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Drought Monitoring using Drought Indices and GIS Techniques in Kuan Kreng Peat Swamp, Southern Thailand

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Abstract

This research aims to study the spatial characteristics of drought throughout the year in Kuan Kreng Peat Swamp (KKPS) by using various drought indices. Meteorological drought indices were analysed by using data of precipitation during the period of the study 1984 - 2013. The standardized precipitation index (SPI) was calculated on the basis of precipitation deficit. Vegetation-based drought indices were also derived from the analysis of Landsat satellite images based on the normalized difference drought index (NDDI). In addition, hydrological drought indices were studied based on the water table level (WTL) and drought assessments were also based on the standardized water level index (SWI) calculated from data on surface water and the groundwater level in the peat swamp forest. The results are presented in the form of maps of geographic information system (GIS) based on the SPI, NDDI, WTL and SWI. The study focused on the droughts in 2 years: 2010 and 2012. The year 2010 was subject to the El Niño phenomenon while 2012 was not. However, peat fires occurred in both years. The assessment of drought using the SPI, WTL and SWI reveals that drought occurred from April to October due to there being less rainfall during that period. The NDDI reveals that vegetation was affected by the drought between February and September due to this being the summer season with high temperatures and less moisture in the air. The 3 types of drought indices used, meteorological, vegetation and hydrological for the period of April to September indicate the likelihood of peat fires in the KKPS area during that period. The results of this study contribute to the understanding of how spatial and temporal data can be used to predict and measure the severity of drought, to which the study area is vulnerable and to the concomitant risk of peat fires.

Keywords: Kuan Kreng Peat Swamp (KKPS), drought, SPI, NDDI, WTL, SWI

Introduction

Drought is a natural hazard that has negative effects on people and the environment and occurs in virtually all climatic zones, and also causes other disasters. Droughts are mostly related to a reduction in the amount of precipitation over an extended period of time, such as a season or a year. Droughts impact both surface and groundwater resources and can lead to forest fires [1-3]. The Kuan Kreng Peat Swamp (KKPS) is the second largest area of tropical peat swamp forest in southern Thailand; the largest area is To Daeng peat swamp forest in Narathiwat province [4]. It is located in the north of Songkhla Lake basin and Pak Phanang Lake basin [5]. The area is important as it is a source of biodiversity, water and food.

Moreover, it is a source of sedge which is an important raw material for the local industry in the surrounding communities [6]. The wetland of the inner swamp forest called Kuan Ki Sian is situated at Thale Noi and is a wildlife-protected wetland area. It was considered to be a perfect area to be designated as a national swamp and was listed as the first Ramsar site in Thailand on 13 May 1998, the 948th such site to be listed in the world [7].

Today, there are many changes around the area of the KKPS as a result of the development of infrastructure in the area as well as changes in land use. The land is under threat because of the ongoing expansion of oil palm plantations as well as the increasing need for water for agricultural purposes. A lot of people in the region suffer because of peat fires and water shortages caused by the degradation of the peatland [8]. This results in a reduction of the amount of water flowing into the peat swamp forest. The level of the ground water table in the swamp forest is a key factor in preventing subsidence as well as effective control of peat fires in the peatland. The risk of peat fires in KKPS has been increased by the draining of the peatland and the occurrence of drought. Both drought and peat fire have been ever present threats to the natural environmental in KKPS over the course of the recent past [6,9].

The objective of this study was to propose the use of spatial analysis as a method of assessing the areas of KKPS subject to drought using a geographical information system (GIS) to map the combined drought indices. The standardized precipitation Index (SPI) has been used to monitor meteorological drought in previous studies [10-13] and the normalized difference drought index (NDDI) has been used to assess vegetative drought [11,14-16] with both the standardized water level index (SWI) and the water table level (WTL) having been used to analyze hydrological drought [17,18]. In this study, maps of drought indices in KKPS were generated using the GIS technique showing drought indices appearing during the dry seasons of the years studied. The study focused on the years 2010 and 2012. 2010 was a moderate El Niño year [19] while 2012 was a non- El Niño year. The phenomenon of forest fires in KKPS was studied throughout the period. The use of the GIS Technique to study drought allows predictions of areas where peat fires are likely to occur in the future and the formulation of guidelines for dealing with the problem. The study will therefore contribute to hazard management and the future sustainability of the tropical peatland in KKPS.

Materials and methods

Study area

The study area of this research is the KKPS area covering 4,418.52 km^2 (latitude N7˚37′ 17.41″ - N8˚26′ 06.34″ and longitude E99˚41′ 58.63″ - E100˚22′ 03.42″). **Figure 1** shows a digital elevation model (DEM) of the area in which the site is located, generated utilizing raster GIS procedures. The topographical features of KKPS are a plain containing swamp forest and wetlands containing water throughout almost the whole year. The water resources in KKPS need to be managed to control flooding during the rainy (monsoon) season, and are utilized to allow the irrigation of areas under vegetation, and use for agriculture during the dry season. The normal water table depth varies in different lithologic domains. In the peatland, during the rainy season, the water table is 100 cm above the surface level of the peat, while in the dry season, the water table may drop to a depth ranging from 10 - 50 cm below the peat surface. The soil in the swamp forest is almost completely composed of a naturally accumulated surface layer of dead organic material (peat). Most of the lowland parts of the wetland have peat soils whereas organic soil covers the upland part of the wetland. In the KKPS peatland, agricultural activities are directly controlled by the rainfall and the availability of water resources. In the plain area and the peatland most of the land is used to cultivate cajuput trees and sedge or as grassland. The area around the boundary of the peatland is also used as animal pasture and for the collection of naturally occurring plant products, as well as for oil palm plantations and paddy fields [9,20]. A flowchart of the method used to process the data collected appears in **Figure 2**.

