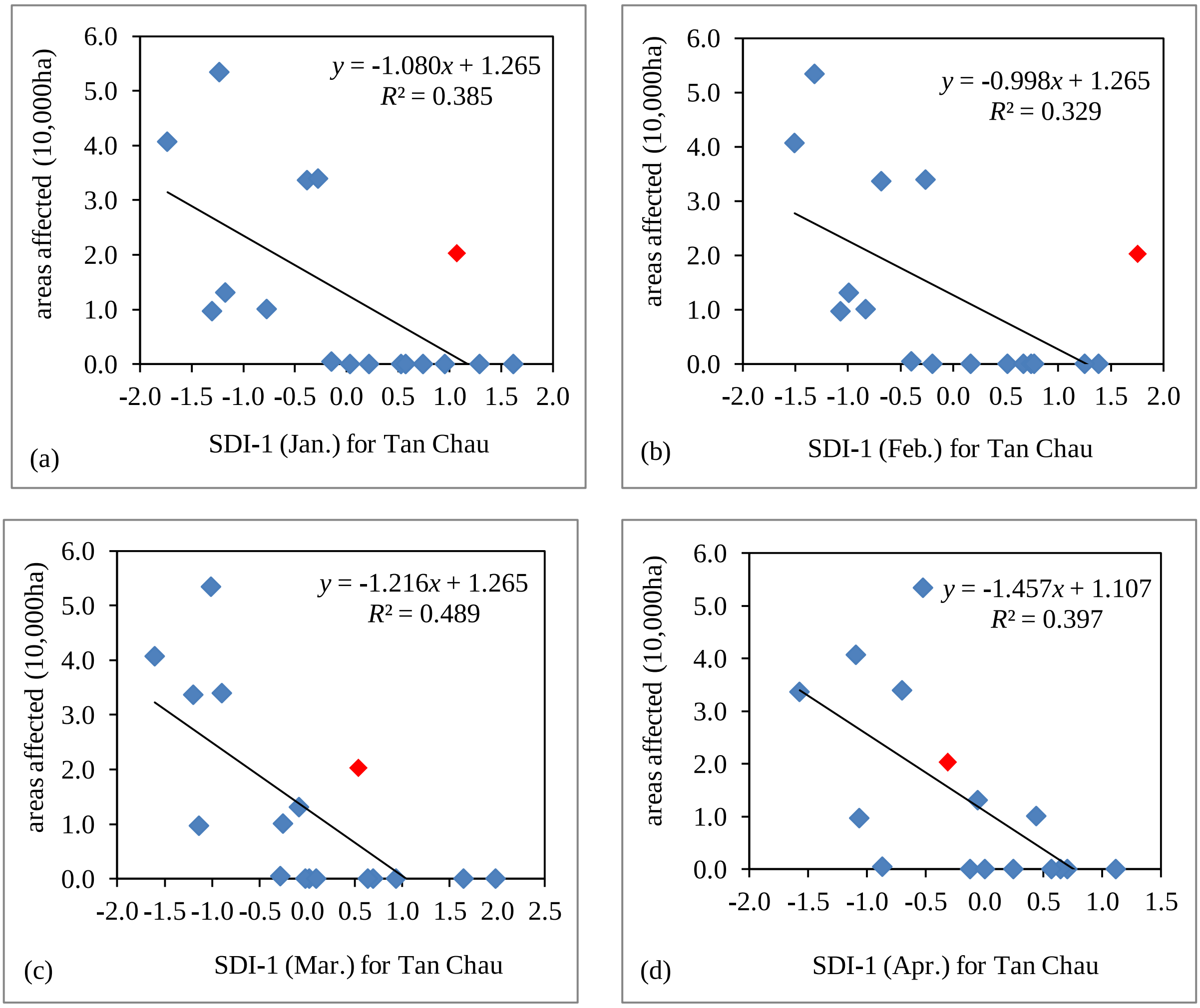

Figure 39: The correlation analysis between one-month SDI for Tan Chau and areas affected

(a): SDI for period of January, (b): SDI for period of February, (c): SDI for period of March, (d): SDI for period of April (red dot illustrates 1999)

In a three-month period, it showed a better correlation compared to the result of one-month period. The R^2 was ranking from 0.42 to 0.438, 0.445 and 0459. The problem of 2002 was found in three of four cases, except for SDI-3 (Mar.-May.); but SDI-3 (Mar.-May.) was underestimated the historical droughts of 1999 and 2013 and failed in 2011 (Figure 40). It is suspected that the was short period of drought in 2002 during March and May.

Regarding six-month period, the SDI-6 (Jan.-Jun.) showed the highest R^2 = 0.49 (Figure 41a) among all results of SDI. It agreed with the aforementioned analysis that it showed the best response pattern to historical droughts. The other periods presented the lower R^2= 0.322 for SDI-6 (Feb.-Jul.) in Figure 41c and R^2=0.226 for SDI-6 (Mar.-Aug.) in Figure 41b. Similarly, SDI-9 (Jan.-Sep.) obtained a low R^2=0.285. It is predictable because it showed a bad response pattern to historical droughts. The results stated that the case of 2002 was the main cause of the correlation between affected areas and SDI. However, SDI-1 (Apr.) could indicate the 2002 drought. It leads to an assumption that in 2002 a hydrological drought could occur in the short period, the case of 2002 illustrates in Figures 40, 41 and 42 (red dots).

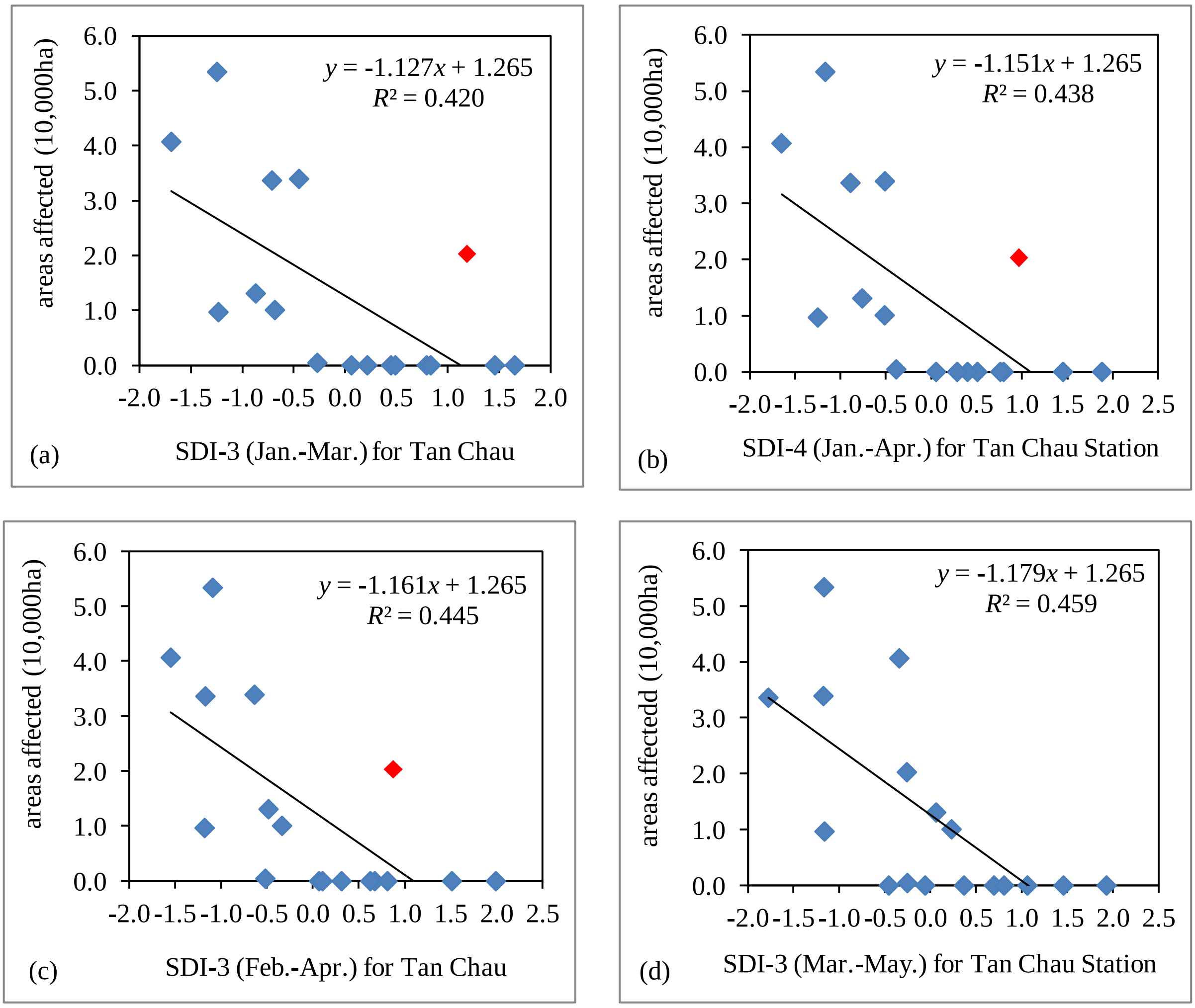

Figure 40: The correlation analysis between 3 and 4-month SDI for Tan Chau and areas affected

(a): SDI for period of January to March, (b): SDI for period of January to April, (c) SDI for period of February to April, and (d): SDI for period of March to May (red dots illustrate 1999)

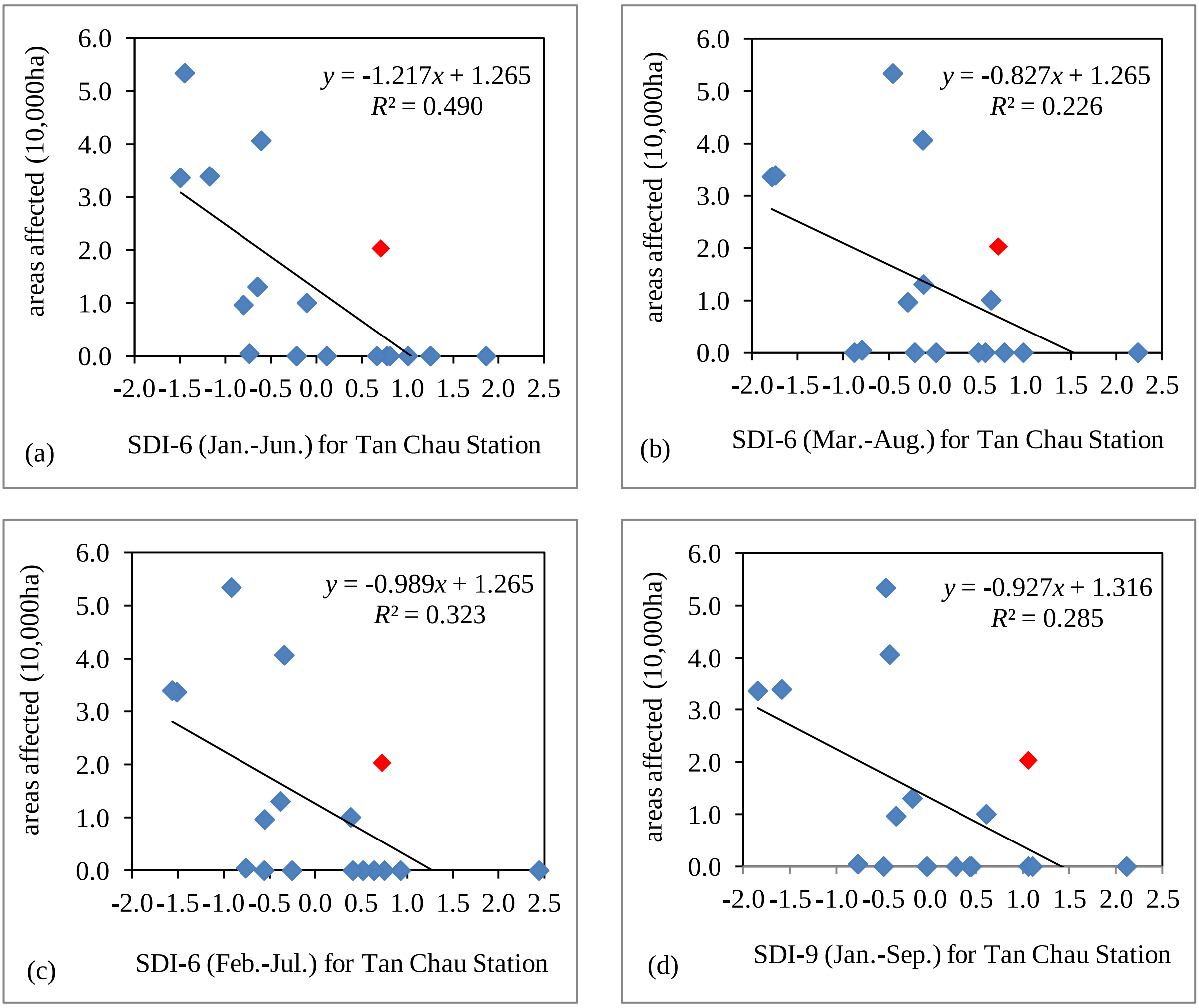

Figure 41: The correlation analysis between 6 and 9-month SDI for Tan Chau and areas affected (a): SDI for period of January to June, (b): SDI for period of March to August, (c): SDI for period of February to July, and (d) SDI for period of January to September (red dots illustrate 1999)

➢ Chau Doc Station

The analysis in Section 4.2.2 showed that the results of SDI for Chau Doc had the bad response patterns to the historical droughts as the discharge at Chau Doc accounts for only about 15 to 20% of the total water volume streamflow into the Mekong Delta. As a result, it revealed the low R^2 in correlation analysis with affected areas. Especially, for one-month period, the SDI for March showed the highest R^2=0.354 while the other months values ranking in 0.181 (April) to 0.301 (February) and 0.33 (January) in Figure 42.

