Spring 2021

Drought Characteristics in the Lower Mekong River Basin and Relationship to Land Cover Change

Heejun Park

Drought characteristics in the Lower Mekong River basin and relationship to land cover change

Heejun Park
Department of Civil and Environmental Engineering, University of Massachusetts Amherst

TITLE

"Drought characteristics in the Lower Mekong River basin and relationship to land cover change"

A Masters Project Presented

by

Heejun Park

Approved as to style and content by:

DocuSigned by:
Kostas Andreadis

Konstantinos Andreadis, Chair

DocuSigned by:
Colin Gleason

Colin Gleason, Member

DocuSigned by:

Caitlyn Butler
Civil and Environmental Engineering Department

Abstract

Drought can have devastating effects on regional water resources and agriculture, with an estimated US$96 billions of damages globally between 2005 and 2015. In the Lower Mekong Basin, the impacts of drought have been a major concern for local stakeholders as the region is the largest rice-producing area in the world. Few studies of long-term drought in the region have directly assessed the effects of land cover changes on both agricultural and hydrological drought. We used a suite of remote sensing data to assess drought characteristics in five countries of this region (Vietnam, Cambodia, Thailand, Laos, Myanmar) where traditional in-situ measurements are not generally available. In addition to satellite data, we used the Variable Infiltration Capacity (VIC) macroscale hydrologic model to simulate drought and evaluate its variability with land cover change. The simulations had a relatively high spatial resolution of 5 km, which facilitated the identification of local patterns of land cover change and their relationship with drought characteristics such as severity, duration, and onset. Our results confirmed that 25% of land cover has changed in the region over the last two decades (2001 to present) by using MODIS observation data. Furthermore, our simulations of drought from 1980 onwards, have allowed us to explore the link between land cover change and hydrological characteristics. and found that drought characteristics in the Mekong River basin do not appear to be significantly affected by land cover change.

1. Introduction

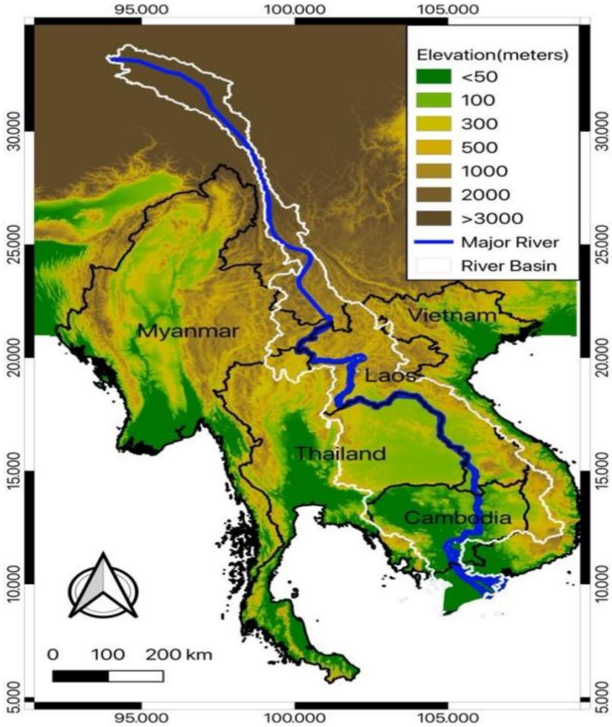


Figure 1 Study Area Map with elevation

The Mekong river basin is one of the largest transboundary basins in the world, and the region has a large impact on the world's food security (Pech and Sunada 2008). Many countries in this region have concentrated and based their economy on agriculture. As a result, they account for a large portion of the world's agricultural sector. For example, rice, a representative crop in the region, is the main food for half of the world's population (Mainuddin, Kirby, and Hoanh 2013). The amount of rice exported from Thailand and Vietnam accounted for 51 percent of the world rice trade in 2008. This shows that most of the world's rice production is concentrated in this area (Mainuddin, Kirby, and Hoanh 2013).

Demand for agricultural products to be supplied to the world's growing population over the next 30 years is expected to increase by 20 to 50 percent (Trisurat et al. 2018). According to Pech & Sunada (2008), the population of the Mekong River Basin exceeded 72 million in 2005 from 63 million in 1995, and it was the same as the actual measured value. In the same study, they predicted that the population in 2050 would increase by at least 60 percent of 2005's population or will be twisted bigger than 2005. (Pech and Sunada 2008). These show that much attention is needed to prevent drought to solve the future food security problem.

Many studies have shown that the Mekong River basin has experienced exceptional drought in the past to 1950 that was not observed in any other study area, and the basin has a wetter year and a drier year in recent decades (Räsänen et al. 2013). For example, in Guo's paper (2017) that analyzed the lower Mekong basin concluded that the basin experienced some severe drought events: November 1982 to February 1984, June 1991 to May 1994, September 1997 to April 1999, and April 2015 to July 2016. The longest drought occurred from May 1991 to June 1994 (38 months), and the strongest drought occurred from 2015 to 2016 (Guo et al. 2017). In the last 45 years, the total annual flow in this region has shown a pattern of consistent droughts, which negatively affects rice production(Sona et al. 2012). Some previous drought studies of the lower Mekong basin focused on regional drought (Guo et al. 2017; S. K. Lee and Dang 2019; Sam et al. 2019; Sona et al. 2012). The results of one study concluded that the "yield of rainfed rice may increase significantly in the upper part of the basin in Laos and Thailand and may decrease in the lower part of the basin in Cambodia and Vietnam." (Mainuddin, Kirby, and Hoanh 2011). More specifically, another study said that the Mekong Delta and southwestern regions are more vulnerable to severe drought with a long-term scale (Guo et al. 2017). The southern and northern parts of the lower Mekong basin were also shown to experience drought more frequently (Guo et al. 2017).

Furthermore, the vulnerability to drought in downstream of the Mekong river called Srepok River Basin is exacerbated because approximately 50% of the land in the basin is covered by agricultural land (Sam et al. 2019). As the agricultural productivity of the region (e.g. rice yield) is greatly affected by the region's monsoons (Sam et al. 2019). And future climate change could increase the impacts of drought on food security (Thilakarathne and Sridhar 2017a). A widespread drought event in Vietnam from 1997 to 1998 caused damage to the 3-million population, and the damage was estimated to be 400 million USD. Also, in 2002, a drought damaged Cambodia's Southern part and destroyed 100,000 ha of paddy fields affecting 2 million people (Thilakarathne and Sridhar 2017b). The region's historical drought damage was 210 million USD in Thailand in 1992, and the region also suffered from droughts in 1997-98 and 2004. And from 1997 to 1998, the widespread damage to Vietnam affected 3 million people, with an estimated cost of $400 million. Finally, in 2002 100,000 ha of paddy fields were destroyed in southern Cambodia, and 2 million people were damaged (Thilakarathne and Sridhar 2017b). Another factor that could impact water availability in the region and the resilience to droughts is related to dams and energy production. China's hydropower systems, located upstream, will bring water shortages to the downstream countries with a significant impact on the agricultural sector expected (Leinenkugel, Oppelt, and Kuenzer 2014).

The impact of land cover change on droughts has been receiving increased focus in recent years (Schilling et al. 2008). Humans have changed 41% of the Earth's surface, and anthropogenic changed land cover accounts for a quarter of the Earth's land cover. Land cover changes can significantly modify evapotranspiration through changes in available water, energy, land surface roughness, and photosynthesis rates (Sterling, Ducharne, and Polcher 2013). One of the most studied areas for droughts caused by land cover change is the Amazon River, where deforestation has occurred. Many studies confirmed that deforestation has an effect on the water cycle and can increase the damage of drought (Bagley et al. 2014; J. E. Lee et al. 2011; Staal et al. 2020). Specifically, the link between land cover and drought is the change in the depth of the roots and the area of the leaves (J. E. Lee et al. 2011). Deep roots hold more water, controlling transpiration of water even during dry periods, and delivering more water in rainy times. The changed land cover also affects local patterns of precipitation because of biophysical factors. When deforestation occurs, the leaf area decreases reducing the amount of CO_2 and H_2O exchanges. For example, in South America, regional evapotranspiration contributes a high percentage of precipitation, and therefore the reduction of leaf area can reduce regional precipitation (J. E. Lee et al. 2011).