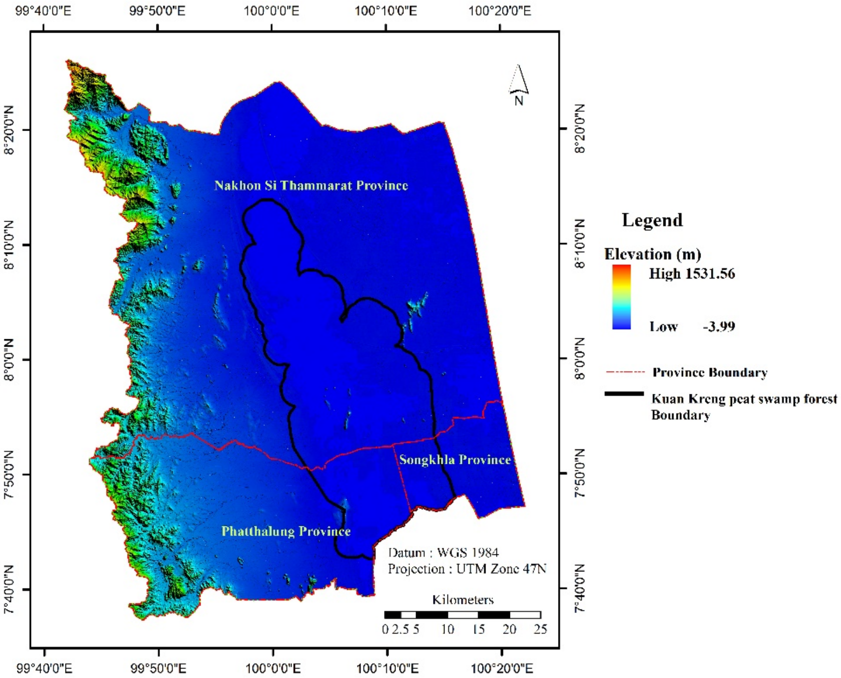


Figure 1 Location of study area.

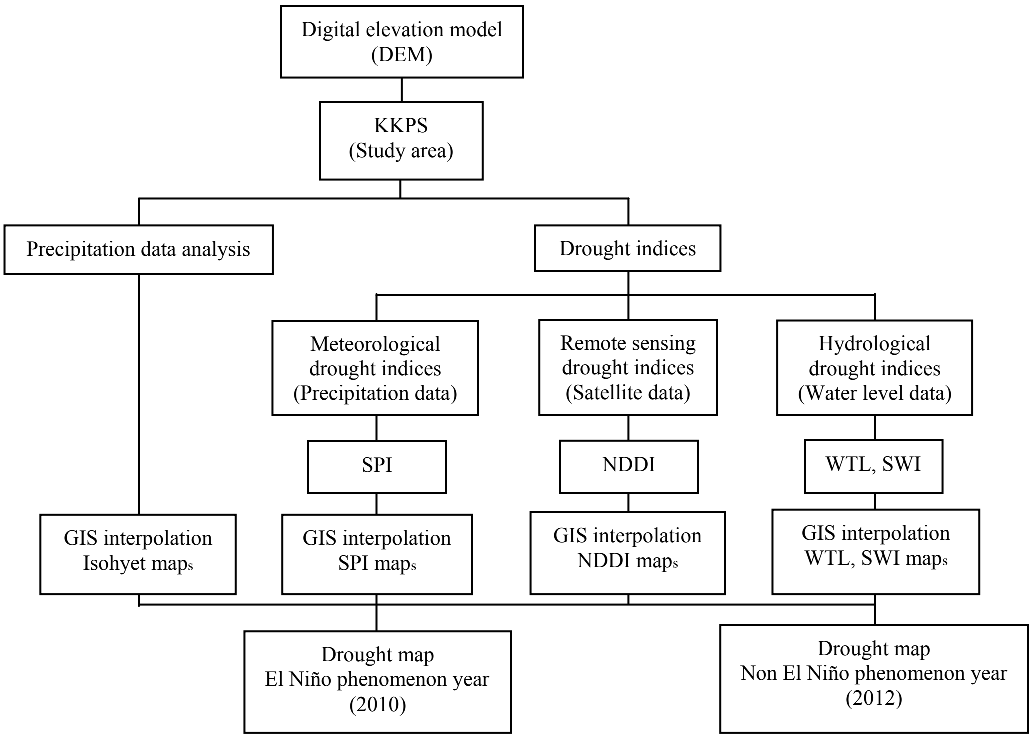


Figure 2 Flowchart of process method.

Drought indices

Meteorological-based drought indices

The SPI is based on the probability of precipitation occurring during any period of time. The probability of precipitation being observed is then transformed into an indicator of drought. The SPI is computed by dividing the difference between the normalized seasonal precipitation and its long-term seasonal mean by the standard deviation as in Eq. (1);

$$\text{SPI} = \frac{X_{ij} - X_{im}}{\sigma} \tag{1}$$

where, X_{ij} is the seasonal precipitation at the i^{th} rain-gauge station and j^{th} observation, X_{im} the long-term seasonal mean and σ is its standard deviation [10,21].

The meteorological data used in this research were acquired from the Thai Meteorological Department. The daily precipitation figures over a period of 30 years (1984 - 2013) were gathered from 20 rain-gauge stations and data from 3 rain-gauge stations over a period of 4 years (2010 - 2013) were also obtained from the Pak Phanang Fire Control Station, Nakhon Si Thammarat Province. The daily rainfall figures were calculated using multi-scale SPI (3-month, 6-month, and 9-month) using SPI freeware (http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx) [22]. The classification of the SPI was carried out using the method of McKee *et al.* [10] which produces 5 classes of SPI that are used to represent various meteorological drought levels (**Table 1**). The SPI values from the 23 rain-gauge stations in and around the KKPS were mapped using the interpolation technique in the ArcGIS software to ensure consistent spatial resolution.