For the three-month period, only SDI-3 (Jan.-Mar.) and (Feb.-Apr.) showed a better R^2=0.338 and 0.323 (Figures 43a and 43c) while other periods obtained the R^2 as low as 0.156 and 0.051 (Figures 43b and 43d). Likewise, the SDI-6 gave the low R^2 varying from 0.066 to 0.133 and 0.199 (Figures 44a, 44b and 44c). The additional test for the dry period from January to April for SDI-4 (Jan.-Apr.) also showed the similar result with SDI-3 with R^2=0.34. It is recognized that the results of SDI for Chau Doc showed a main problem with the 1999 drought, especially for a six-month period in Figures 43 and 44 (red dots).

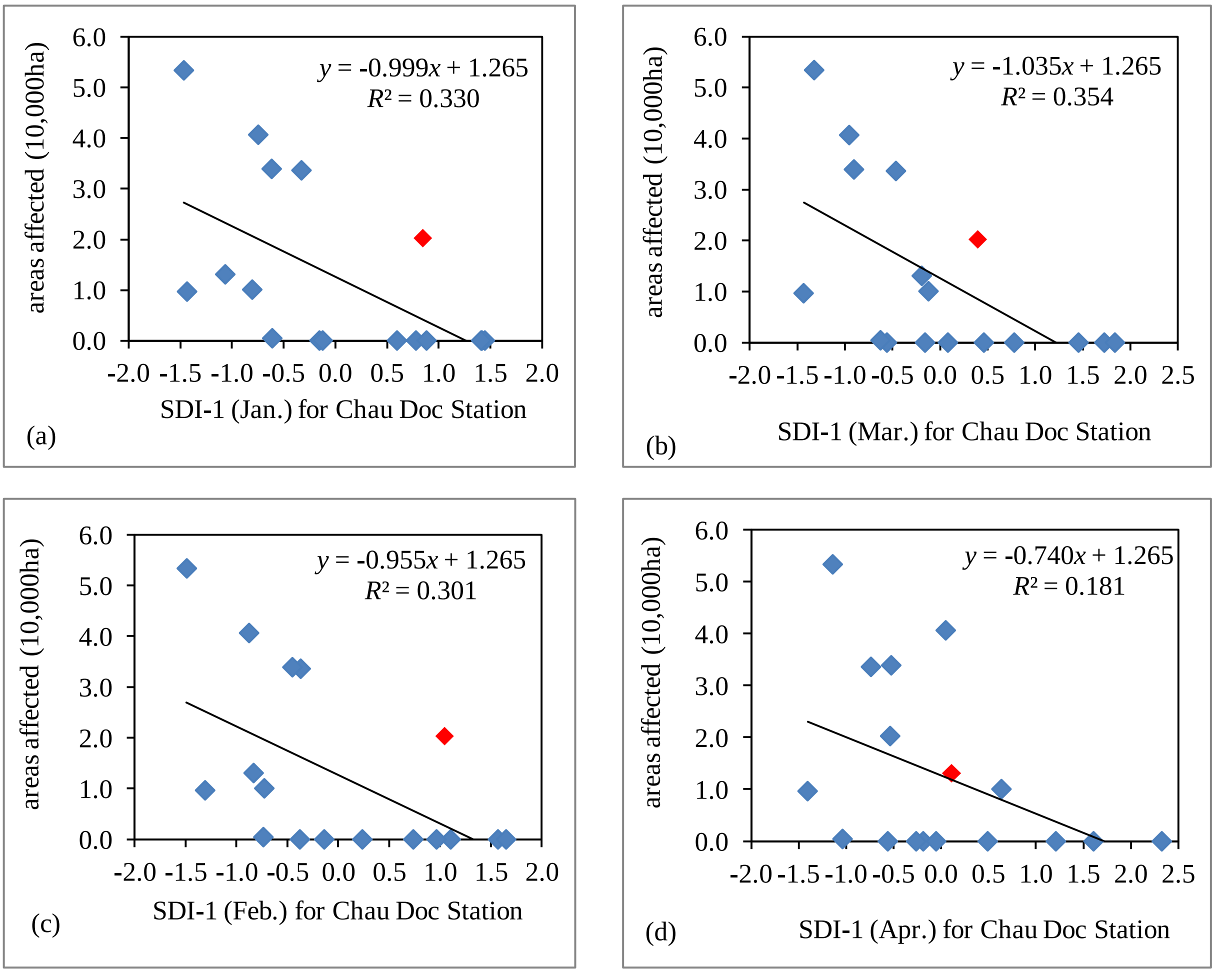

Figure 42: The correlation analysis between one-month SDI for Chau Doc and areas affected (a): SDI for period of January, (b): SDI for period of March, (c): SDI for period of February, (d): SDI for period of April (red dots illustrate 1999)

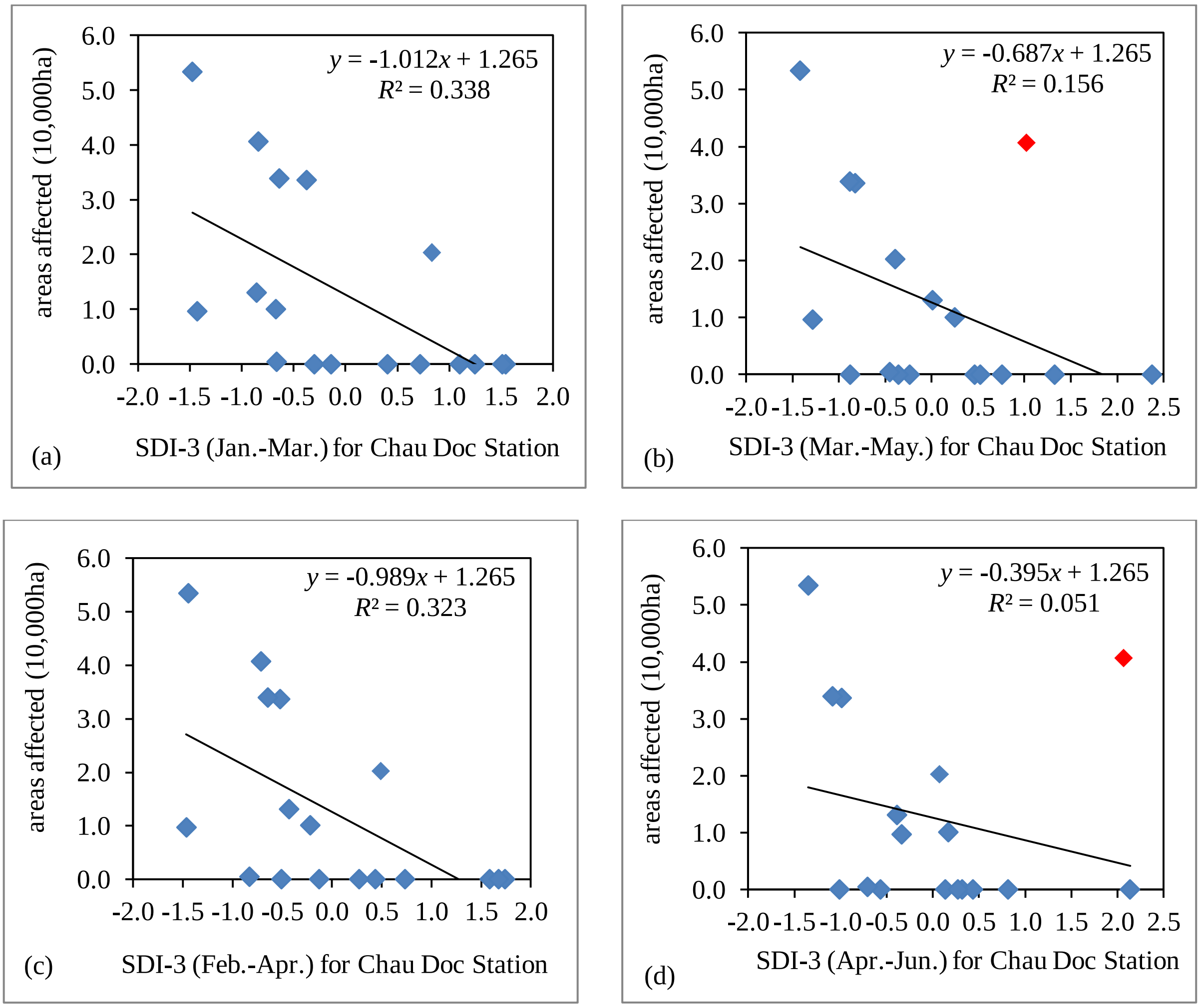

Figure 43: The correlation analysis between 3-month SDI for Chau Doc and areas affected

(a): SDI for period of January to March, (b): SDI for period of March to May, (c): SDI for period of February to April, (d): SDI for period of April to June (red dots illustrate 2002)

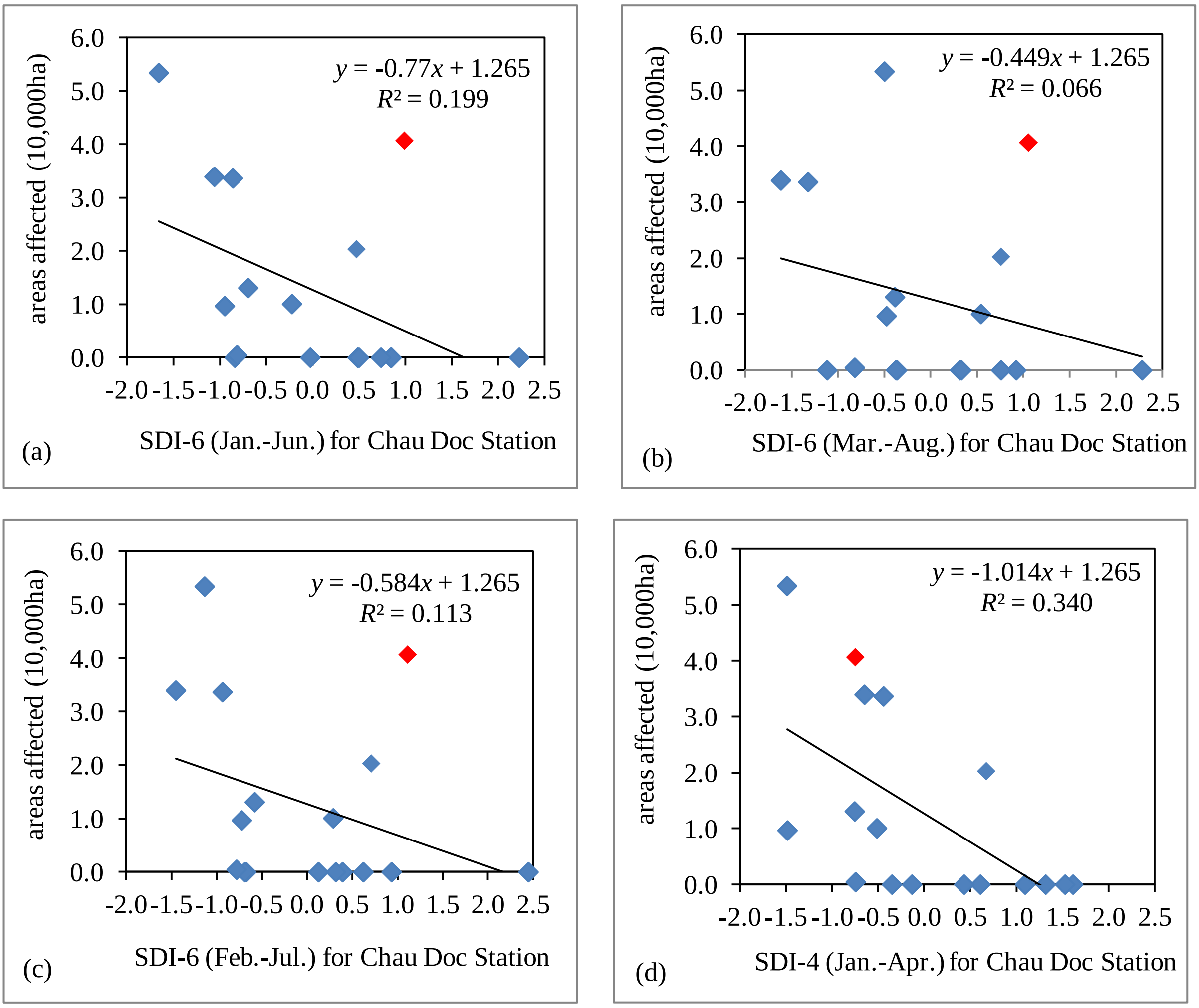

Figure 44: The correlation analysis between 4 and 6-month SDI for Chau Doc and areas affected (a): SDI for period of January to June, (b): SDI for period of March to August, (c): SDI for period of February to July, and (d): SDI for period of January to April (red dots illustrate 2002)

The case of 1999 at Chau Doc Station might be explained by the historical drought in 1998 and historical flood in 2000. It is suspected that the 1998 drought extended to the early in 1999 and it only occurred from January to April. Then, the streamflow at Chau Doc increased since May 1999 that continued happening to generate the historical flood in 2000.