Due to the land cover that humans have changed, the world's average annual Terrestrial Evapotranspiration (TET) has increased by 3,500 km3/yr, which is 5% of the total TET (Sterling, Ducharne, and Polcher 2013). Among the land cover changes, urbanization and agricultural activity are the biggest reasons for increasing cropland, water body, and built-up area and reducing forest and shrubland. These kinds of land cover changes reduce overall evaporation and infiltration rates and increase surface runoff. Specifically, if the forest area decreased, the amount of infiltration decreases, which increases the surface runoff, built-up areas such as urban area and cropland will lose soil, which leads to a decrease in surface roughness, these will eventually increase surface runoff (Koneti, Sunkara, and Roy 2018). India's Mahanadi River basin, for example, decreased 5.71% in total forest area over 31 years and increased 5.55% in agricultural areas, and this increased annual streamflow by 4.53% (3514.2 x 106 m3) and also the amount of runoff.

The overall goal of this study is to identify the characteristics of historical drought events by using a combination of remotely sensed and model data from 1980 to now with drought indices such as SPI and drought severity. An additional goal is to determine the land cover change over the last 20 years in the Lower Mekong Basin to see the impact of the change on agricultural and hydrological drought.

2. Study Area and Land Cover Change

The Mekong River is 4,350 km long, the 7th longest river in Asia, and the 12th longest river in the world. The five countries of the study area (Cambodia, Thailand, Vietnam, Laos, Myanmar) are all located in the Lower Mekong Region of South East Asia. (Leinenkugel et al., 2014). This region is considered the fastest growing area in terms of population and economy in the world. There are 70 million people who live here and 54.8 million people are concentrated on the lower side (Kummu and Varis 2007). Two-thirds of the people in the Lower Mekong Region live in rural areas, and their livelihoods depend heavily on this Mekong river, such as farming and fisheries (Ziv et al. 2012). The population growth rate in Lower Mekong countries has increased annually by 1.12%, using data from 2010 to 2016[1]. It is expected that world rice demand is going to increase as a result of the increase in population here and elsewhere, due to the fact that half of the world's population relies on rice to eat (Mainuddin, Kirby, and Hoanh 2013).

Thailand and Vietnam account for most of the rice exports in the world. According to Trisurat et al. 2018, the overall amount of water in the LMB will not be changed, but there will be a change in the rainfall pattern, and they are worried about future rice production and the impact on agriculture. Because in the dry season (November to May) crop damage has been reported and this will increase further in the future (Trisurat et al. 2018).

The area of the Mekong river basin is 795000 km^2, and the annual water flow in this river is 475 km3. The annual discharge from the upper basin of this river to the Chinese border is 73.6 km3. Starting with a dam in 1993, two hydropower dams were completed in the Mekong area in 2005, two dams were under construction in 2007, and four dams were planned. The eight dams, combined with existing and planned dams, will have a capacity of 40 km3 which is more than half of the annual discharge (Kummu and Varis 2007). The hydro-development systems in the upper reaches of the Mekong River will cause significant disruption to the region's water resources, and it is expected that nearly 103 of the 877 species of fish on this lower river basin will disappear due to these hydro systems and dam construction affected 50% of the large rivers, and they had a significant impact on biodiversity and the ecosystem (Ziv et al. 2012). Also, due to the dam construction in the late 50s, the annual discharge of the wet season from 1979 to 1998 was reduced by 11% compared to the previous period (1924-1956), but the internal variation became increased extremely. This reduction was not related to the change in the rainfall pattern during this period and appeared to come from dam construction activities (van Zalingen et al. 2003). In addition, people expected dams to negatively affect the natural flow pattern of the river such as increasing flow fluctuation, average downstream flow in the dry season, reducing the flow of the wet season, changing the flooding site, or changing the time of the flood. On the contrary, the positive effect of the dam is the assured flow in a dry period, while another advantage is the reduction of salt intrusion in the Delta area. (Kummu and Varis 2007)

The climate of the Lower Mekong Basin (LMB) is categorized as tropical monsoonal which contains dry and wet seasons. Most precipitation in the region is dominated by the southwest monsoon, and the monsoon season usually starts in May and lasts until September or October.

---

[1] "Population and censuses", OpenDevelopment Mekong.net, last modified March 25, 2019, https://opendevelopmentmekong.net/topics/population-and-censuses/

Also, the average annual rainfall in this region between 1964 and 2005 was from 850mm to 2500mm (Thilakarathne and Sridhar 2017a). Between March and April refers to the warm season and average temperatures are from 30°C to 38°C. From November to February, the area prevails cooler temperatures and the average winter temperature of the Lao People's Democratic Republic (PDR) is 15 degrees Celsius. (www.mrcmekong.org). The LMB drought begins in May and usually lasts until early October. The average annual precipitation of the Mekong basin from 1964 to 2005 is 850mm to 2500mm. (Thilakarathne and Sridhar 2017a). The Lao PDR and Cambodia which are rain-soaked uplands get the most precipitation (3,000 mm). The semi-arid Khorat Plateau in northeast Thailand receives at least 1,000 to 1,600mm (MRC 2005)

In the LMB, the total amount of water is not restricted, but some areas would be influenced by suddenly changed rainfall patterns, especially from November through May (Dry season) (Trisurat et al. 2018). In this season, it is observed the water shortage and people in the area would be suffered by the shortages. Recently, global warming causes climate change to alter precipitation patterns and although climate change would not change the dry and wet season flow in the Mekong, Variability will increase, and patterns of more dry and wet season flow will cause more severe floods and drought damage (Yamauchi 2014).

Many studies have confirmed that using satellite data is useful to check the Land Use Land Cover (LULC) (e.g., Petchprayoon et al. 2010). In this study, in order to confirm land use information, we selected data from the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor. MODIS is NASA's first mission to deliver daily global data in high resolution (250m) (Sona et al. 2012). In this study, we used 500m resolution of landcover data, although MODIS has problems with cloud contamination, this study uses annual landcover data, making it suitable for detecting and monitoring land cover data. The MODIS satellite provides observations at relatively high spectral and spatial resolutions (250, 500m, and 1000m) from 1999 to the present (https://modis.gsfc.nasa.gov/data/). Between many resolutions, we used 500 m resolution of MODIS satellite data since 2001 when the data is available and created 4 different vegetation parameter data to input land cover sources at different times (2001,2006,2011,2018). So, we put the 2001 land cover data when running the VIC model from 1981 to 2001, put the 2006 land cover data from 2002 to 2006, 2011 data from 2007 to 2011 and 2018.

The land cover data in MODIS are classified into 16 categories, and when putting the vegetation parameter information into the VIC model we used 16 different information, but to simplify the interpretation, we will group the layers with similar characteristics and explain them. When we look at the land cover with 16 categories, the Mekong River basin has experienced land cover changes in 25% of the land. Except for Thailand, most countries have undergone deforestation over the past 20 years, and Thailand also showed a decrease in forest area for 10 years from 2002 to 2012 but has steadily increased since then. The country where the forest area fell the most was Laos, which fell from 70% to 60% of the entire country.