Remote sensing-based drought indices

Remote sensing using data based on images from the satellite were used to derive further drought indices. The normalized difference vegetation index (NDVI) is based on the reflectance from the red channel around 0.66 µm and a near-IR channel around 0.86 µm. The red channel is located in the strong chlorophyll absorption region, while the near-IR channel is located in the high reflectance plateau of vegetation canopies. The 2 channels sense very different depths through vegetation canopies [23]. The normalized difference water index (NDWI) can be used for the remote sensing of vegetation liquid water status from images taken from space, using the reflectance properties of green vegetation, dry vegetation and soils, and the absorption and scattering properties of atmospheric gases. NDWI is a satellite-derived index calculated according to Eq. (3) below as {ρ(0.86 µm) - ρ(1.24 µm)}/{ρ(0.86 µm + ρ(1.24 µm)} where ρ represents the radiance in reflectance units. Both the 0.86 µm and the 1.24 µm channels are located in the high reflectance plateau of vegetation canopies [24]. The NDWI is derived using similar principles to the NDVI. However, NDWI is sensitive to changes in the liquid water content of vegetation canopies. It is less sensitive to atmospheric effects than NDVI. The NDWI has recently been used to detect and monitor the moisture condition of vegetation canopies over large areas for drought monitoring [25].

The NDVI is calculated as in Eq. (2).

$$\text{NDVI} = \frac{\rho NIR - \rho RED}{\rho NIR + \rho RED} \tag{2}$$

The equation for Gao's NDWI is defined as in Eq. (3).

$$\text{NDWI} = \frac{\rho VIS - \rho SWIR}{\rho VIS + \rho SWIR} \tag{3}$$

The normalized difference drought index (NDDI) is a new vegetation drought index, which combines information from visible, NIR, and SWIR channels. It is an appropriate measure of the dryness of a particular area, because it combines information on both vegetation and water. NDDI combines information from the NDVI and NDWI data. NDDI has a stronger response to summer drought conditions than a simple difference between NDVI and NDWI. The NDDI was generated from the NDVI and NDWI using Eq. (4) [26].

$$\text{NDDI} = \frac{\rho NDVI - \rho NDWI}{\rho NDVI + \rho NDWI} \tag{4}$$

In this study, the remotely sensed data was acquired from the Landsat satellite system of the U.S. Geological Survey (USGS) via the Data Sharing Service System (http://landsat7.usgs.gov/landsat8.php). Digital data from the Landsat 8 (L8) and Landsat 5 thematic mapper appear on path 128 row 54, path 128 row 55, path 129 row 54 and path 129 row 55 from 2010 to 2015. The data required to calculate the NDWI and NDDI were obtained from Landsat 8 digital images by selecting the data required during non-monsoon and monsoon seasons, preprocessing including image geo-referencing (UTM-WGS84), radiometric correction, subsetting image of study area and generating the raster data with a pixel size to produce a 30×30 m^2 resolution. Based on the reflectance values, the NDVI, NDWI and NDDI were calculated in accordance with Eqs. (4) - (6). The NDWI and NDDI were processed in ERDAS Imagine software using the model maker technique. The NDDI value was classified and used as a reference for drought severity (**Table 1**).

Hydrological based drought indices

SWI was used to monitor anomalies in the ground-water level as an indication of aquifer-stress [17]. The SWI is an indicator of water-table decline and an indirect measure of recharge (and therefore an indirect indicator of drought) [27]. Since the ground-water level is measured from the ground surface down into observation wells, positive anomalies correspond to water-stress and negative anomalies represent a 'no drought' situation. The SWI is computed by normalizing the seasonal ground-water level and dividing the difference between the seasonal water level and its long-term seasonal mean, by the standard deviation. For normalization, an incomplete gamma function is used similarly to the calculation of the SPI, as shown in Eq. (5).

$$\text{SWI} = \frac{W_{ij} - W_{im}}{\sigma} \tag{5}$$

where W_{ij} is the seasonal water level for the i^{th} well, j^{th} is observation, W_{im} is the seasonal mean, and σ is the standard deviation. WTL was selected in the study to predict the water quantity under varying water use regimes and management conditions. In this study, WTL and SWI were used to represent 5 classes of hydrological drought levels as shown in **Table 1**. SWI and WTL maps were constructed using the ArcGIS application tool using a similar technique to that used to map the SPI data.

Table 1 SPI, NDDI, WTL and SWI classification schemes.

Drought classes	Classification schemes			
	SPI [26]	**NDDI [10] Revised classes introduced in this paper**	**WTL Proposed in this paper**	**SWI [27]**
Extreme drought	< -2	0.50 to 1	> -40	> 2
Severe drought	< -1.5	0.40 to 0.50	-40 to -20	> 1.5
Moderate drought	< -1.0	0.30 to 0.40	-10 to -20	> 1.0
Mild drought	< 0.0	0.20 to 0.30	-1 to - 10	> 0.0
No drought	> 0.0	-1 to 0.20	> 0.0	< 0.0

Results

KKPS is in the east of southern Thailand. The south west monsoon passes this area between May and September every year. The rainfall is low with an irregular scattered distribution before the rainy season. The frequency of rainfall is high between October and December. The average annual rainfall between 1984 and 2013 (30 years) was 2,225 mm/year. The maximum monthly average is 525 mm in November whereas the lowest monthly average is 65 mm in February. Between February and April, the number of days on which rain falls is the lowest. On the other hand, the period between October and December has the highest number of days on which rain falls. As shown in **Table 2**, 2010 was an El Niño year with an abnormally low rainfall both in amount and season. There was drought in some areas caused by rainfall of lower than 50 mm per month. The ambient temperature was higher than normal both during the rainy season and in the summer. In 2010, drought occurred between February and September but the situation improved with the rainfall which occurred between October and December.