4.3 Standardized Precipitation Evapotranspiration Index

4.3.1 The results of different periods

➢ One-month and three-month period for Ben Tre Station

From January to March (Figure 45), SPEI-1 (Jan.) indicated the severe drought in 1998. Despite this, it failed for the other years except for 2004 and 2005 for which it showed mild drought signals. SPEI-1 (Mar.) indicated the extreme drought in 2004 and it revealed the mild drought signals for other years except for 2001 and 2006. SPEI-1 (Mar.) was not good because it presented similar results from 2002 to 2007 and from 2010 to 2014 with mild drought signals. For other periods, it is similar to SPI as it showed severe or extreme drought signals in May and June (Figure 46). However, it failed in the other years; for example, it showed drought signal in the normal years of 2003, 2009 and/or 2012.

Regarding three-month period, the results showed that results are similar to each other. They indicated the severe or extreme drought signals in 2004 and 2010, the mild droughts in 2002, 2005, 2007 and 2013. Even though, failures were found in some cases; especially, SPEI-3 (Feb.-Apr.) in 2003 and SPEI-3 (Jun.-Aug.) in 2012 (Figure 49).

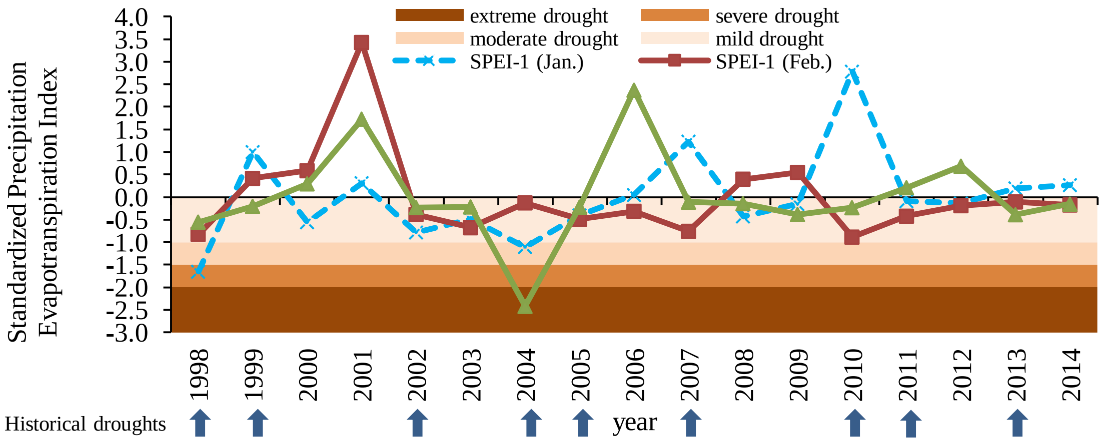

Figure 45: The SPEI for one-month period during January to March of Ben Tre Station

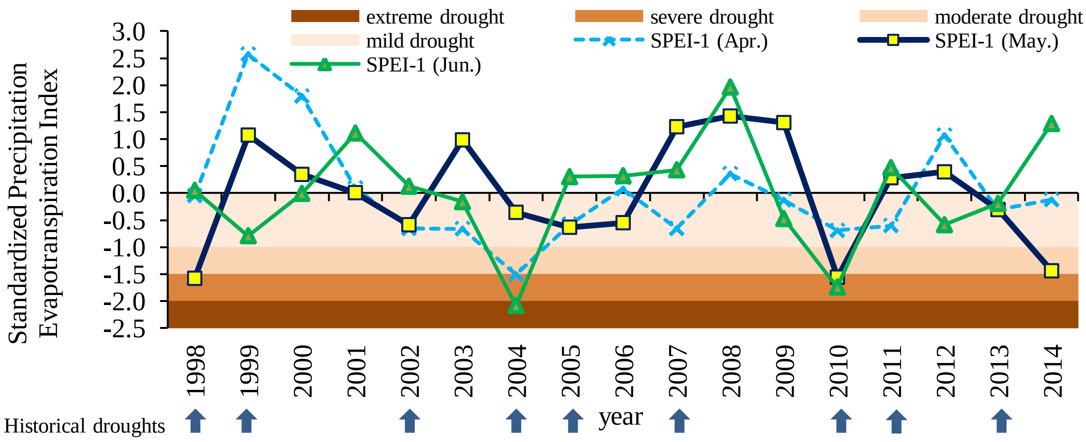

Figure 46: The SPEI for one-month period during April to June of Ben Tre Station

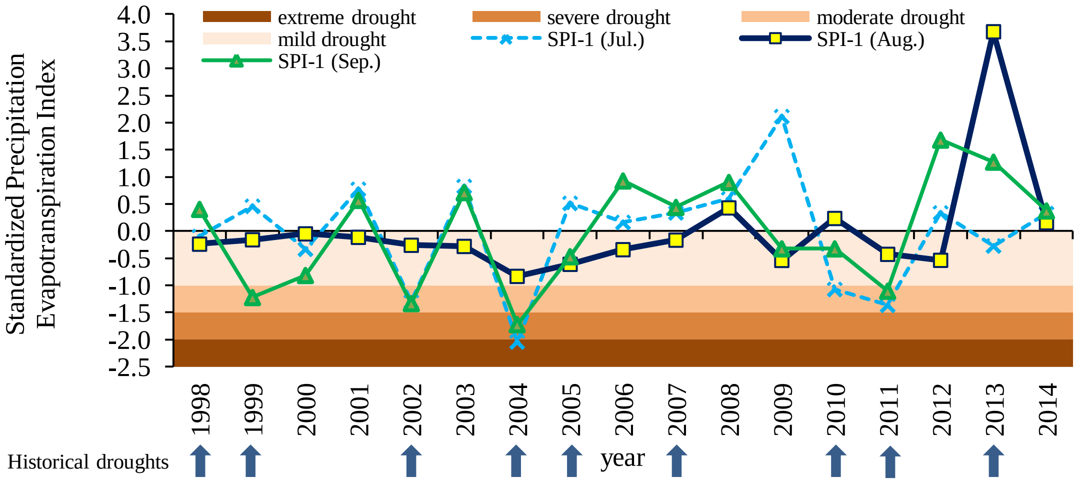

Figure 47: The SPEI for one-month period during July to September of Ben Tre Station

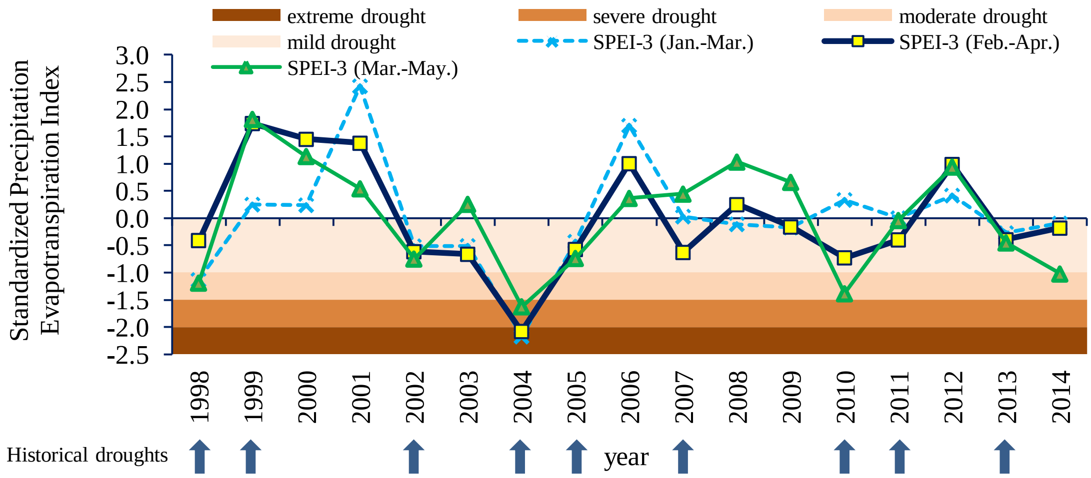

Figure 48: The SPEI for three-month period during January to May of Ben Tre Station

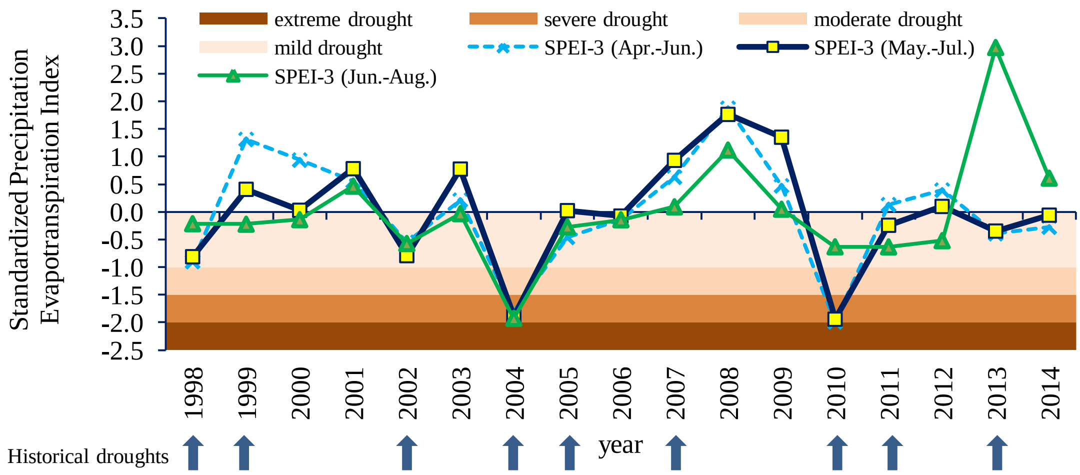

Figure 49: The SPEI for three-month period during April to August of Ben Tre Station

➢ Six-month period for Ben Tre Station

For the six-month period, SPEI-6 for periods of (Jan.-Jun.), (Feb.-Jul.) and (Mar.-Aug.) showed the similar patterns. They indicated the extreme drought in 2004, severe drought in 2010, and mild droughts in 2002, 2005, 2011 and 2013. Despite this, the disagreement was still found in 2013 of SPEI-6 (Mar.-Aug.) and in 2007 for all cases (Figure 50). The results for the remaining other periods (Figure 51), were not good because they underestimated all the severity of the historical severe drought in 1998, 1999, 2005 and 2010. Moreover, they could not define drought signals in the drought years of 2007 and 2013 (Figure 51). It is recognized that SPEI-6 showed the similar patterns to SPI-6 for the period from January to June. This similarity may have occurred due to the stable meteorological characteristic such as temperature and humidity through the years of the MKD.