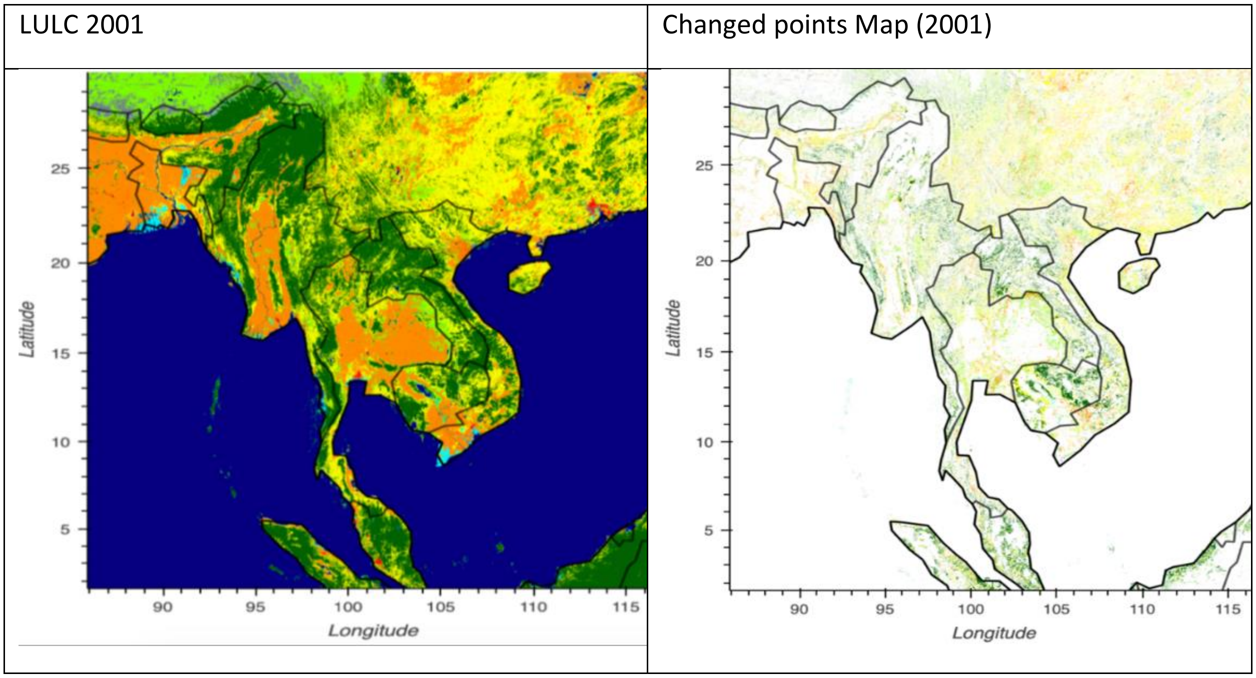


Figure 2 LMB LULC Map and Changed part (2001)

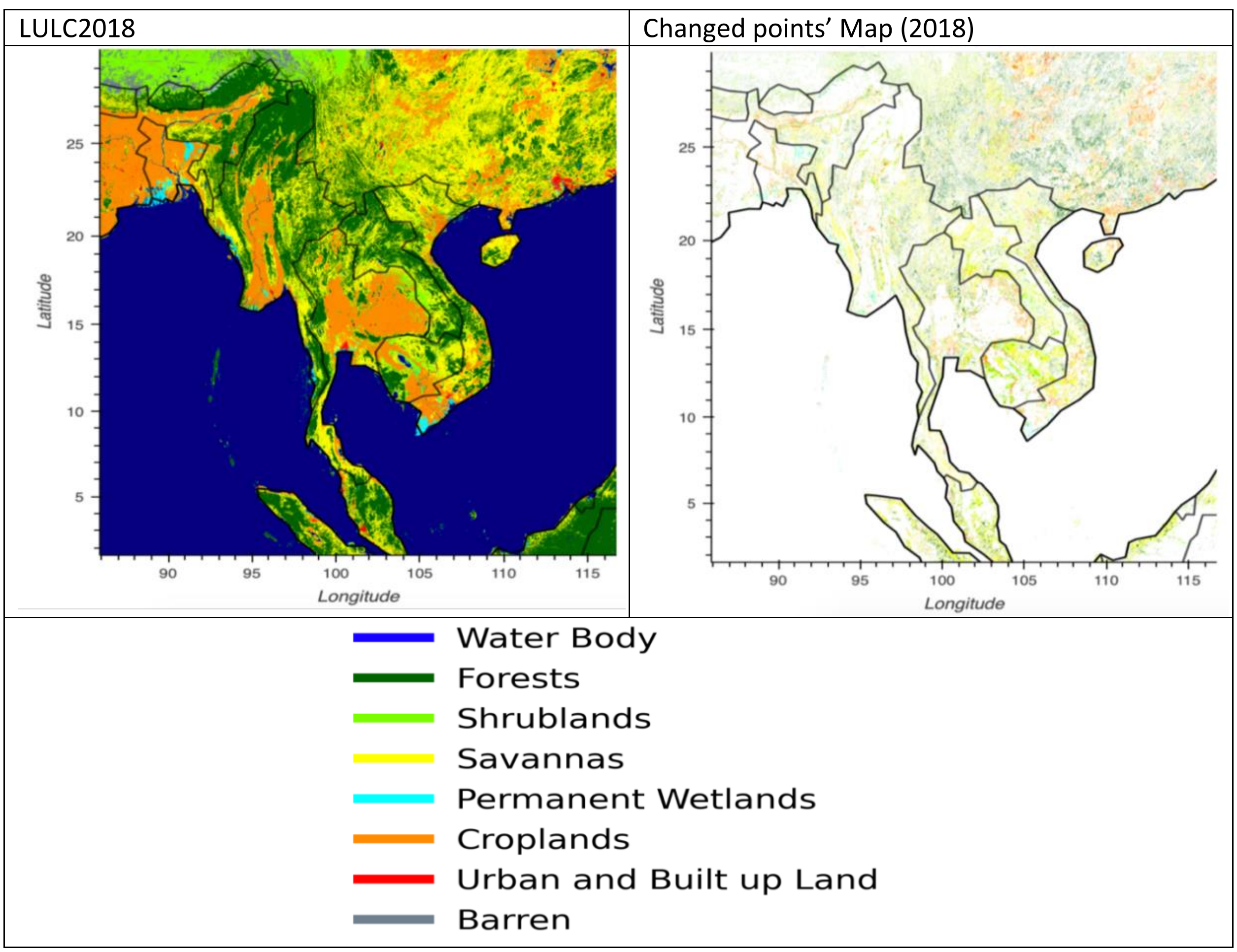


Figure 3 LMB LULC Map and Changed part (2018)

3. Hydrologic Modeling and Drought Estimation

Product	Variable	Special Resolution	Available Period
NCEP	Temperature	1.875°	1948– Present
	Wind speed		
CHIRPS	Precipitation	5km	1981 – Present
MODIS	Land Cover	250m,500m,1000m	1999 – Present

Table 1 Description of the data used in this study.

To monitor drought in the area, temperature and wind speed data were taken from NCEP satellite (National Centers for Environmental Prediction) and precipitation data from CHIRPS data product (Climate Hazard's center InfraRed Precipitation with the station) from 1981 to 2018, since both datasets were available for this period. In this study, soil moisture, base flow, runoff, evaporation, and potential evaporation were calculated over the LMB 5 countries with a high resolution of 5 km using the VIC model (Variable Infiltration Capacity Model). CHIRPS provides high-resolution (5km) precipitation data from 1981 to the present with latitude between 50°S-50°N and all longitude. NCEP data provides global temperature and wind speed data from 1948 to the present with a 1.87° special resolution.

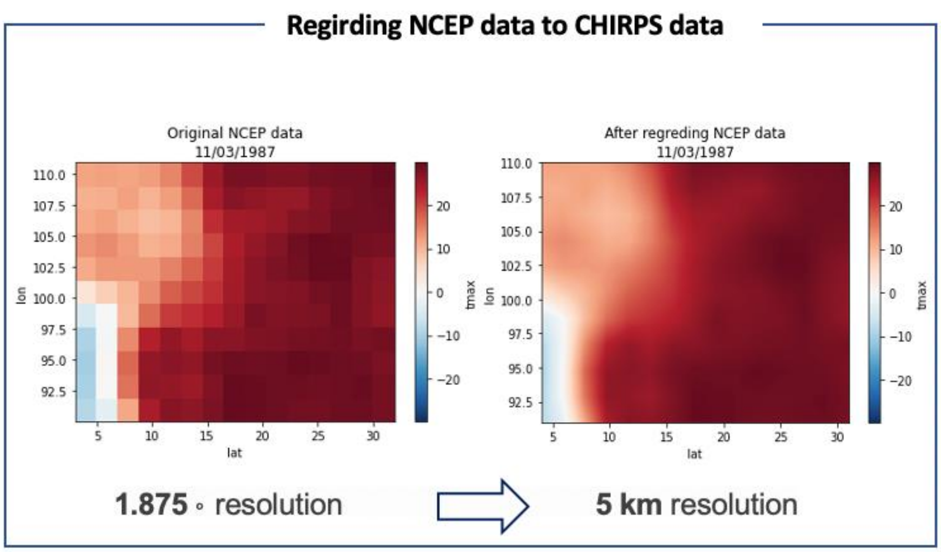


Figure 4 Comparison of resolution change of temperature data on November 3, 1987.

Since the NCEP data have a lower resolution than the CHIRPS data, we regridded them (Figure 4) to match the CHIRPS data resolution (5km). Bilinear interpolation using the XESMF module in Python was used for regridding data. In order to run the VIC model, data was put into Metsim tool (Meteorology Simulator) to create 6 hours sub-daily meteorological time series forcing data (short wave, long wave, vapor pressure, air pressure, wind speed, precipitation, temperature).