Table 2 Monthly precipitation for the period 2009 - 2012 (mm).

Year/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2009	151	19	151	291	165	25	122	115	98	252	686	257	2332
2010	172	14	33	38	37	34	179	82	64	213	839	312	2017
2011	433	41	971	155	115	66	102	188	128	352	600	544	3695
2012	911	51	188	128	77	82	44	95	147	366	572	657	3318

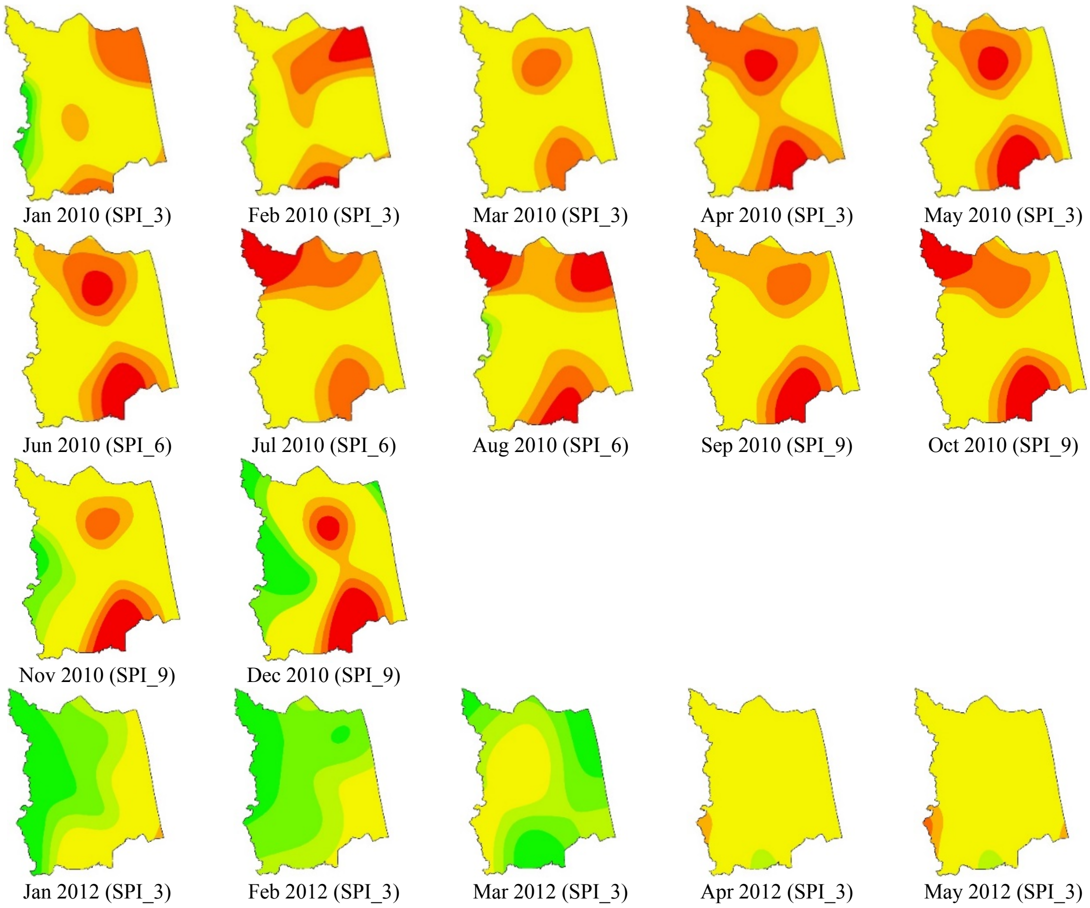
Meteorological drought

The SPI index is a method of drought analysis using only rainfall. In this study the short term drought indices, SPI_3, SPI_6, and SPI_9 based on the SPIs for 3, 6, and 9 months were used as intermediate term drought indices. In the study area, the SPI is positive or wetter than the normal rate. This might be because of the influence of the sea to the East and the mountain to the West. As can be seen from **Table 3**, over the course of 30 years (360 months), the SPI_3, SPI_6, and SPI_9 conformed to the normal rate for 245 months or 68.1 % of the time, 273 months or 75.8 % of the time, and 272 months or 75.6 % of the time, respectively.

Table 3 SPI classification schemes for the period 1984-2013 (360 months) in KKPS

	SPI	**Classes**	**SPI_3**		**SPI_6**		**SPI_9**	
			Month	**%**	**Month**	**%**	**Month**	**%**
Wet	≥ 2	Extreme	11	3.1	13	3.6	15	4.2
	1.50 to 1.99	Severe	16	4.4	17	4.7	12	3.3
	1.00 to 1.49	Moderate	31	8.6	17	4.7	21	5.8
Normal	-0.99 to 0.99	No drought	245	68.1	273	75.8	272	75.6
Drought	-1.00 to -1.49	Moderate	41	11.4	25	6.9	25	6.9
	-1.50 to -1.99	Severe	12	3.3	9	2.5	13	3.6
	≤ -2	Extreme	4	1.1	6	1.7	2	0.6

The SPI_3, SPI_6, and SPI_9 in 2010 and 2012 are shown in **Figure 3**. Taken together with the record of rainfall from 2009 to 2012 in **Table 2** they show that there was drought in KKPS from the beginning of 2010 until June of the same year with the situation improving around July and August. In contrast, in 2012, at the beginning of the year the area was wet because of the rainy season at the end of the previous year with drought occurring during July and August and the situation recovering at the end of the year.