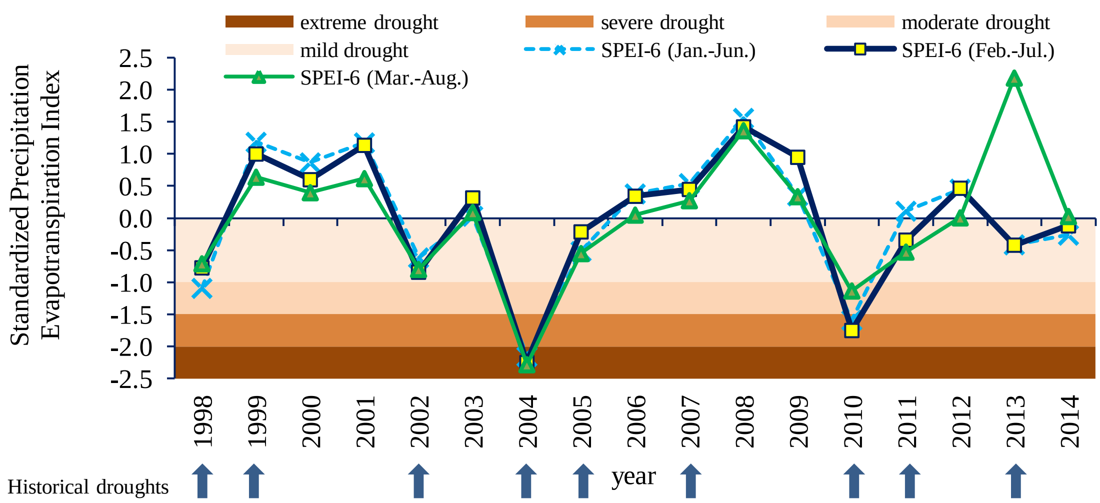

Figure 50: The SPEI for six-month period during January to August of Ben Tre Station

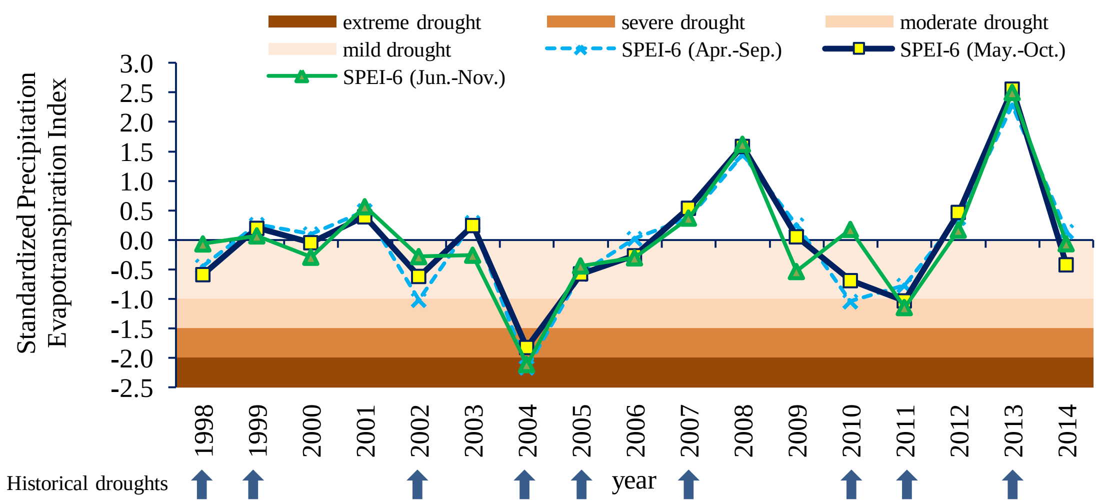

Figure 51: The SPEI for six-month period during April to November of Ben Tre Station

➢ Nine-month and twelve-month periods for Ben Tre Station

For the nine-month and twelve-month periods, the results were not good due to underestimation of the historical severe droughts in 1998, 1999, 2005 and 2010. Moreover, they failed to detect the historical mild droughts in 2007 and 2013 (Figures 52 and 53). These results are similar to a six-month period.

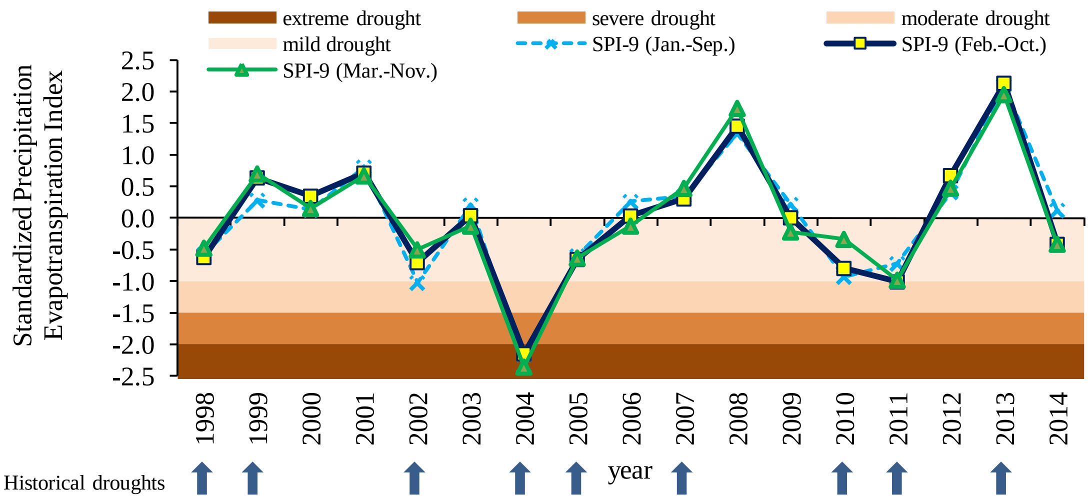

Figure 52: The SPEI for nine-month period during January to November of Ben Tre Station

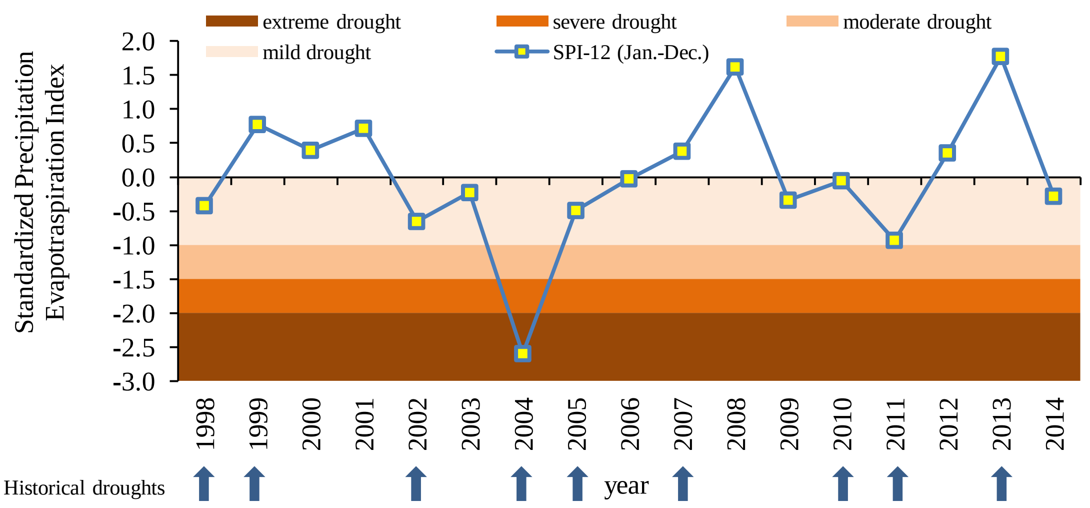

Figure 53: The SPEI for twelve-month period during January to December of Ben Tre Station

4.3.2 The correlation analysis between SPEI and affected areas

The analysis in Section 4.3.1 shows that the results of SPEI revealed the bad response patterns to the historical droughts. As a result, it presented a low R^2 varying from 0.02 to 0.103, 0.163 and 0.149 (the highest value for SPEI-6) in correlation analysis with affected areas (Figure 54). In other words, SPEI was not a promising index.

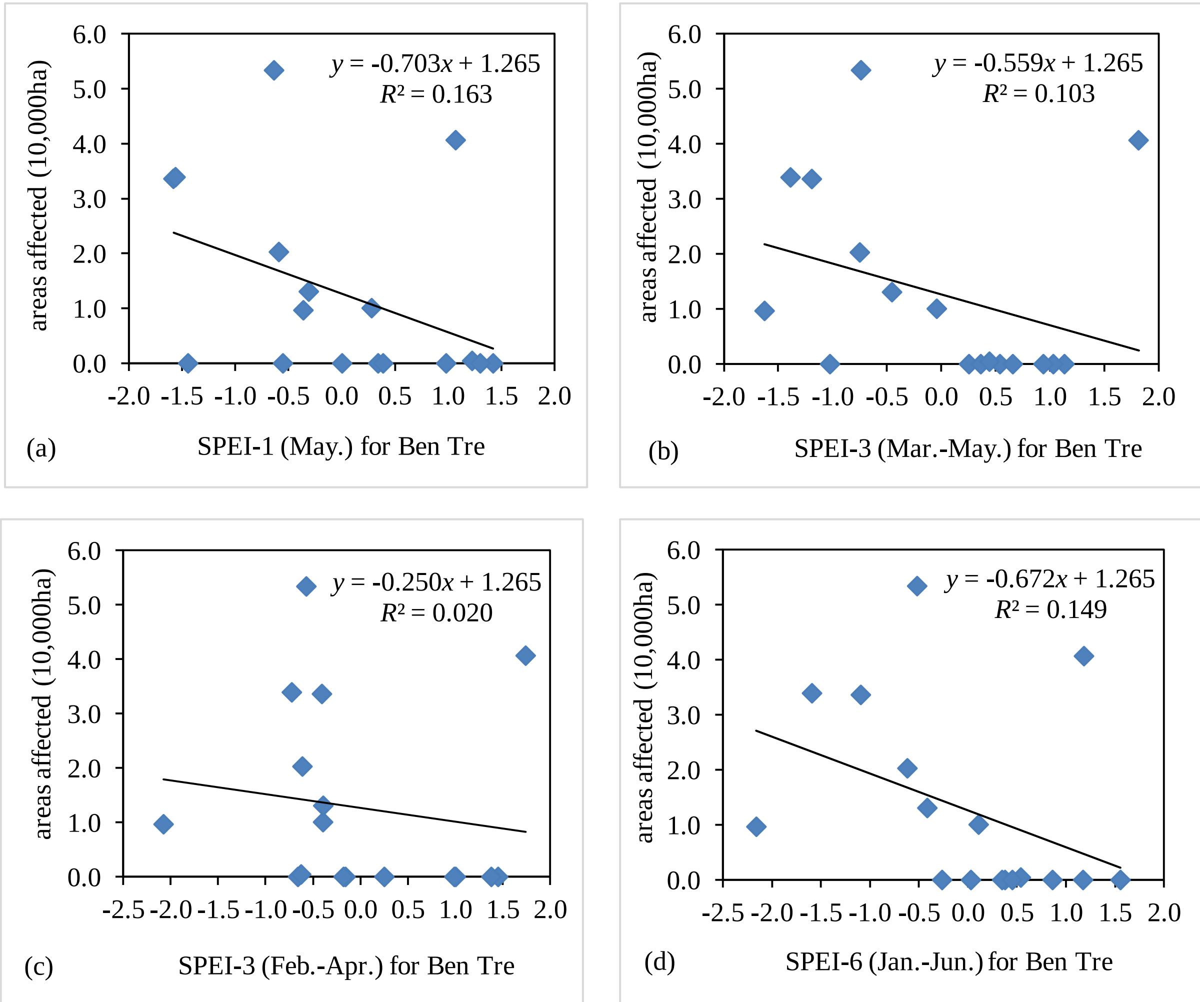

Figure 54: The correlation analysis between SPEI and areas affected
(a): SPEI for period of May, (b) SPEI for period of March to May, (c): SPEI for period of February to April, (d): SPEI for period of January to June

4.4 Salinity Index and the correlation analysis with Streamflow Drought Index

4.4.1 Salinity Index

A Salinity Index as the number of hours recording saline concentration higher than 1 ppt or 4 ppt (hereafter referred to as S1 and S4) in April or in March and April clearly showed the agreement with drought events (2004-2005, 2007, 2010, 2011, 2013 and 2016), especially in March and in March to April (Figures 55b and 55c).