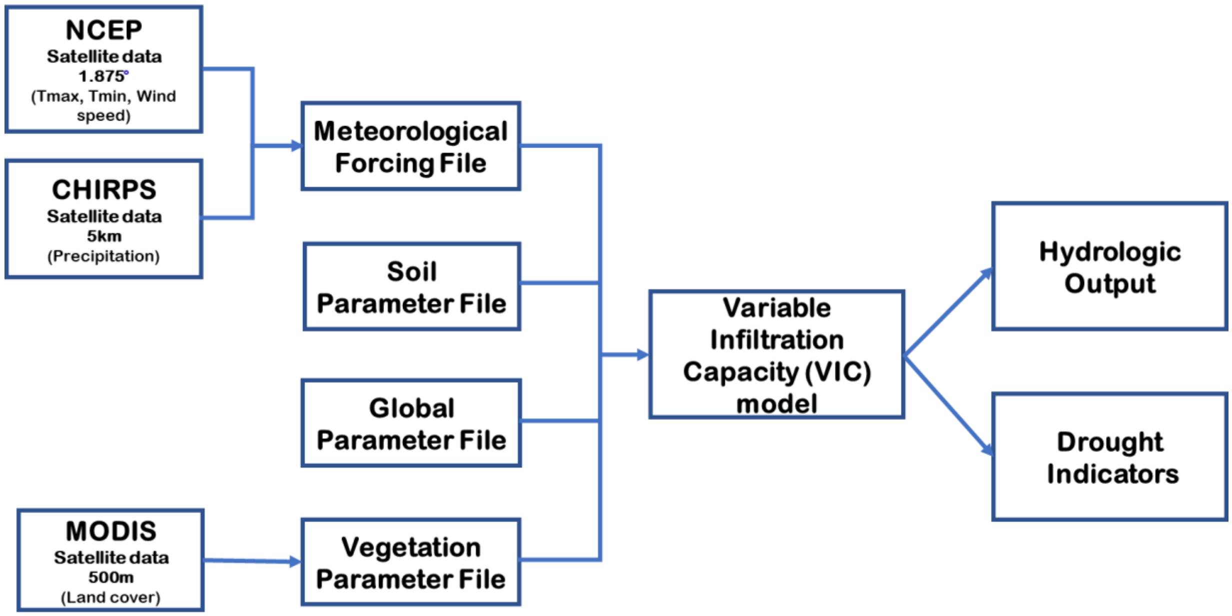


Figure 5 Experimental Design figure

In this study, we used the variable infiltration capacity (VIC) hydrologic model to simulate historical water flux changes in the LMB region (Figure 5). The VIC model was created at the University of Washington in the early 1990s and has been used in a wide range of hydrological studies, climate modeling, and podcasting from basin-scale to global size. Because VIC models can simulate various water resource variables, it can be very useful for impact study or planning research, and it allows large-scale simulations to be performed on computers with lower performance than other models (Hamman et al., 2018). The model balances water, energy, and land surface with sub-daily time steps, as with other Soil vegetation atmosphere transfer schemes (SVATS), but the difference is VIC can express soil moisture in sub-grid units and represents the effect of runoff generation or non-linear baseflow. Early models had two soil layers and used one or more resolutions and the recent model uses three soil layers in most cases but can also use any number of soil layers (Cherkauer, Bowling, and Lettenmaier 2003)

Drought simply means continuous dryness, but compared to other natural disasters, drought is very slow in progress and difficult to define the beginning and end of time and place. In addition, it is difficult to define the scale because the effects of drought are long-term and the effects spread to various fields such as environment, society, and economy. For this reason, interpreting drought is not easy depending on the purpose being handled. Many studies divide drought into three major categories: agricultural drought, hydrological drought, meteorological drought. Agricultural drought is a drought that affects agriculture, which is related to the amount of soil moisture directly related to the growth of crops, and hydrological drought means a lack of available water resources such as river flow, reservoir groundwater, and water supply. Finally, meteorological drought refers to the case where there is a continuous period of low rainfall or no rain during a certain period and means the effect of meteorological phenomena (A. K. Mishra and Singh 2010). In this study, the SPI drought index was used to identify and define drought events. The SPI drought index was developed by Mckee, Doesken & Kleist in 1993 (McKee and Kleist 1993). This index can calculate how much less or more precipitation than the average precipitation for specific months (3, 6, 9, 12 months), and it can flexibly represent both short-term droughts and long period drought. Also, it can recognize early drought and it is highly utilized, so it is a drought index that is universally used around the world(Guo et al. 2017). SPI is usually between -2 and 2, negative numbers indicate dry conditions and positive numbers indicate wet conditions. The wet condition means more rainfall than average, and the dry condition means less rainfall than average.

For the SPI drought index, we calculated the average precipitation by continuously overlapping monthly precipitation over time units to calculate the average precipitation time series for each time unit. Then, normal precipitation data is converted to a normal distribution because it usually does not have a normal distribution. In general, precipitation is known to follow the Gamma distribution, and this study utilized this (Edwards, Daniel C.; McKee 1997). Gamma distribution is defined by frequency or probability density.

$$g(x) = \frac{1}{\beta^{\alpha} T(\alpha)} x^{\alpha 1} e^{-x/\beta}$$

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

In here, α means shape parameter
ß means scale parameter
X means precipitation amount
$\Gamma(\alpha)$ is the gamma function

In the Gamma probability density function α, ß are estimated with each point and with each time (3 months, 6 months, 12 months). Using the calculated parameters, we calculated the cumulative probability of precipitation for each time interval by point. The cumulative probability is:

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

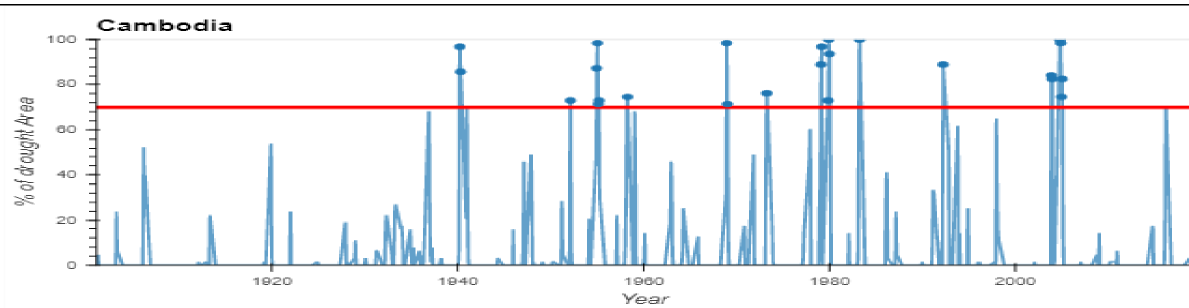
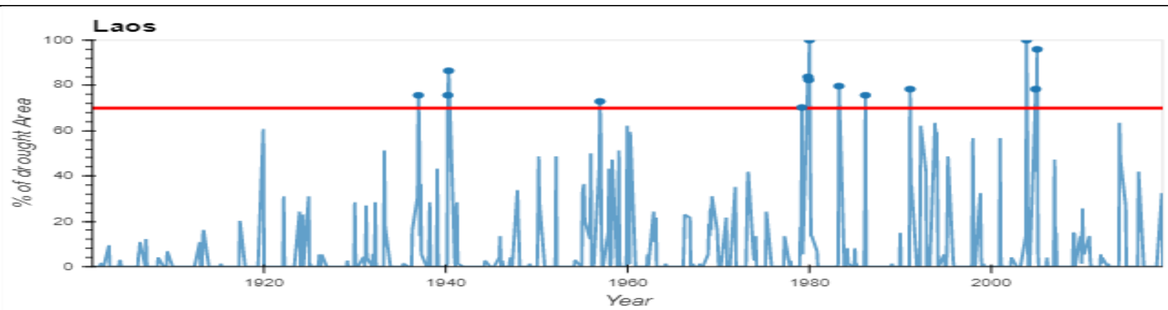
After calculating the cumulative probability of each rainfall thought, then apply it to the standard normal distribution to calculate the standard precipitation index.