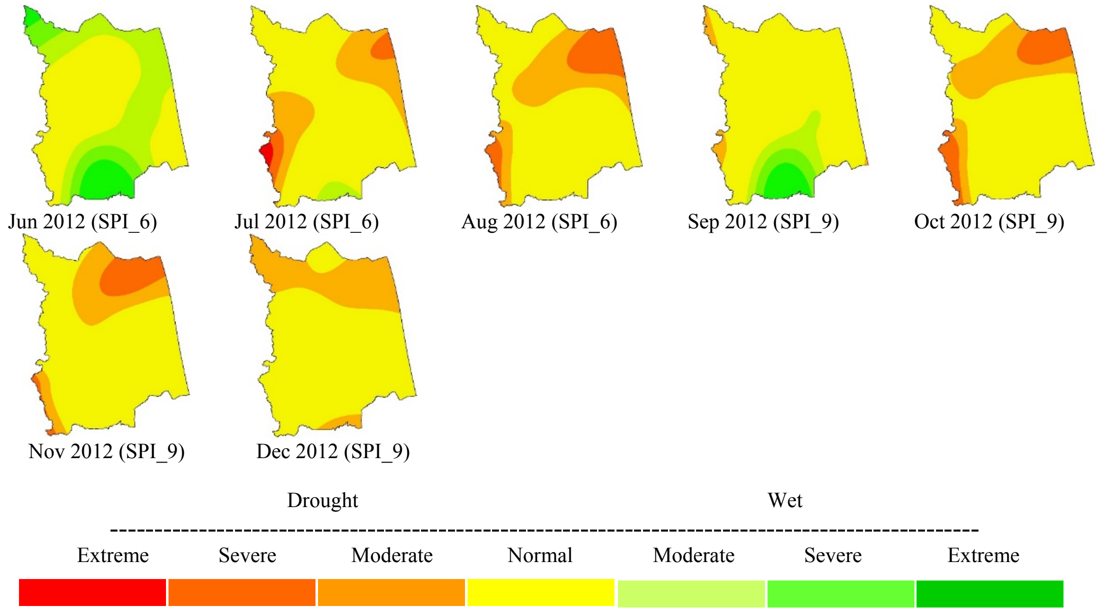


Figure 3 SPI Map of years 2010 and 2012 in the KKPS.

Vegetative drought

The NDVI analysis, based on data from Landsat5 TM at wavelengths of 4 NIR (0.77 - 0.90 µm) and 3 RED (0.63 - 0.69 µm), and Landsat 8 at wavelengths of 5 NIR (0.85 - 0.88 µm) and 4 RED (0.64 - 0.67 µm), is capable of identifying the biomass density related to rainfall. The NDWI is used to identify the water content in plants which is in turn related to the surface water. The NDWI is therefore sensitive to the water in the treetops. This study used satellite images from Landsat-5 TM with wavelengths of 4 NIR and 5 SWIR (0.85 - 0.88 µm), and Landsat 8 with wavelengths of 5 NIR and 6 SWIR (1.57 - 1.65 µm). The NDDI is a composite index and has the advantage of using the biomass density from the NDVI and the water content from the treetops from the NDWI to identify drought in certain areas. This method is more sensitive than the use of NDVI and NDWI on their own.

From **Table 1** and **Figure 4**, during August 2010, there was an effect from El Niño and severe-extreme drought conditions in KKPS which affected agriculture, such as oil palm plantations and rice paddies. Between 2012 and 2015, when normal rainfall was experienced, drought conditions occurred only slightly between January and June and to a greater extent between July and September, but only for the oil palm plantations, rice paddies open areas for agriculture and in the peat swamp forest including the denuded forest. Between October and December, the influence of the monsoon in the south of Thailand caused high rainfall in this area.

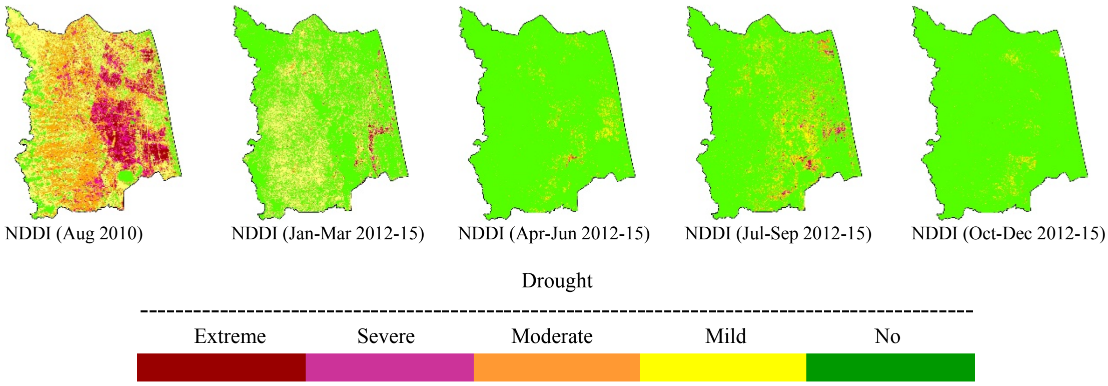


Figure 4 Map of NDDI in the year 2010 and between 2012 and 2015 in the KKPS.