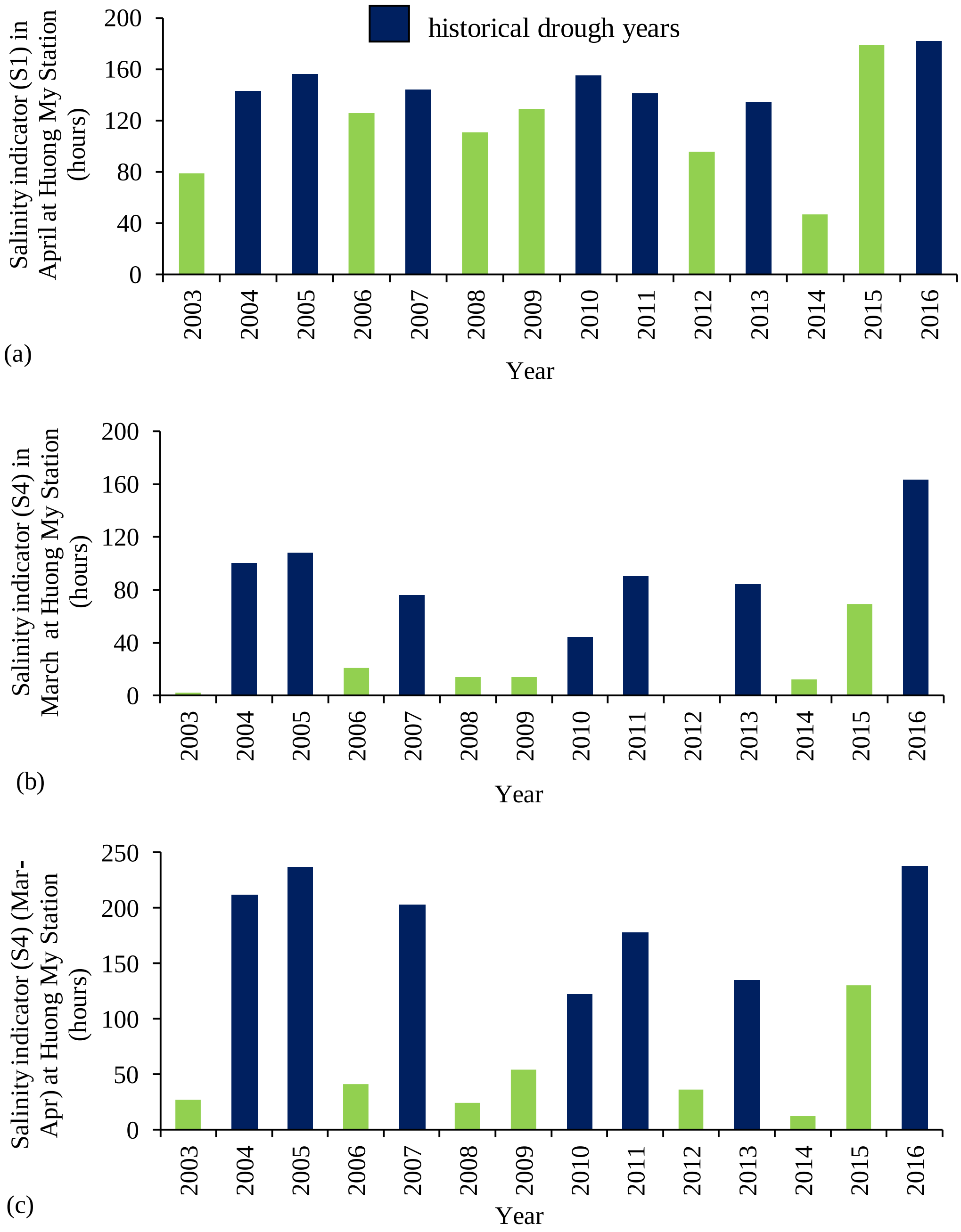

Figure 55: Salinity Index for Huong My Station

(a): S1 in April, (b): S4 in March, and (c): S4 in March and April.

4.4.2 The correlation analysis between Salinity Index and promising indices

The Salinity Index showed clear evidence of the historical droughts. On the other hand, the SDI showed good response patterns to droughts. Moreover, the salinity intrusion reaching its peak synchronizes with the drought in March or April. Therefore, this study conducted the analysis between Salinity Index and SDI to figure out an index for the drought early warning.

The correlation analysis showed the high correlation between SDI for dry periods and Salinity Index. Salinity Index 1 ppt (S1) and SDI-3 (Jan.-Mar.) presented R^2=0.755 (Figure 56a) while SDI-1 (Mar.) and SDI-2 (Feb.-Mar.) revealed R^2=0.817 and 0.788, respectively (Figures 56b and 56c). Especially, R^2 was higher in the case of S4, SDI-2 (Jan.-Feb.) and SDI-1 (Feb.) respectively produced R^2=0.844 and 0.816 (Figures 56d and 56e). Huong My is just one of saline observation stations in Ben Tre. To examine thoroughly, the salinity of other stations of Son Doc and Tra Vinh Stations were tested. Figure 57 shows the locations of these stations.

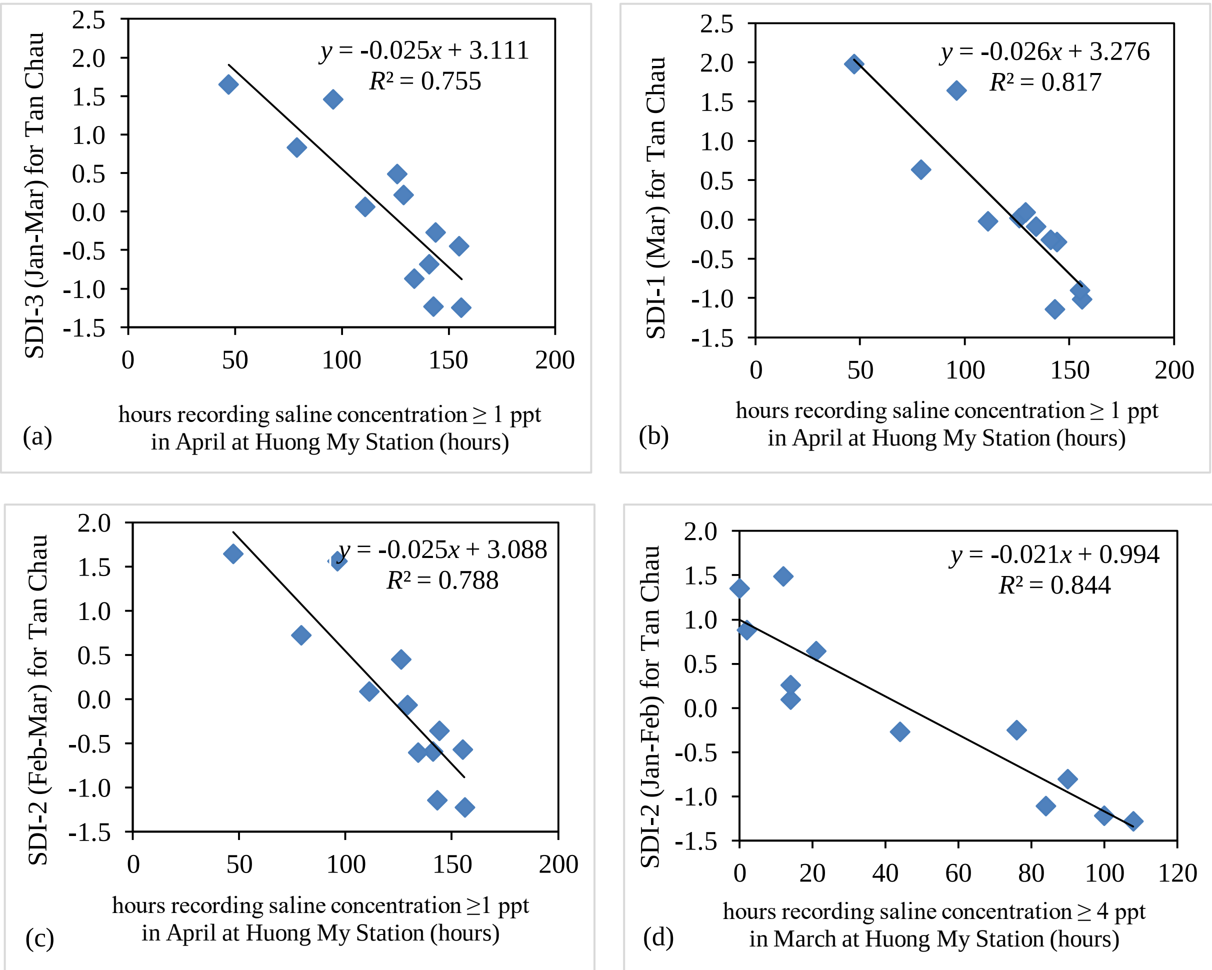

Figure 56: The correlation between SDI for Tan Chau and Salinity Index at Huong My (a): SDI-3 (January to March) and S1 in April, (b): SDI-1 (January) and S1 in April, (c): SDI-2 (February to March) and S1 in April, (d): SDI-2 (January-February) and S4 in March, and (e) SDI-1 (February) and S4 in March.

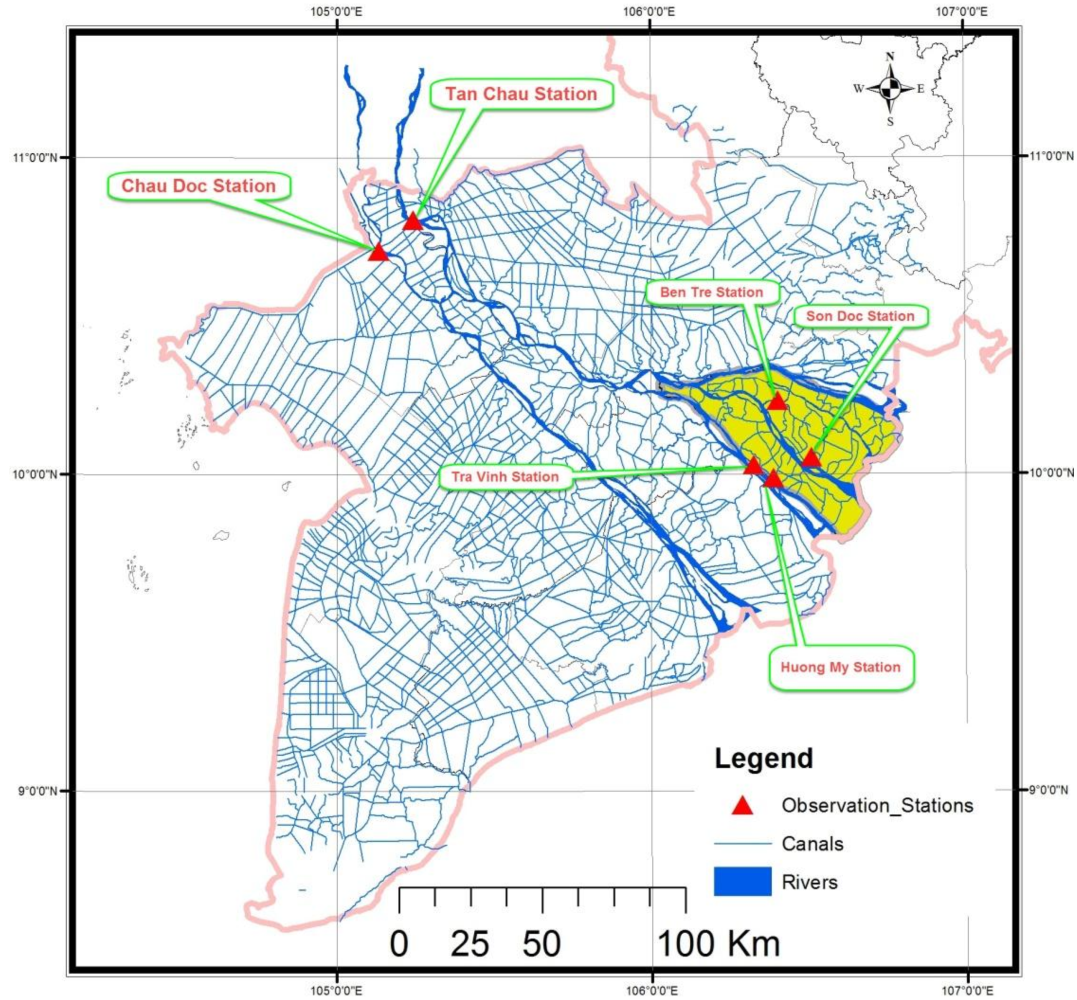

Figure 57: The location map of additional salinity observation stations for analysis

Figure 58 illustrates the results of correlation analysis between SDI for the dry season and Salinity Index. The SDI-2 (Mar.-Apr.) for Tan Chau showed a good correlation with Salinity Index, R^2 ranking from 0.54 to 0.76. Especially, SDI-2 (Jan.-Feb.) revealed a better result for the both Tan Chau and Chau Doc Station (Table 23), so it may be suitable for the early warning.