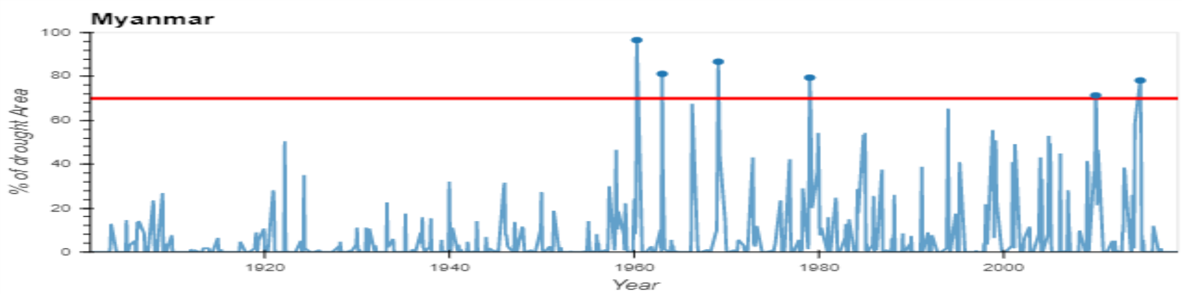
SPI Values	Classification
> 2	Extremely Wet
1.5 to 1.99	Very wet
1 to 1.49	Moderate Wet

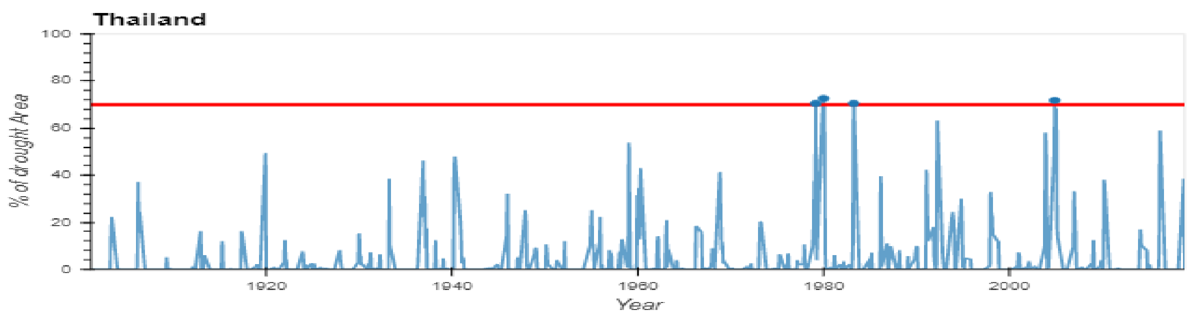
0 to 0.99	Near Normal
-0.99 to 0	Mild Dry
-1.0 to - 1.49	Moderately Dry
-1.5 to -1.99	Severely Dry
<-2	Extremely Dry

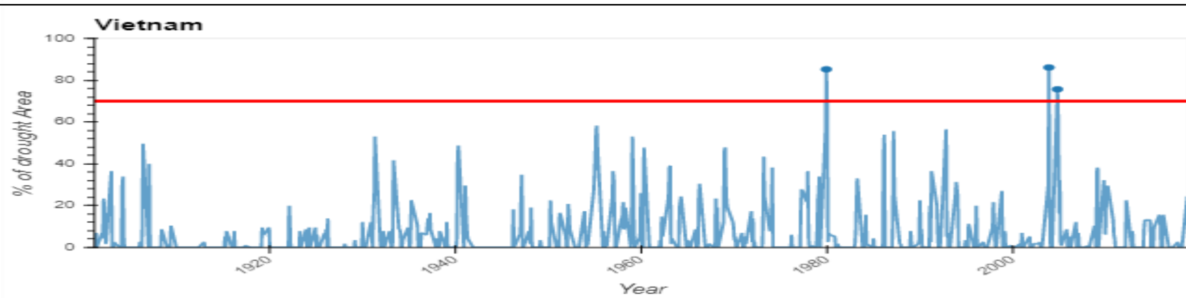
Table 2 Classification of SPI drought index

In addition to the VIC model, we identified drought events with SPEI (The Standardised Precipitation-Evapotranspiration Index) data. The SPEI data is 0.5 degree from 1901 to 2018 (117 years) and downloaded from http://sac.csic.es/spei. First, we checked the changes in the dry season (Dec to April) during this period then I calculated the percentage of the area in each country where the SPEI value is drier than -1.5 (severe drought) and then sorted the months that were affected by drought over 70% of each country and confirmed that Cambodia had the most frequent droughts (24 times) in the last 708 dry season's months. On average, Cambodia also has drought over the largest area. Then, the months with the damaged area exceeding 70% were collected and compared before 1959 (58 years) and after 1960 (58 years). Every country in the Lower Mekong region has experienced more frequent droughts after 1960, so it shows the drought in the Mekong region began to increase dramatically from as early as 1940 to as late as 1980 depending on each country.

Damaged Area by severe drought	# of over 70% / All month
	24/708
	14/708

<table>
<tr><td>


</td><td>6/708</td></tr>
<tr><td>


</td><td>4/708</td></tr>
<tr><td>


</td><td>3/708</td></tr>
</table>

Figure 6 Percentage of the area affected by severe drought (SPEI <-1.5) in each country during the dry season

	Cambodia		Laos		Myanmar		Thailand		Vietnam	
#	time	% of Damaged area	time	% of Damaged area	time	% of Damaged area	time	% of Damaged area	time	% of Damaged area
1	1940-03	96.82	1936-12	75.67	1960-04	96.58	1979-03	70.51	1979-12	85.21
2	1940-04	85.71	1940-03	75.67	1963-01	81.19	1980-01	72.64	2003-12	86.08
3	1952-02	73.01	1940-04	86.48	1969-02	86.75	1983-04	70.51	2004-11	75.65
4	1954-12	87.30	1956-12	72.97	1979-01	79.48	2004-12	71.79		
5	1955-01	98.41	1979-03	70.27	2010-01	71.36				
6	1955-02	71.42	1979-11	83.78	2014-11	78.20				
7	1955-03	73.01	1979-12	82.43						
8	1958-04	74.60	1980-01	100.0						
9	1968-12	98.41	1983-04	79.72						
10	1969-01	71.42	1986-03	75.67						
11	1973-04	76.19	1991-02	78.37						
12	1979-02	88.88	2003-12	100.0						
13	1979-03	96.82	2004-12	78.37						
14	1979-11	73.01								
15	1979-12	100.0								
16	1980-01	93.65								
17	1983-04	100.0								
18	1992-04	88.88								
19	2003-12	84.12								
20	2004-01	82.53								
21	2004-11	100.0								
22	2004-12	98.41								
23	2005-01	74.60								
24	2005-02	82.53								

Table3 Drought events (SPEI <-1.5) that damaged area was more than 70 percent.

4. Results

All five forest categories (Evergreen Needleleaf Forests, Evergreen Broadleaf Forests, Deciduous Needleleaf Forests, Deciduous Broadleaf Forests, Mixed Forests) were integrated into forests. Closed Shrublands, Open Shrublands, and Grasslands were considered Shrublands, and Croplands and Cropland Natural Vegetation Mosaics were simply simplified to Croplands. The table5 shows the area by type of land in 2001 and 2018. We grouped land cover data into eight categories, the percentage of changes over the past 17 years has been decreased from the previous 25 % to 20% due to changes between landcover in one category (eg. Deciduous Broadleaf Forests to Mixed Forests), but 20.329% of the total study area has changed.

	Cambodia	Vietnam	Myanmar	Thailand	Laos
Changed Area	62947.25	86575	121186.3	106117.3	55786
Total Area	217381	401834.3	839509.8	623359	283386.5
% of Changed Area	28.96	21.54	14.44	17.02	19.69

Table 4 Description of Changed Area and % between 8 categories.