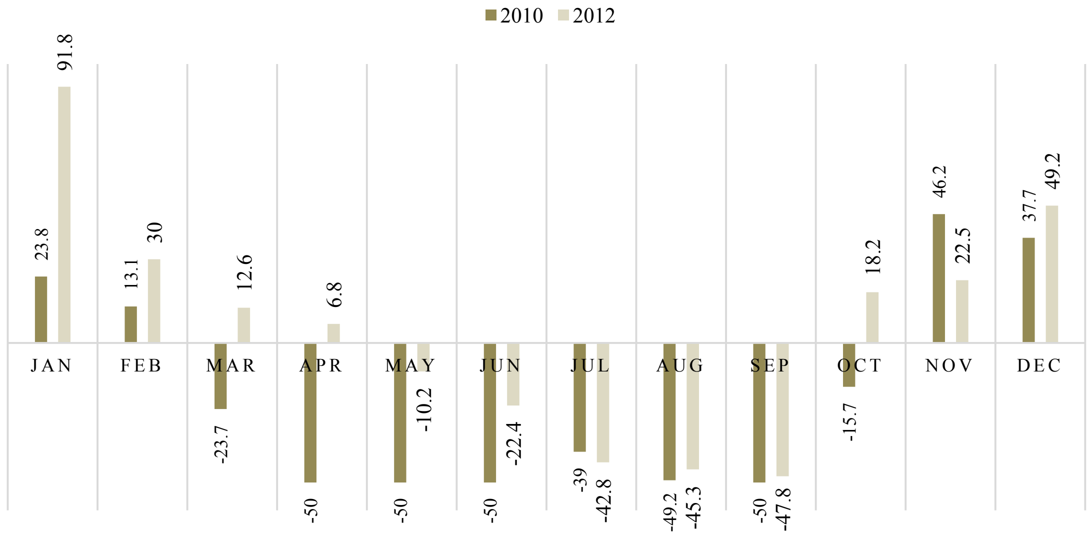


Figure 5 Graph of mean average of WTL for the years 2010 and 2012 in the peat swamp forest.

Hydrological drought

The study of hydrological drought is confined only to peat swamp forest of the wildlife-protected areas of Bor Lor and Thale Noi in Nakhon Si Thammarat province because of the availability of 50 water level monitoring stations installed in the 2 non-hunting zones, where there have been frequent and continuous incidents of forest fires for several consecutive years. Assessments of hydrological drought are based on the WTL, which includes the Water Surface Level (WSL) and Ground Water Level (GWL). Consideration of the monthly mean levels of surface water and groundwater in the years 2010 and 2012 reveals that in 2010 severe drought occurred in all 5 zones in the peat swamps as shown in **Figure 5** and the maps in **Figure 6**. This was due to the prolonged drought caused by El Niño which started in 2009. In 2010, the surface water level dropped very quickly for 8 months from March until October. This was particularly notable during the dry season from April to June, with the water level in most of the forest zones reduced to −50 cm, whereas during the rainy season of that year between October and December, the level of the surface water did not reach 50 cm as it normally does in years with normal rainfall. A less severe drought occurred in 2012; however, the water level rose at a slower pace than normal. The water level rose continuously from November 2011 to February 2012 and the level started to reduce in March and continued to fall until June when the water level dropped below the surface remaining there until September for a period of 4 months because there was less rain than normal. Particularly in the month of September, the water level in all the forest zones was reduced to almost −50 cm.

The results of the evaluation of drought using the SWI in the year 2012 are shown in **Figure 7** and reveal that the drought in the peat swamp forest area in that year started in the month of April and then gradually increased in intensity during the dry season. However, there was only a small degree of drought in the area, most of which occurred at the edges of the peat swamp. Drought occurred in almost all areas in July, August and September; particularly in September when the area experienced a severe drought for almost the whole of the month due to low rainfall. During periods without rain, both the surface water and the groundwater in the peat swamp ran dry. To make matters worse, the water from the peat swamp is drained for use in agricultural areas during the dry season, a practice which causes the water in the swamp to dry up more quickly. Thus, in such periods, there is a huge risk of forest fires.