Table 23: The correlation analysis between SDI and Salinity Index (R^2)

Tan Chau Station	Huong My	Tra Vinh	Son Doc
SDI-2 (Mar.-Apr.)	0.53	0.72	0.76
SDI-2 (Jan.-Feb.)	0.75	0.81	0.75
Chau Doc Station	Huong My	Tra Vinh	Son Doc
SDI-2 (Mar.-Apr.)	0.49	0.62	0.72
SDI-2 (Jan.-Feb.)	0.72	0.82	0.84

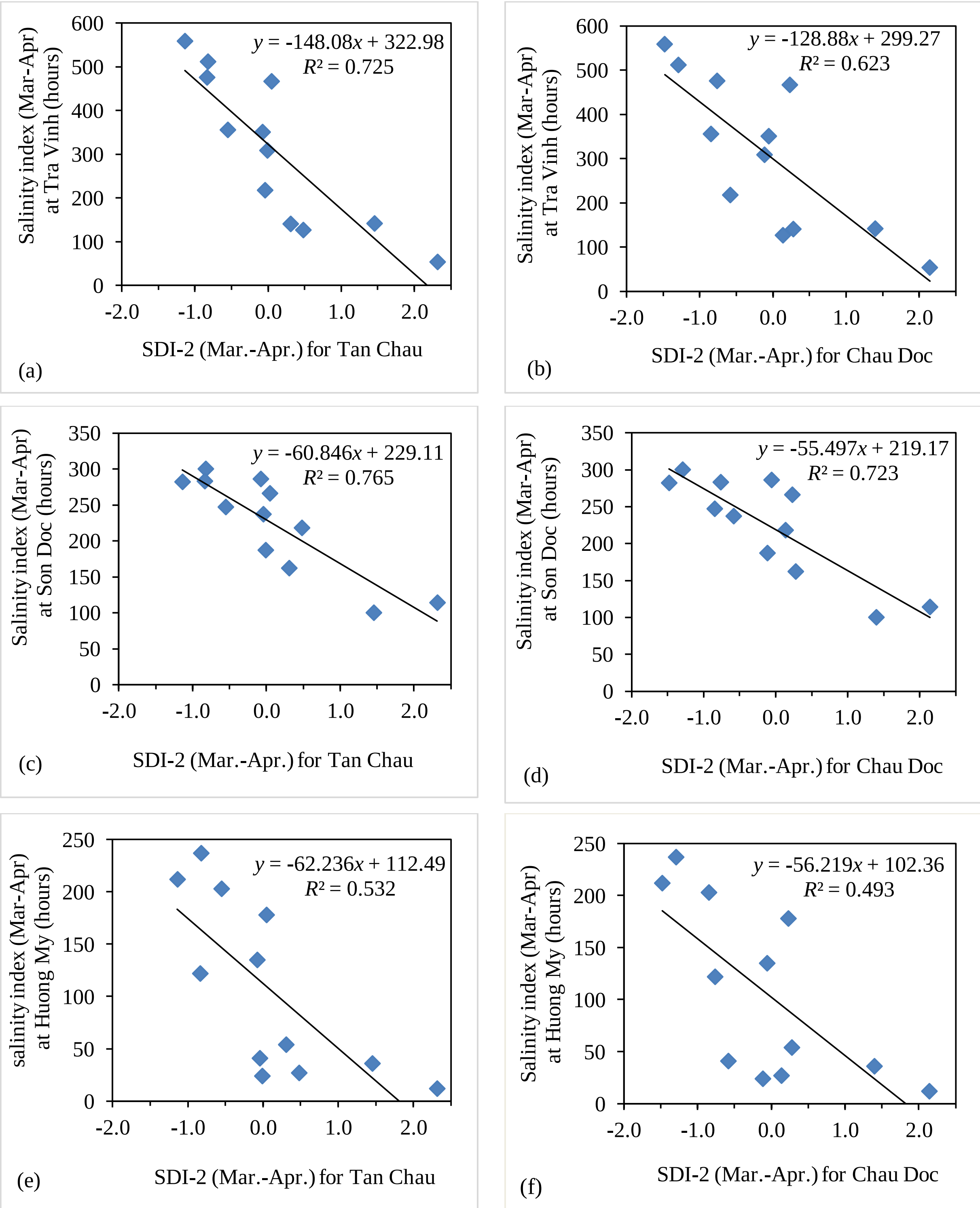

Figure 58: The correlation analysis between SDI and salinity Tra Vinh, Son Doc, and Huong My

(a): SDI-2 (Mar.-Apr.) for Tan Chau and S4 at Tra Vinh, (b): SDI-2 (Mar.-Apr.) for Chau Doc and S4 at Tra Vinh, (c): SDI-2 (Mar.-Apr.) for Tan Chau and S4 at Son Doc, (d): SDI-2 (Mar.-Apr.) for Chau Doc and S4 at Son Doc, (e): SDI-2 (Mar.-Apr.) for Tan Chau and S4 at Huong My, (f): SDI-2 (Mar.-Apr.) for Chau Doc and Huong My

4.5 Discussion

- Standardized Precipitation Index

The SPI-6 (Jan.-Jun.) showed the best responded patterns to severe drought events such as 1998, 2002, 2005, 2010 and 2013. The correlation analysis between SPI-6 (Feb.-Jul.) and areas affected revealed the highest R^2 of 0.283 while SPI-6 (Jan.-Jun.) only showed low R^2 value of 0.265. The other periods had smaller R^2 in comparison with SPI-6 (Jan.-Jun.). The results showed that rainfall in the dry season has a certain role on the severe droughts. In other words, the level of rainfall in May, June and July partially contribute to the intensity of droughts. Hence, the drought monitoring for Ben Tre should consider this point.

Table 24: The correlation analysis between SPI and areas affected (R^2)

Index	SPI-3	SPI-3	SPI-3	SPI-6	SPI-6	SPI-9
Periods	Jan.-Mar.	Feb.-Apr.	Mar.-May.	Jan.-Jun.	Feb.-Jul.	Jan.-Sep.
R^2	0.067	0.028	0.148	0.265	0.283	0.211

- Standardized Precipitation Evapotranspiration Index

SPEI-6, especially SPEI-6 (Jan.-Jun.) had quite good response patterns to severe droughts of 1998, 2004 and 2010. It had a similar trend to SPI. It is understandable because the temperature, humidity, sunshine, and wind speed in the MKD are stable during a year. However, SPEI showed the low R^2 in the correlation analysis with areas affected by droughts. The highest R^2 was obtained by SPEI-6 as 0.149 while the other periods showed very low R^2 values. Therefore, SPEI was not a good index to detect droughts.

Table 25: The correlation analysis between SPEI and areas affected (R^2)

Index	SPEI-3	SPEI-3	SPEI-3	SPEI-6	SPEI-6	SPEI-9
Periods	Jan.-Mar.	Feb.-Apr.	Mar.-May.	Jan.-Jun.	Feb.-Jul.	Jan.-Sep.
R^2	0.071	0.02	0.103	0.149	0.137	0.116

- Streamflow Drought Index and Salinity Index

Salinity Index clearly showed the evidence of droughts, especially in Son Doc Station that located in Ham Luong River running through Ben Tre Province. In the severe drought events of 2004-2005, 2010 and 2013, the maximum salinity was always higher than 15 ppt in both March and April. Additionally, the number of hours recording salinity higher than 4 ppt in both March and April at Son Doc Station are significantly higher than normal years.

The correlation analysis between SDI-2 (Jan.-Feb.) and (Mar.-Apr.), and Salinity Index (Mar.-Apr.) revealed a good correlation (Table 23). Overall, SDI-2 (Jan.-Feb.) is suitable for the drought early warning through Salinity Index. The reason is that the SI for period (Mar.-Apr.) clearly showed the evidences of the historical droughts and the SDI-2 (Jan.-Feb.) had a good association with the SI for period (Mar.-Apr.). To clarify this point, for example the historical drought of 2016, the drought reached to peak at the end of March when salinity intrusion was the most severe. This situation started to become less serious at the end of April.

The qualitative analysis showed that SDI is the most matched up with historical drought events, especially SDI-6 (Jan.-Jun.), SDI-2 (Jan.-Feb.) and SDI-1 (Apr.). One exception occurred in 2002 in cases of SDI-6 and SDI-2, and in this year only SDI-1 (Apr.) showed the drought signal. Since 2002 was a flood year, it could have been a meteorological drought or a short hydrological drought. Therefore, a hybrid index (Drought Index) that includes SDI-6 (Jan.-Jun.), SDI-2 (Jan.-Feb.) and SDI-1 (Apr.) is suggested to deal with this exception Equation (18).

$$\text{Drought Index} = \text{minimum [SDI-6; SDI-2; SDI-1]} \quad (18)$$

This suggests Drought Index covers the early, mid, and whole drought period. This intention is to aim dealing with the change of drought phenomenon in the context of climate change, especially the onset of droughts. It indicated all drought events (Table 26). This Drought Index also had a good correlation with affected areas, and it showed R^2=0.729 (Figure 59). One problem occurred in 2006 (red dot), the 2006 was reported as a drought year but no affected areas recorded (Table 22).

Table 26: The agreement between SDI and the historical droughts

Indices	The historical droughts								
	1998	1999	2002	2004	2005	2007	2010	2011	2013
SDI-6 (Jan.-Jun.)	+	+	-	+	+	+	+	+	+
SDI-2 (Jan.-Feb.)	+	+	-	+	+	+	+	+	+
SDI-1 (Apr.)	+	+	+	+	+	+	+	-	+
Drought Index	+	+	+	+	+	+	+	+	+

(+): agreement; (-): disagreement

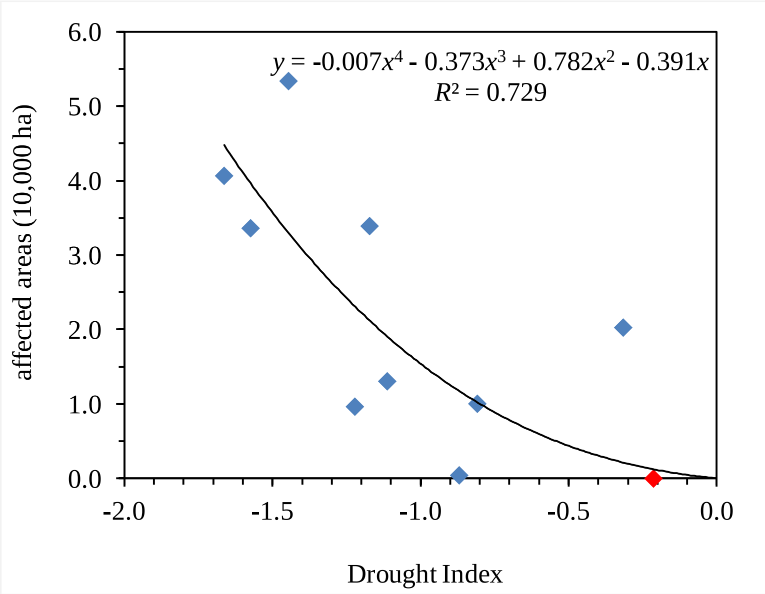

Figure 59: The correlation analysis between a hybrid index and affected areas (red dot illustrates 2006)

5 Conclusions and recommendations

5.1 Conclusions

It was aforementioned in Section 1.3.4 and Section 2.5.1 that the drought in the MKD occurs in the dry season (January to June) associated with salinity intrusion. The process of drought in the MDK starts when the low level of rainfall in the upstream in the early dry season. Then, it results in the reduction in streamflow at Tan Chau and Chau Doc Station. At the same time, the low water level period happens in the downstream of MKD. In addition, there is no rain and the water demand is the significantly high in this time. Consequently, the salinity intrusion occurs and inverts its role in affecting and aggravating back to the drought phenomenon. The importance of this point is to classify the role of each factor to droughts in the MKD. There has been confusion over the role and contribution of streamflow and salinity intrusion to droughts in the MKD. This clarification is a basic premise of the selection drought indices for monitoring and early warning.

In this study, the results from calculation were tested by the severity of the historical droughts. There is no clear classification standard of drought in the MDK; hence, the severity of the historical droughts was classified based on the affected areas and references. Based on the affected areas in Table 22 and references, this study classified the severity of historical droughts into two types. The severe drought years were in 1998, 1999, 2005, 2010 and 2016, and the mild drought years in 2002, 2004, 2007, 2011 and 2013. This step is important because it could lead to the unintended biases on the evaluation and selection of indices.

The monthly rainfall data of Ben Tre Station was used to calculate SPI for different period and time scales. Specifically, it was calculated for one-month period (SPI-1), three-month period (SPI-3), six-month period (SPI-6), nine-month period (SPI-9) and twelve-month period (SPI-12). Then, the results were tested by the historical droughts. SPIs only showed good results in the severe drought years, especially SPI-6 (Jan.-Jun.); this finding was similar to Terink (2011) for the Low Mekong Basin. It did not describe drought well for a specific area like the Mekong Delta; however, it is necessary to measure due to some areas highly depending on rainfall. Moreover, it is essential to consider SPIs for the upstream of the Mekong Delta.

The monthly rainfall (*P*) and potential evapotranspiration (*PE*) data of Ben Tre Station were used to calculate the difference between them (Di=P-PE). The *PE* had obtained from the FAO-56 Monteith equation as Equation (8). Then, Di was used to calculate SPEI. Similar to SPI, SPEI was calculated for different period and time scales. The results showed that SPEI only responded to some of the severe drought events. In fact, only rainfall significantly changes in the MDK due to seasons, the other factors such as temperature, potential evaporation, humidity, and wind speed slightly changes through the years. That is why the results of SPEI were similar to SPI. The results of SPEI and SPI are not good is reasonable because the MDK are not closed watershed. It highly depends on the hydrological regime at upstream. Furthermore, 80% of the Mekong Delta areas are agricultural land, mainly irrigated areas.