	Cambodia (28.957%)		**Vietnam (21.545%)**		**Thailand (17.023%)**		**Myanmar (14.435%)**		**Laos (19.685%)**	
	Km^2 2001	**Km^2 2018**	**Km^2 2001**	**Km^2 2018**	**Km^2 2001**	**Km^2 2018**	**Km^2 2001**	**Km^2 2018**	**Km^2 2001**	**Km^2 2018**
Water body	4640.75	4651.5	3545.25	3621.75	3734.75	3543	4894.5	5471.25	797.25	1018
Forests	88293.25	56053.25	126727.5	111031.3	144167.5	145901.5	455934	420605.8	201551.8	169883.8
Shrublands	15924.75	30565.75	21214.5	22513.25	59154.5	40297.5	44885.5	48435	15867	24171.75
Savannas	54342.5	65052	147996.8	160561	151936.3	167593.5	158226.8	183874	61005	82285.25
Permanent Wetlands	2784.75	2739.25	13996.25	15303	6697.25	7477.75	9008	10462	469.75	708
Croplands	50942.25	57763.75	81741.75	81649.5	251115.3	251319	163298.3	167205.8	3403.75	5028.25
Urban and Built-up	434.75	541.25	5454.25	6465.5	6320	7128.25	1856	1916.5	208.75	229.25
Barren	16.25	11.75	860.75	601.25	229	90.75	1406.75	1533	83.25	62.25

Table 5 Comparison Landcover area between 2001 to 2018

Over the past 20 years, Lower Mekong River Basin has lost 11% of its forest in 2001 because 17% of its forest area has changed to another land cover, and about 6% of its other land cover has changed to a forest cover. Eighty-nine percent of the 17 percent (179322.75 km2) of the changed forest turned to Savannas, followed by turning to the Shrublands (8.6 percent). Cambodia has changed the biggest ratio (28.96%) and Myanmar, the largest of the study countries, has changed the largest area of 121186.3 km2. The commonality of the five countries except for Thailand is that Forest has decreased, and Savannas has increased, and the croplands and Urban regions have not increased significantly. To be more specific, there were 1016674 km2 forests in 2001, and 179322.75 km2 had changed to other land covers, which is 17.638% of the total forest area. The area of forest in 18 years was reduced by only 11.13% compared to 2001 because other land cover areas also changed to the forest (reforestation or in forestation. Except for Cambodia, the changed forest in all countries showed that it changed to Savannas by about 90 percent or more. Also, unlike other countries, 21.9% of the changed forests in Cambodia have turned into Shrubland. This shows that the part that used to be forest has not been urbanized or crop landed. When checking drought indices calculated from the results of the VIC model, which included this changed landcover information, the results matched the drought events mentioned in previous studies such as drought events from 1982–84, 1991–94, 1997–99, 2015–16 and so on.

Unit (km^2)	To water body	To shrublands	To savannas	To wetland	To Cropland	To Urban
Cambodia (36156.5)	17.25	7927	26766	388	1058.25	0
Vietnam (28966.5)	0.75	1088.5	27215.5	99.25	562	0.5
Myanmar (58164.5)	37.25	4275	52565.75	392	894.25	0.25
Thailand (18728.25)	0	241	18260	137	90	0.25
Laos (37307)	88.5	1884.5	35210.75	58.5	64.75	0
Total	143.75	15416	160018	1074.75	2669.25	1

Table6 Area of 17 % of forests changed to other land types in 2018.

Unit (%)	To Waterbody	To shrublands	To savannas	To wetland	To Cropland	To Urban
Cambodia (To land cover /36156.5)	0.048	21.924	74.028	1.073	2.927	0.048
Vietnam (To land cover /28966.5)	0.003	3.758	93.955	0.343	1.940	0.003
Myanmar (To land cover /58164.5)	0.064	7.350	90.3743	0.674	1.537	0.064
Thailand (To land cover /18728.25)	0	1.287	97.5	0.732	0.481	0
Laos (To land cover 37307)	0.237	5.051	94.381	0.157	0.174	0.237
% (To land cover / 179322.75)	0.08	8.597	89.235	0.599	1.4885	0.00056

Table 7 % of 17% of forests changed to other land types in 2018.

1) Validation with GLEAM.

Since hydrological data is not available in this study area, Model validation was performed with some satellite data. To check the evaporation output, we used GLEAM (Global Land Evaporation Amsterdam Model) data, and there are two datasets (Gleam v 3.5a and Gleam v 3.5 b) available at https://www.gleam.eu. GLEAM v3.5a is available from 1980 to December 2020, which is based on satellite data and reanalysis data. GLEAM v3.5 b is available from January 2003 to July 2020, and it was created based only on satellite data. They provide a total of 10 kinds of data such as Actual Evaporation, Soil Evaporation, and Potential Evaporation, and in this study, we used actual Evaporation € data. When we performed validation with GLEAM data, the average correlation was 0.61, and the highest was Thailand at 0.67. In Thailand, in detail, the correlation with GLEAM data was higher in the northern part, and the number gradually decreased toward the south part. Similar values were obtained either gridded to VIC at 5 km resolution or gridded to the resolution of Gleam at 0.25°. When compared with the Landcover map, the model showed a missing value in the area with the cover of the water body or wetland. In addition, VIC's evaporation figure (Table8) showed to fit better in areas with more Cropland (in the center of

Thailand or the northwest of Cambodia) than in areas with a lot of forests (the northern edge of Myanmar or the center of Laos or Vietnam).

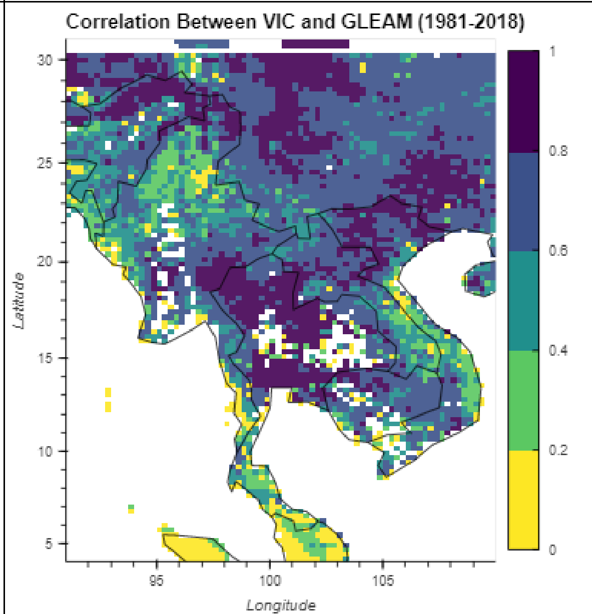
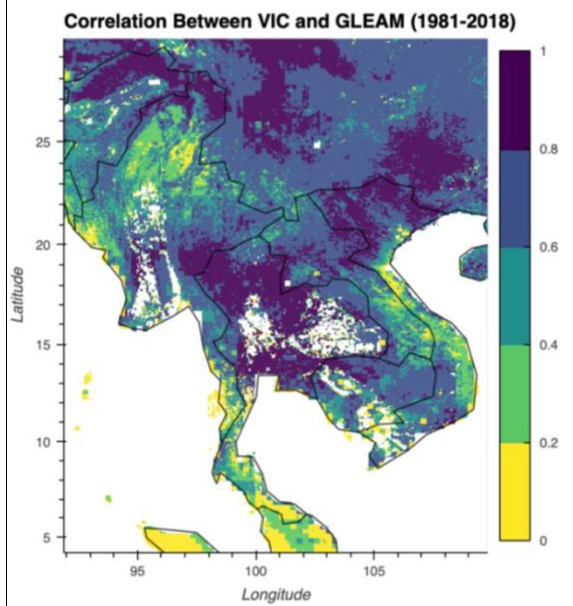
	Regrid to Gleam	Regrid to VIC
		
Cambodia	0.63	0.612
Vietnam	0.600	0.597
Thailand	0.673	0.669
Myanmar	0.533	0.551
Laos	0.638	0.640
Mean	0.615	0.614