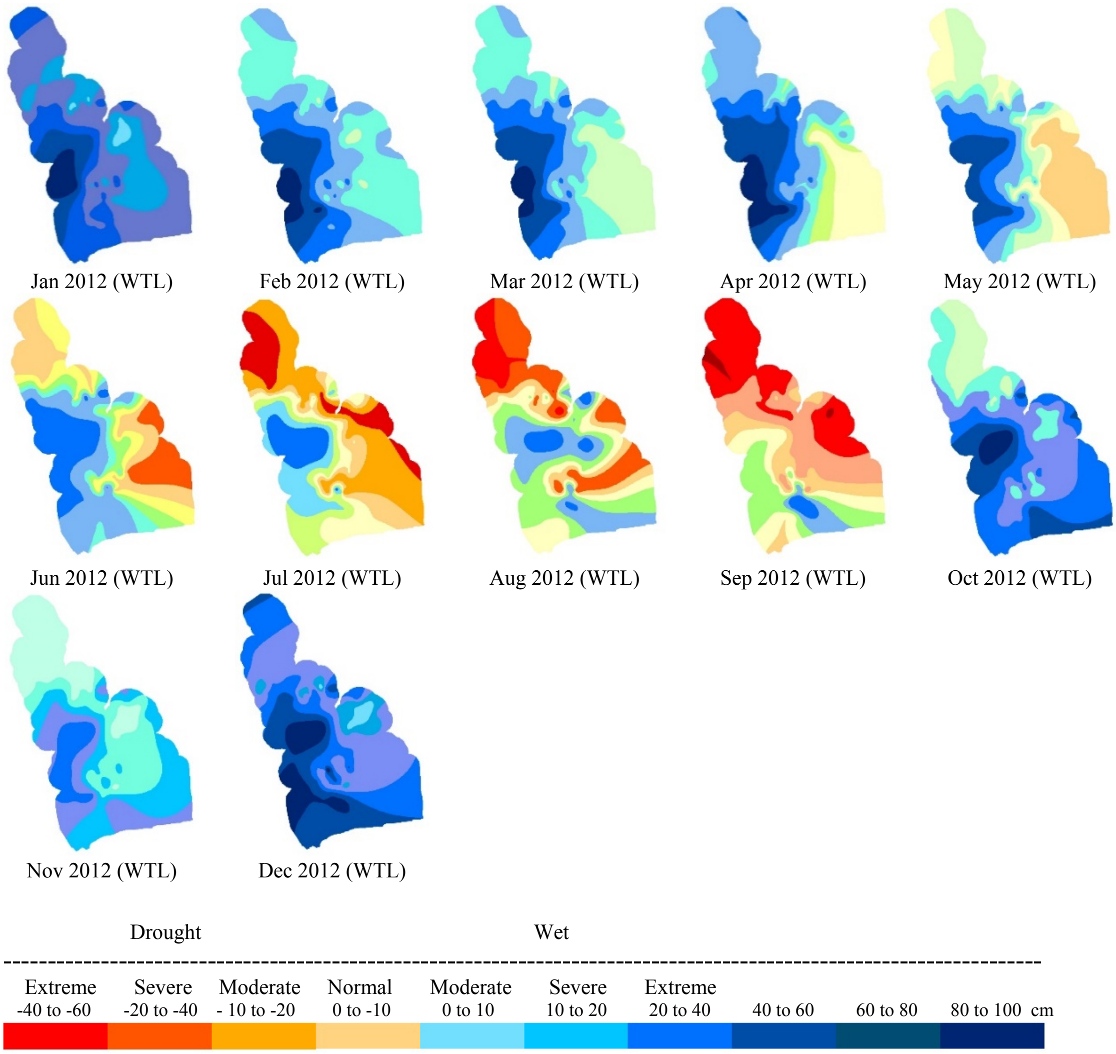


Figure 6 Map of WTL for the year 2012 in the peat swamp forest.

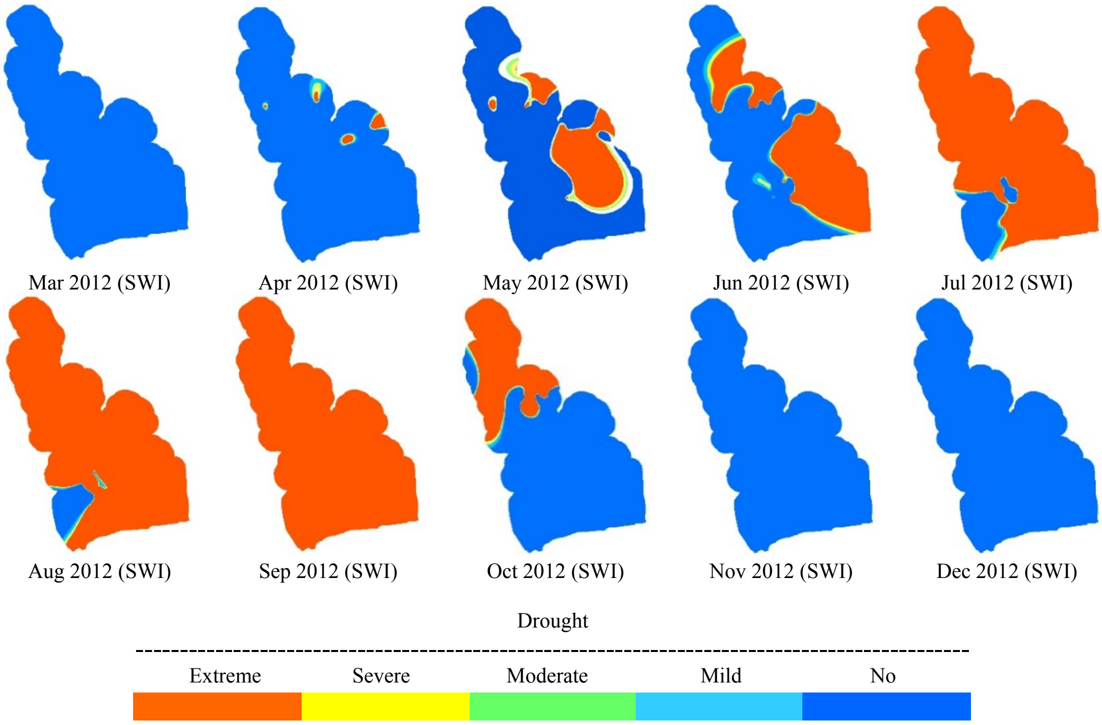


Figure 7 Map of SWI for the year 2012 in the peat swamp forest.

Discussion

This study has shown that the SPI index map can indicate the severity of meteorological drought in the KKPS in the form of abnormal rain patterns, which is conspicuous during an abnormal monsoon, causing a delay in the beginning of the rainy season or the amount of rainfall being less than normal. The SPI is a very popular meteorological drought index which has been frequently used by decision makers for measuring and monitoring the intensity of meteorological drought events [28]. During the El Niño phenomenon in 2010, the monthly SPI maps show that drought occurred in the area under study throughout almost the whole year and was most severe during the dry season. The vegetative drought as shown on the NDDI map was found to be associated with seasonal rainfall and land use during the dry season between February and September, when there is a combination of low rainfall and high temperatures. Plants normally wither when soil moisture is low. Vegetative drought was conspicuous around August and September because of the drought conditions which had built up since February.