The hourly salinity data of Huong My, Son Doc and Tra Vinh were used to calculate the Salinity Index (SI). The Salinity Index was obtained from the number of hours recording salt concentration above 4 ppt. This is because; a drought index is developed to describe not only severity but also duration of droughts. Moreover, the salt concentration changes significantly following the changes in water level in rives during tidal periods. In addition, in the future, the severity of salinity intrusion could be controlled by constructing hydraulic system; however, the duration of salinity intrusion is important. Specifically, the sluice gates will be closed to prevent salinity intrusion but it could not be closed for a long time that causing environmental degradation due to trapped wastewater. In addition, the number of hours recording salt concentration enables Salinity Index to be calculated the cumulative total for target periods. The results showed that the SI in March and April clearly indicated the historical droughts. Specifically, the SI in the normal years were about 50 hours or less than while these values in the historical droughts were all higher than 120 hours. Hence, Salinity Index is suitable and good index for the drought management in Ben Tre.

Streamflow data at Tan Chau and Chau Doc Station were utilized to obtain Streamflow Drought Index (SDI) for different periods as one-month period (SDI-1), three-month period (SDI-3), and six-month period (SDI-6) as SPI. SDI showed the best result in comparison to SPI and SPEI. It is the best matched up with historical drought events as timing. Especially, SDI-6 (Jan.-Jun.), SDI-2 (Jan.-Feb.), and SDI-1 (Apr.) almost responded to the historical droughts. Therefore, a hybrid index (Drought Index) that was developed from these indices indicating all historical droughts. As a result, the Drought Index had the highest R^2=0.729 in correlation analysis with the statistic on drought damage. In the other words, it fully explains the drought phenomenon in Ben Tre Province among indices examined. SDI is good index to conduct the drought study in Ben Tre. Streamflow data is suggested to apply for the drought management in the Ben Tre.

In the future, the hydraulic infrastructure system that are under construction would alleviate the affected areas of droughts and change to the drought phenomenon. The salinity data have observed in the main rives from stations that are located outside the hydraulic infrastructure system will be less affected. Therefore, it is better to utilize the streamflow and salinity data in the drought management in Ben Tre because both of these data clearly showed the historical droughts in this study. To strengthen this argumentation, the correlation analysis between SDI and salinity was conducted to figure out an index for the early warning. This is because the number of hours recording saline concentration higher than 4 ppt in the period of March to April clearly showed the drought signals in the historical drought years. Following this concept, the regression analysis showed that SDI-2 (Jan.-Feb.) of both Tan Chau and Chau Doc Station had a good association with Salinity Index as 4 ppt (Feb.-Jun.) at Huong My, Tra Vinh and Son Doc Station. The R^2 for these cases were 0.76, 0.84 and 0.84 respectively. As a result, SDI-2 (Jan.-Feb.) is possible to apply for the drought early warning.

5.2 Recommendations

In this study, the length of data was only 17 years (1998-2014) and only standard normal distribution was considered; therefore, the results might be affected. A rigorous analysis with the longer length of data (ideally 30 years) and different probability distributions may contribute a better view. This reason is that in Section 2.1 mentioned it is that historical droughts occurred five times in the period from 1981 to 1987. Hence, it is suspected that the cycle of the hydrology is in the other of 30 years; therefore, there was the high frequency of the occurrence of drought in the period from 2004 to 2013 with six times.

Based on the discussion above, this study recommends applying SDI-6 (Jan.-Jun.) together with SDI-2 (Jan.-Feb.) and SDI-1 (Apr.) of Tan Chau and Chau Doc for drought monitoring in Ben Tre. SDI-2 (Jan.-Feb.) not only describes droughts well but also associates with a Salinity Index (4 ppt) from March to April in saline observation gauges in Ben Tre Province. However, it is needed to examine with the longer data set and other gauges in the upstream of the province (40-50 km from the sea). In Ben Tre, there is a growing tendency of salinity intrusion with an increase in severity so that many additional salinity observation gauges are suggested to install. The involvement of the new gauges may contribute a better view on the association between streamflow in upstream and salinity intrusion in the downstream. The change in salt concentration of surface water along rivers associated with the change in streamflow is crucial for the drought monitoring and early warning. Lastly, a hybrid index includes the SDI-6 (Jan.-Jun.), SDI-1 (Apr.) and SDI-2 (Jan.-Feb.) is recommended for drought management in Ben Tre while SDI-2 (Jan.-Feb.) is suggested for the drought early warning.

Furthermore, the application of drought indices requires an essential step in which the indices should be tested on a certain drought and the explanation of water supply system during this drought. In Ben Tre, many sluice gates and river embankments are under construction, and these facilities may affect the river flow and the concentration of brackish water when they are completed. Therefore, the operational procedure for the water works system in the Ben Tre has not been proposed yet. In the future, the severity of salinity intrusion could be controlled by constructing hydraulic system; however, the duration of salinity intrusion is important. Specifically, the sluice gates will be closed to prevent salinity intrusion but it could not be closed for a long time that causing environmental degradation due to trapped wastewater. It is necessary to open periodically for fresh water intake and wastewater disposal. In other words, there is no index could accurately explain drought event because water availability depending on water supply system (Karavitis *et al.*, 2011: Rossi, 2008).

The meteorological data from only Ben Tre Station was utilized therefore it would occur the biases due to various reasons. For example, the renovation of the Ben Tre Station in 2011 with the new facilities and equipment may affect data. Hence, it is necessary to explain and collect the information related to the history of stations.

The triple paddy is a major challenge in the context of drought to water management. From environment and water management’s point of view, triple paddy should be restricted or gradually replaced by others with less water demand. Since 2017, Ben Tre has applied double paddy to avoid risk from salinity from February to April, specifically Winter-Spring Paddy (from early November to late February) and Summer-Autumn Paddy (from early June to early October).

References

ADB. (2011). *Preparing The Greater Mekong Sub-region Flood and Drought Risk Management and Mitigation Project: Final main report for Viet Nam*. Regional Technical Assistance Report Project Number: 40190. New Delhi, India.

ADPC. (2007). *Drought Information Booklet for Vietnam*. Asian Disaster Preparedness Center. http://www.adpc.net/v2007/Programs/DMS/PROGRAMS/FPP/Downloads/4GoodPracticeDocuments/Drought%20Booklet%20vietnam%20.En.pdf.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). FAO 56: Crop Evapotranspiration (guidelines for computing crop water requirements). *FAO Irrigation and Drainage Paper, 300*(56), 300. https://doi.org/10.1016/j.eja.2010.12.001.

Balint, Z., Mutua, F., Muchiri, P., & Omuto, C. T. (2013). Monitoring Drought with the Combined Drought Index in Kenya. *Developments in Earth Surface Processes, 16*, 341–356. https://doi.org/10.1016/B978-0-444-59559-1.00023-2

Banimahd, S. A., & Khalili, D. (2013). Factors Influencing Markov Chains Predictability Characteristics, Utilizing SPI, RDI, EDI and SPEI Drought Indices in Different Climatic Zones. *Water Resources Management,27*(11), 3911-3928. doi:10.1007/s11269-013-0387-z.

Beilfuss, R. and Triet, T. (2014). *Climate Change and Hydropower in the Mekong River Basin: A Synthesis Research*. Vientiane, Lao PDR: Mekong River Commission-GIZ Cooperation Programme

Ben Tre Statistical Office. (2015). *Ben Tre Statistical Yearbook 2014*. Ben Tre, Vietnam.

Cai, W., Purich, A., Cowan, T., van Rensch, P., & Weller, E. (2014). Did climate change-induced rainfall trends contribute to the Australian millennium drought? *Journal of Climate, 27*(9), 3145-3168. https://doi.org/10.1175/JCLI-D-13-00322.1.

Chhinh, N & Millington, A.C. (2015). Drought monitoring for rice production in Cambodia. *Climate*, *3*(4), 792–811. https://doi.org/10.3390/cli3040792

Christos A. Karavitis, Stavros Alexandris, Demetrios E. Tsesmelis, & George Athanasopoulos. (2011). Application of the Standardized Precipitation Index (SPI) in Greece. *Water*, *3*(4), 787-805.

Dubrovsky, M., Svoboda, M. D., Trnka, M., Hayes, M. J., Wilhite, D. A., Zalud, Z., & Hlavinka, P. (2009). Application of relative drought indices in assessing climate-change impacts on drought conditions in Czechia. *Theoretical and Applied Climatology, 96*(1), 155-171.

Fisher, M., & Botterill, L. C. (2003). *Beyond Drought: People, Policy and Perspectives*. Collingwood, Vic: CSIRO.

Geological Survey (U.S.). (1960). *General Introduction and Hydrologic Definitions: Manual of Hydrology: Part 1. General Surface-water Techniques*. Washington, D.C: GPO.

Guttman, N. B. (1994). On the sensitivity of sample L-moments to sample size. *Journal of Climate, 7*(6), 1026-1029.

Guttman, N. B. (1999). Accepting the Standardize Precipitation Index: A calculation algorithm [1]. *JAWRA Journal of the American Water Resources Association*, *35*(2), 311–322. https://doi.org/10.1111/j.1752-1688.1999.tb03592.x.

Hayes M. (2000). Revisiting the SPI: clarifying the process. *Drought Network News*, *12*(1), 13–14 [available online at http://enso.unl.edu.ndmc/center/dnn/winspr.pdf].

Heim, J. R. R. (2002). A Review of Twentieth-Century Drought Indices Used in the United

States. *Bulletin of the American Meteorological Society*, *83*(8), 1149-1165.

Helsloot, I. (2012). *Mega-crises: Understanding the Prospects, Nature, Characteristics, and the Effects of Cataclysmic Events*. Springfield, Ill: Charles C Thomas, Publisher.

Homdee, T., Pongput, K., & Kanae, S. (2016). A comparative performance analysis of three standardized climatic drought indices in the Chi River Basin, Thailand. *Agriculture and Natural Resources, 50*(3), 211-219.

Hong, X., Guo, S., Zhou, Y., & Xiong, L. (2015). Uncertainties in assessing hydrological drought using streamflow drought index for the upper Yangtze River basin. *Stochastic Environmental Research and Risk Assessment, 29*(4), 1235-1247. doi:10.1007/s00477-014-0949-5

ICEM. (2010). *MRC Strategic Environmental Assessment (SEA) of Hydropower on the Mekong Mainstream*: Summary of the Final Report. Hanoi, Vietnam: Ministry of Natural Resources and Environment.

Intergovernmental Panel on Climate Change (IPCC). (2007). Climate Change 2007: Impacts, adaptation and vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the IPCC, Parry ML, Canzaniani OF, Palutikof JP, van der Linden P J, Hanson CE (Eds.): Cambridge University Press, Cambridge, UK.

JICA. (2013). *Project for Climate Change Adaptation for Sustainable Agriculture and Rural Development in the Coastal Mekong Delta in Vietnam*. Technical report.

JICA. (2016). *The Preparatory Survey for Ben Tre Water Management Project*. Technical report.

Keskinen, M., Someth, P., Salmivaara, A., & Kummu, M. (2015). Water-energy-food nexus in a transboundary river basin: The case of Tonle Sap Lake, Mekong River Basin. *Water (Switzerland), 7*(10), 5416–5436. https://doi.org/10.3390/w7105416.

Łabędzki, L., & Bąk, B. (2014). Meteorological and agricultural drought indices used in drought monitoring in Poland: a review. *Meteorology Hydrology and Water Management*, *2*(2), 1–12. Retrieved from: yadda.icm.edu.pl/yadda/element/labedzki_bak_meteorological_2_2014.pdf.

Le, T. T.H., Nguyen, K. A. T., Jolly, C. M. (2016). Perception, preparedness and severity of climate change triggered events in Ben Tre Province, Vietnam. *International Journal of Food and Agricultural Economics. Economics, 4*(4), 29-44.

Mahfouz, P., Mitri, G., Jazi, M., & Karam, F. (2016). Investigating the Temporal Variability of the Standardized Precipitation Index in Lebanon. *Climate, 4*(2), 27.

McKee, T. B., Doesken, N. J., Klleist, J. (1993). The Relationship of drought frequency and duration to time scales. Paper Presented at *AMS 8th Conference on Applied Climatology*. American Meteorological Society, Anaheim, CA. 179–184. https://doi.org/citeulike-article-id:10490403

MDP. (2013). *Mekong Delta Plan*. Vietnam-Netherlands Co-operation, Water Sector Synthesis, Hanoi, Vietnam, February 2013.

Mekong River Commission (MRC). (2005). *Overview of the Hydrology of the Mekong Basin*. Vientiane, Lao PDR: Mekong River Commission.

Mekong River Commission (MRC). (2012). *The Impact and Management of Floods and Droughts in the Lower Mekong Basin and the Implication of Possible Climate Change*. Vientiane, Lao PDR: Mekong River Commission.

Mekong River Commission and Ministry of Water Resources of the People's Republic of China (2016). *Technical Report – Joint Observation and Evaluation of the Emergency Water Supplement from*

China to the Mekong River. Mekong River Commission, Vientiane, Lao PDR.

Mishra, A. K., & Singh, V. P. (2010, September). A review of drought concepts. *Journal of Hydrology, 391*(1), 202-216 https://doi.org/10.1016/j.jhydrol.2010.07.012.