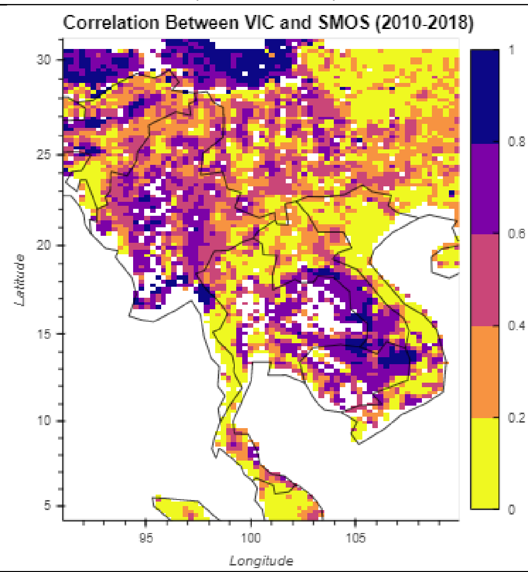
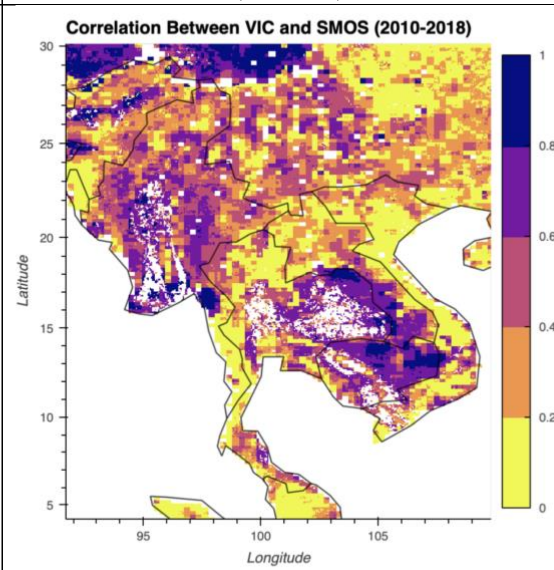
Table 8 Validation with VIC Evaporation VS GLEAM data

2) Validation with SMOS

For validation of soil moisture, we used soil moisture data from SMOS (Soil Moisture and Ocean Salinity) with a resolution of 25 km. SMOS satellite launched from the ESA in early 2009, provides global interferometric L band radiometric observations and provides near-surface soil moisture data every three days (Cui et al. 2018). SMOS is the first mission created to monitor the surface soil moisture of the Earth and provides a resolution of 25 km (A. Mishra et al. 2017). The soil moisture of VIC was better matched with SMAP than SMOS. However, there was some in common between the two data. For example, Vietnam showed the worst fit (0.4999 with SMAP and 0.147 with SMOS). Given the correlation between the two satellite datasets in this respect, the two satellite data products also show some discrepancies. For example, in Vietnam and southern Laos, the average correlation was 0.3-0.4, but most areas were less than 0.2.

3) Validation with SMAP

We also performed validation with SMAP (Soil Moisture Active and Passive) satellite data with a 36km resolution. SMAP is a satellite launched on January 31, 2015, providing measurements of global soil moisture and freeze-thaw state in 2-3 days. The SMAP is the first Earth observation satellite mission developed by NASA (Entekhabi et al. 2010). SMAP provides agricultural products such as potential yields, water availability, and natural stress. When we compared the correlation with SMOS satellite soil moisture data (Table 9). Unlike SMOS data, the SMAP data has a higher correlation of around 0.679 and is the best fit in Myanmar, followed by Laos Cambodia. Also, SMAP showed that a higher correlation than 0.8 (dark purple) in the center of Myanmar and Thailand, and 0.6 in the delta region of Vietnam. So, these locations are in the cropland region has higher than other regions in these countries.

	Regridded to Lower resolution (to SMOS)	To Higher resolution (to VIC)
		
Cambodia	0.583	0.609
Vietnam	0.147	0.157
Thailand	0.347	0.351
Myanmar	0.472	0.465
Laos	0.392	0.339
	Regridded to Lower resolution (to SMAP)	To Higher resolution (to VIC)

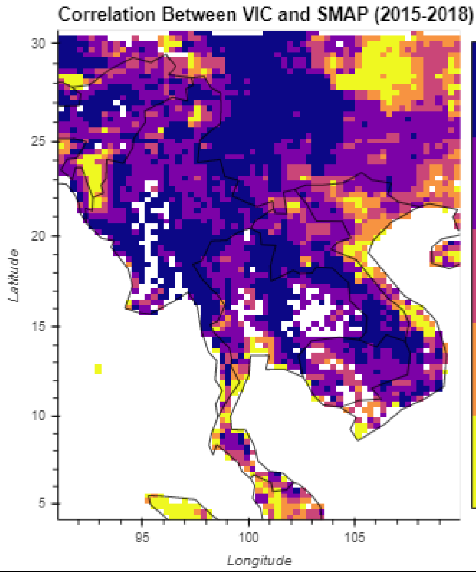
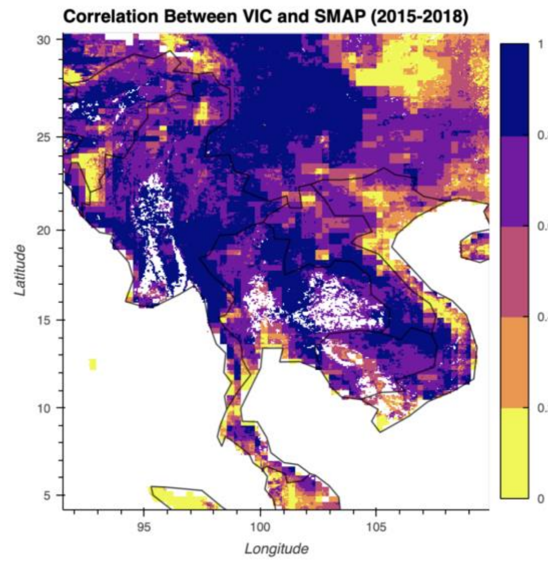
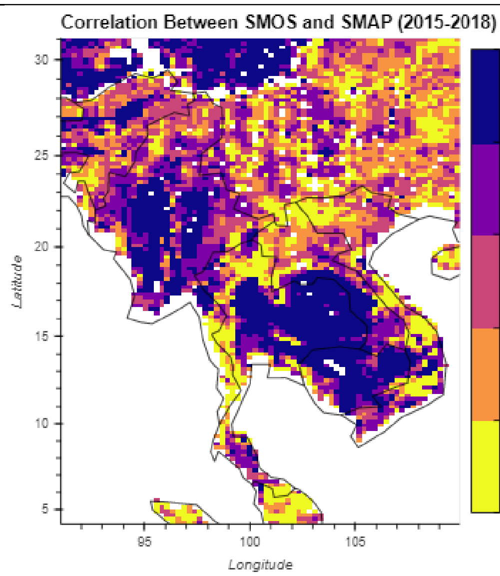
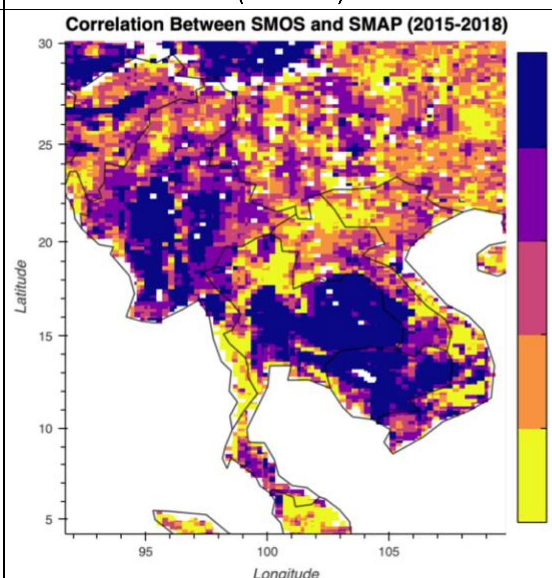
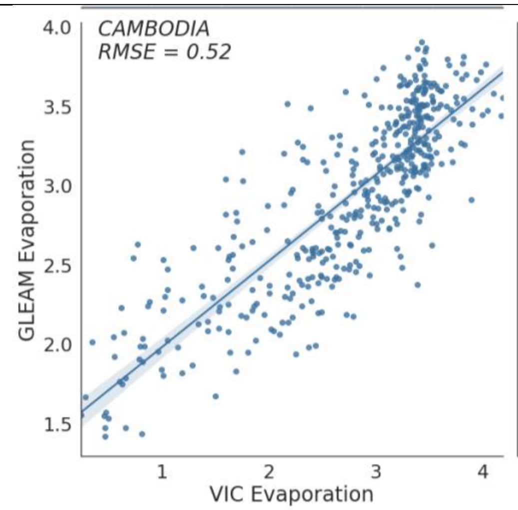
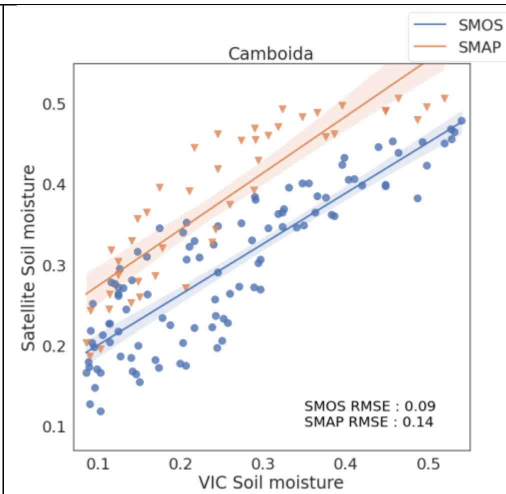
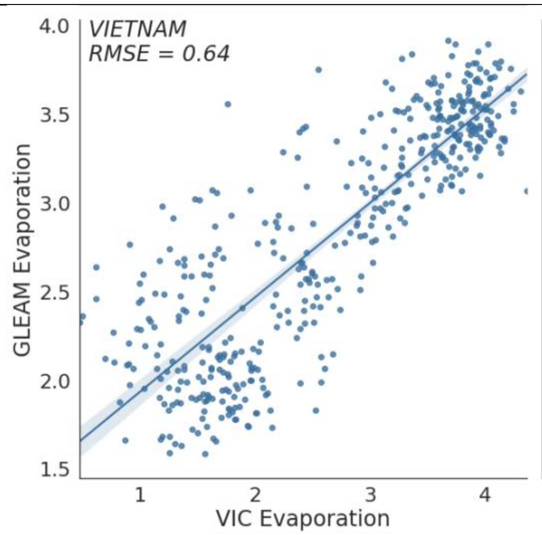
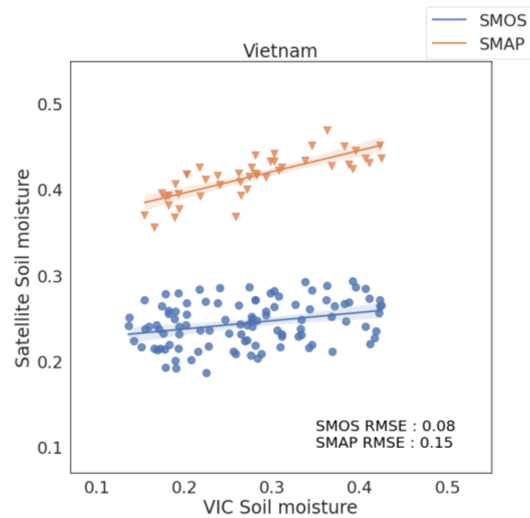
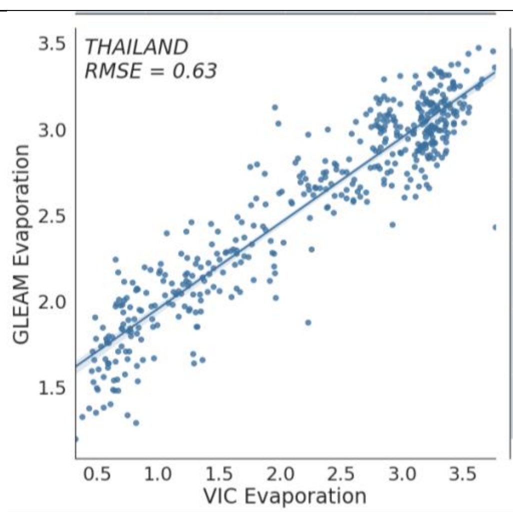
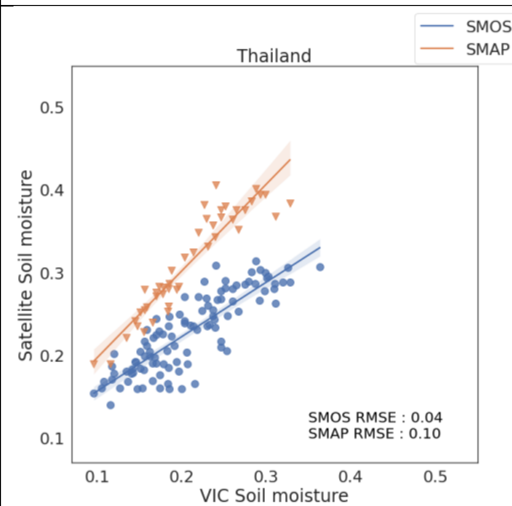
		