Land use can also cause drought. Drought often occurs in farmland rather than in forest land because farmland consists of bare soil or is covered only with grass. On the other hand, the forest land is kept moist because it is densely covered, which is better able to prevent the evaporation of water from the soil during a drought. Gu *et al*. [26] found that the NDDI values increased during summer drought conditions, which demonstrated that this index can be used as an additional indicator for large grassland area drought monitoring. The wilting of vegetation can be seen from the NDDI indices ranging from 0.2 to 1.0. In addition, an NDDI higher than 0.6 is found to be associated with forest fires frequently occurring in the peat swamps. For hydrological drought in the peat swamp area, the WTL and SWI maps indicate a relationship between hydrological drought and the seasons, rainfall and topography. Bhuiyan *et al*. [27] suggest that the SWI shows the negative impact of adverse hydrological conditions on water and that the SWI presents a better picture of drought. Maps of the water level in tropical peatland areas can be used to predict fire hazards and can act as a warning system as well as a tool for land utilization and restoration planning [5]. Water table depth in peatlands is important for determining the response of streamflow to rainfall, and peatland carbon dynamics [29]. Ideally, to prevent subsidence and fire, groundwater levels should be maintained between 40 cm below and 100 cm above the peat surface [30]. The study by Susilo *et al*. [31] found that in El Niño years, the elevation of groundwater in the area observed decreases dramatically, especially in the dry season. The decline was to a level more than 40 cm below the soil surface. This presents a high risk of peat fires for this area.

The period of hydrological drought in the KKPS occurs from February until September, the period of the dry season, with lower rainfall and rising temperatures. Hydrological drought begins at the northern and eastern edges of the peat swamp because the slopes at these edges are higher than those in other areas. Severe drought conditions are conspicuous during the 3 months from July to September because of the drought accumulating since February. The drought is made more severe with the draining of water through irrigation canals for use in agriculture in the dry season, which reduces the amount of water in the peat swamp and causes a hydrological drought over the whole area. During the rainy season between October and January, the amount of rain in many areas markedly increases and causes a restoration of normal moisture levels. However, in the event of abnormal seasonal conditions such as the occurrence of El Niño in 2010 there may be less rain than normal prolonging the drought until the end of the year. This can be seen from the agreement of the data from the Meteorological Drought indices, vegetative drought indices and the hydrological drought indices in 2010 between April and September, associated with the season of forest fires in the KKPS, as shown in **Figure 8**.

Consideration of the relationship of the SPI, NDDI, WTL and SWI indices reveals that meteorological drought (SPI) and hydrological drought (WTL and SWI) are strongly correlated with the amount of rainfall and that drought can occur at any time, even during normal rainfall due to factors such as the use of water for irrigation and draining of the area.

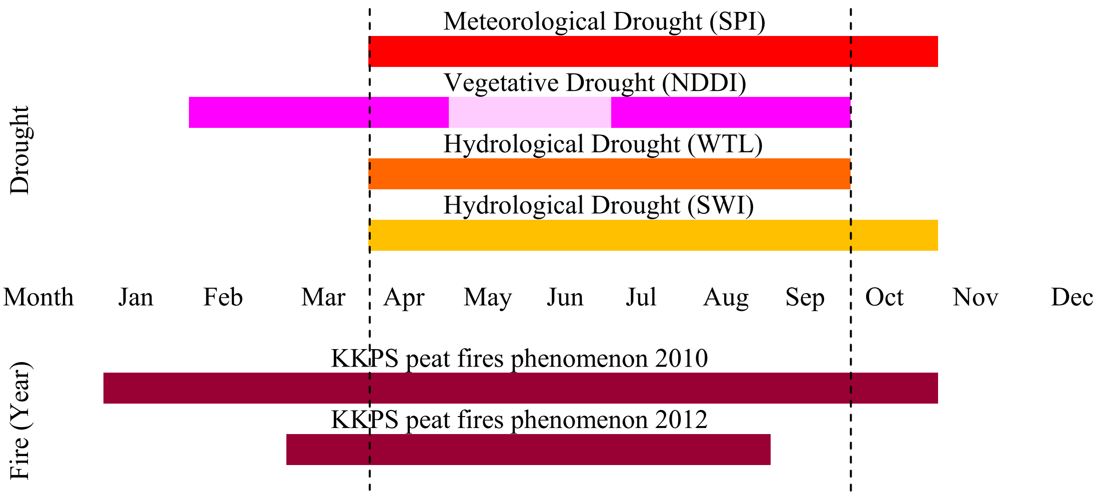


Figure 8 Months of drought as related to peat fires in the KKPS.

Conclusions

This study analyzed drought in the peat swamp of KKPS during the summer months both as a time series and as spatial data, using the data from 3 drought indexes. In particular, the SPI index provides effective assessment of drought caused by abnormally low rainfall. The NDDI index based on satellite images can be used to validate the wilting of vegetation or its lack of water. However, this index is not suitable for monitoring short term drought. The NDDI index can also be used for the study of areas which have been affected by forest fires. However, the use of satellite images based on optical wavelengths may be adversely affected by cloud covering the study area, the areas of interest in the South of Thailand are often covered with cloud for almost the entire year. The WTL and SWI indices can also be used to track and monitor drought in the peat swamp based on the available water in the swamp. These indices can assess dryness of the peat swamp which can cause subsidence and facilitate the occurrence of peat fires. These indices of the area's water reserves can also be used to identify water to extinguish fires.

In addition, the findings of this study can be used as a baseline for further studies of the drought hazard in the area along with other physical indices which can be analyzed to assess the risk of peat fires in KKPS and to identify fire-vulnerable areas. Finally, the data collected in this study can be used in planning for the sustainable management of KKPS.

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