Mishra, A. K., & Singh, V. P. (2011). Drought modelling – A review. *Journal of Hydrology, 403*(1), 157-175. http://dx.doi.org/10.1016/j.jhydrol.2011.03.049.

MONRE. (2009). *Climate Change and Sea Level Rise, Scenarios for Viet Nam.* Ministry of Natural Resources and Environment, Vietnam.

MONRE. (2016). *Groundwater in Long An, Tien Giang and Ben Tre, Viet Nam.* Ministry of Natural Resources and Environment, Vietnam.

MRC. (2009a). *Economic, Environmental and Social Impact Assessment of Basin-wide Water Resources Development Scenarios, Assessment Methodology*. Mekong River Commission (MRC) technical note, Vientiane Laos. Retrieved from: www.mrcmekong.org/assets/Other-Documents/BDP/Tech-Note2-Scenarioassessment-methodology-complete-Report091104.pdf

MRC. (2011). *Planning Atlas of the Lower Mekong River Basin*. Mekong River Commission (MRC) technical note, Vientiane Laos.

Nalbantis, I. (2008). Evaluation of a Hydrological Drought Index. *European Water, 23*(24), 67–77.

Nalbantis, I., & Tsakiris, G. (2009). Assessment of hydrological drought revisited. *Water Resources Management, 23*(5), 881–897. https://doi.org/10.1007/s11269-008-9305-1

Naresh Kumar, M., Murthy, C. S., Sesha Sai, M. V. R. and Roy, P. S. (2009), On the use of Standardized Precipitation Index (SPI) for drought intensity assessment. *Meteorological Applications, 16*(3), 381–389. https://doi.org/10.1002/met.136.

Nguyen, K.A.T.; T.T.H. Le; C.N.P.T. Bui; T.A.T. Nguyen; and C.M. Jolly. (2017). *Climate change impact and vulnerability assessment and economic analysis of climate change adaptation strategies in Ben Tre province, Vietnam*. EEPSEA Research Report No. 2017-RR14. Economy and Environment Program for Southeast Asia, Laguna, Philippines.

Nguyen, L.B., Li, Q. F., Ngoc, T. A., Hiramatsu, K. (2015). Drought assessment in cai river basin, Vietnam: A comparison with regard to SPI, SPEI, SSI, and SIDI. *Food Weekly Focus,60(2)*, 417-425.

Oxfam International. (2008). *Vietnam: Climate Change, Adaptation and Poor People.* Oxfam International.

Palmer, W. C. (1965). Meteorological Drought. *U.S. Weather Bureau, Res. Pap. No. 45*.
Retrieved from https://www.ncdc.noaa.gov/temp-and-precip/drought/docs/palmer.pdf.

Palmer, W.C. (1968). Keeping track of crop moisture conditions, nationwide: The new crop moisture index. *Weatherwise, 21*(4), 156–161. https://doi.org/10.1080/00431672.1968.9932814.

Pearson, K. (1901). On lines and planes of closest fit to systems of points in space. *Philosophical Magazine Series 6, 2*(11): 559-572. https://doi.org/10.1080/14786440109462720.

Potop, V. (2011). the Application a New Drought Index - Standardized Precipitation Evapotranspiration Index in the Czech Republic. *Mikroklima a Mezoklima Krajinnych Struktur an Antropogennnich Prostredi, 2*(2010), 4.2.

Rasanen, T. A., Kummu, M., Koponen, J., & Lauri, H. (2012). Downstream Hydrological Impacts of Hydropower Development in the Upper Mekong Basin. *Water Resources Management, 26*(12), 3495–3513. https://doi.org/10.1007/s11269-012-0087-0.

Renaud, F.G., Le, T.T.H., Lindener, C., Guong, V.T., Sebesvari, Z., 2015. Resilience and shifts in agro-ecosystems facing increasing sea-level rise and salinity intrusion in Ben Tre Province, Mekong Delta. *Climatic Change, 133*(1), 69-84. http://dx.doi.org/10.1007/s10584-014-1113-4.

Ribbe, L., Nauditt, A., Meinardi, D., Morbach, M., Becker, R., & Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). (2013). *Comparison of key drivers regarding their significance for Hydro-meteorological Extremes and Their Impacts on Selected Hotspots within the Mekong River Basin.* Vientiane, Lao PDR: Mekong River Commission.

Rossi, G., & Cancelliere, A. (2013). Managing drought risk in water supply systems in Europe: a review. *International Journal of Water Resources Development, 29*(2), 272-289. http://dx.doi.org/10.1080/07900627.2012.713848

Rossi, G., Nicolosi, V., & Cancelliere, A. (2008). Recent methods and techniques for managing hydrological droughts. *Drought Management: Scientific and Technological Innovations*, 251 266. Retrieved:http://om.ciheam.org/article.php?IDPDF=800450http://www.ciheam.org/

Sharma, T. C., & Panu, U. S. (2008). Drought analysis of monthly hydrological sequences: A case study of Canadian rivers. *Hydrological Sciences Journal, 53*(3), 503-518. doi:10.1623/hysj.53.3.503.

Shukla, S., & Wood, A. W. (2008). Use of a standardized runoff index for characterizing hydrologic drought. *Geophysical Research Letters*, *35*(2). Retrieved from https://doi.org/10.1029/2007GL032487.

SIUP. (2012). *The Urban and Rural Planning for Ben Tre Province towards 2030*. Ho Chi Minh, Vietnam: Sub-Institute for Urban and Rural Planning. (in Vietnamese).

SIWRP. (2016). *Water Resources Planning for the Agricultural Restructuring in the Mekong Delta.* Ho Chi Minh, Vietnam: Southern Institute for Water Resources Planning. (in Vietnamese).

SIWRP. (2009). *Water Resources Planning for the Area Between Tien and Hau River in the Mekong Delta.* Ho Chi Minh, Vietnam: Southern Institute for Water Resources Planning. (in Vietnamese).

SIWRP. (2011a). *Water Resources Planning of Ben Tre Province Toward 2020*. Technical report. Ho Chi Minh, Vietnam: Southern Institute for Water Resources Planning (in Vietnamese).

SIWRP. (2011b). *Water Resources Planning of the Mekong Delta under the context of climate change and sea level rise*. Technical report. Ho Chi Minh, Vietnam: Southern Institute for Water Resources Planning (in Vietnamese).

Steinemann, A. C., & Cavalcanti, L. F. N. (2006). Developing Multiple Indicators and Triggers for Drought Plans. *Journal of Water Resources Planning and Management*, *132*(3), 164–174. https://doi.org/10.1061/(ASCE)0733-9496(2006)132:3(164)

Svoboda M., Hayes M. and Wood D. (2012). *Standardized Precipitation Index User Guide.* WMO-No. 1090. https://doi.org/10.1175/2007JCLI1348.1

Tabari, H., Nikbakht, J., & Hosseinzadeh Talaee, P. (2013). Hydrological Drought Assessment in Northwestern Iran Based on Streamflow Drought Index (SDI). *Water Resources Management*, *27*(1), 137–151. https://doi.org/10.1007/s11269-012-0173-3

Terink, W., Immerzeel, W.W. and Droogers, P. (2011). *Drought Monitoring and Impact Assessment in the Mekong River Basin.* Report Future Water: 104, Wageningen.

The United Nations Secretariat of the International Strategy for Disaster Reduction (UNISDR). (2009). *Drought Risk Reduction Framework and Practices: Contributing to the Implementation* *of the Hyogo Framework for Action*. Geneva: United Nations.

Tinh, N. D. (2012). Evaluation and Assessment the Meteorological Drought in the Mekong Delta. *Water Resources Journal*. Ha Noi, Vietnam: University of Thuy Loi.

Tsakiris, G., & Vangelis, H. (2005). Establishing a drought index incorporating evapotranspiration. *European Water*, *9*(10), 3–11.

Tsakiris, G., Pangalou, D., & Vangelis, H. (May 01, 2007). Regional Drought Assessment Based on the Reconnaissance Drought Index (RDI). *Water Resources Management: an International Journal - Published for the European Water Resources Association*, *21* (5), 821-833. https://doi.org/10.1007/s11269-006-9105-4

Ty, T. V., Hoai, D. T. V., and Minh, H. T. V.(2015). Drought Mapping of the Mekong Delta in the Context of Climate Change. *Can Tho University, Scientific Journal*. Can Tho, Vietnam: Can Tho University.

United Nation (UN). (2016). *Viet Nam Drought and Saltwater Intrusion Rapid Assessment Report.* Ha Noi, Vietnam: The United Nations in Vietnam.

Van Loon, A. F. (2015). Hydrological drought explained. *Wiley Interdisciplinary Reviews: Water*, *2*(4), 359–392. https://doi.org/10.1002/wat2.1085

Vicente-Serrano, S. M., López-Moreno, J. I., Beguería, S., Lorenzo-Lacruz, J., Azorín-Molina, C., & Morán-Tejeda, E. (2012). Accurate Computation of a Streamflow Drought Index. *Journal of Hydrologic Engineering*, *17*(2), 318–332. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000433

Vicente-Serrano, S., Beguería, S., & López-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, *23*(7), 1696-1718. doi:10.1175/2009JCLI2909.1

Villarreal, M. L., Norman, L. M., Buckley, S., Wallace, C. S. A., & Coe, M. A. (2016). Multi-index time series monitoring of drought and fire effects on desert grasslands. *Remote Sensing of Environment*, *183*, 186-197. doi:http://dx.doi.org/10.1016/j.rse.2016.05.026.

Vreugdenhil, H., Hoang, B., Offermans, A. (2012). Perspectives on Water Management in the Vietnamese Mekong Delta. *In Proceedings of the 2nd World Sustain*. Sciforum Electronic Conference Series, Vol. 2, 2012.

Wang, K., Li, Q., Yang, Y., Zeng, M., Li, P., & Zhang, J. (2015). Analysis of spatio-temporal evolution of droughts in Luanhe River Basin using different drought indices. *Water Science and Engineering*, *8*(4), 282–290. https://doi.org/10.1016/j.wse.2015.11.004

Wilhite, D. A., & Glantz, M. H. (1985). Understanding the drought phenomenon: The role of definitions. *Water International*, *103*, 111-120. https://doi.org/10.1080/02508068508686328.

Wilhite, D. A., & Pulwarty, R. S. (2005). Drought and Water Crises: Lessons learned and the road ahead. In D. A. Wilhite (Ed.), *Drought and Water Crises* (pp. 389– 398). Boca Raton, FL: Taylor & Francis.

Wilhite, D. A., Botterill, L., & Monnik, K. (2005). National Drought Policy: Lessons Learned from Australia, South Africa and the United States. In D. A. Wilhite (Ed.), *Drought and water crises* (pp. 137– 172). Boca Raton, FL: Taylor & Francis.

Wilhite, D. A., Hayes, J. M., & Knutson, L. C. (2005). Drought Preparedness Planning: Building Institutional Capacity. In D. A. Wilhite (Ed.), *Drought and Water Crises: Science, Technology, and Managment Issues* (p. 402).

World Bank. (2016). *Vietnam - Mekong Delta Integrated Climate Resilience and Sustainable Livelihoods (MD-ICRSL) Project: environmental assessment*. Vietnam; Retrieved from: http://documents.worldbank.org/curated/en/855731468312052747/Regional-environmental-assessment-report.

World Meteorological Organization (WMO) and Global Water Partnership (GWP). (2016). *Handbook of Drought Indicators and Indices.* (Svoboda, M., Fuchs, B. A.,). Integrated Drought Management Programme (IDMP), Integrated Drought Management Tools and Guidelines Series 2. Geneva.

Wu, H., Hayes, M. J., Weiss, A., & Hu, Q. (2001). An evolution of the standardized precipitation index, the China-Z index and the statistical Z-score. *International Journal of Climatology*, *21*(6), 745–758. https://doi.org/10.1002/joc.658.

WWF. (2012). *Rapid Vulnerability Assessment and Adaptation Options for Ben Tre province*. Project report. Completed under the 'Global Cooperation on Water Resource Management' and the 'Capacity Building and Sustainable Production' programme by World Wildlife Fund for Nature.

WWF. (2013). *Ecosystem-based Adaptation to Climate change in Ben Tre province, Vietnam*. Project completion report. Department of Natural Resources and Environment of Ben Tre and World Wildlife Fund.

Yeh, C. F., Wang, J., Yeh, H. F., & Lee, C. H. (2015). SDI and Markov chains for regional drought characteristics. *Sustainability (Switzerland)*, *7*(8), 10789–10808.

Zoljoodi, M., & Didevarasl, A. (2013). Evaluation of spatial-temporal variability of drought events in Iran using Palmer drought severity index and its principal factors (through 1951-2005). *Atmospheric and Climate Sciences*, *3*(2), 193-207. doi:10.4236/acs.2013.32021