Cambodia	0.714	0.708
Vietnam	0.499	0.505
Thailand	0.694	0.700
Myanmar	0.761	0.763
Laos	0.723	0.720
	Regridded to Lower resolution (to SMAP)	To Higher resolution (to VIC)
		
Cambodia	0.811	0.804
Vietnam	0.363	0.357
Thailand	0.618	0.603
Myanmar	0.628	0.623
Laos	0.435	0.433

Table 9 Validation with VIC soil moisture VS SMOS VS SMAP

<table>
<tr><td></td><td colspan="2">RMSE</td></tr>
<tr><td>Cambodia</td><td>
</td><td>
</td></tr>
<tr><td>Vietnam</td><td>
</td><td>
</td></tr>
<tr><td>Thailand</td><td>
</td><td>
</td></tr>
</table>

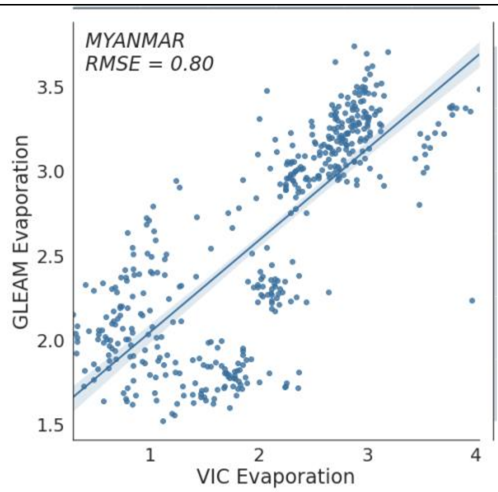
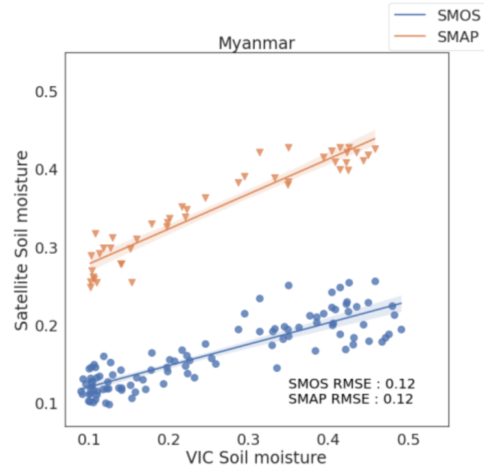
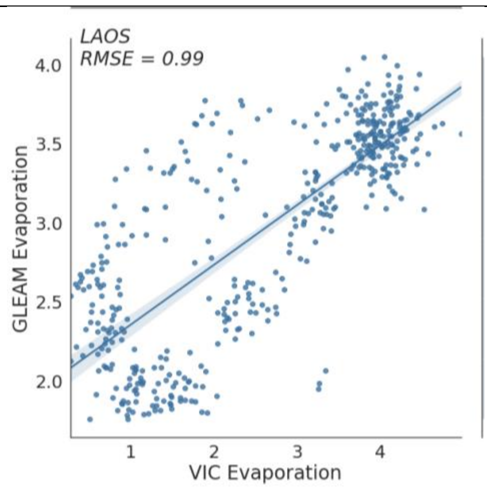
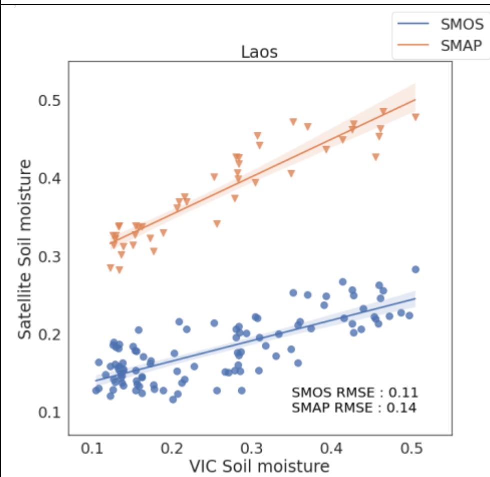
Myanmar		
Laos		
Mean	0.72	SMOS : 0.09 SMAP : 0.13

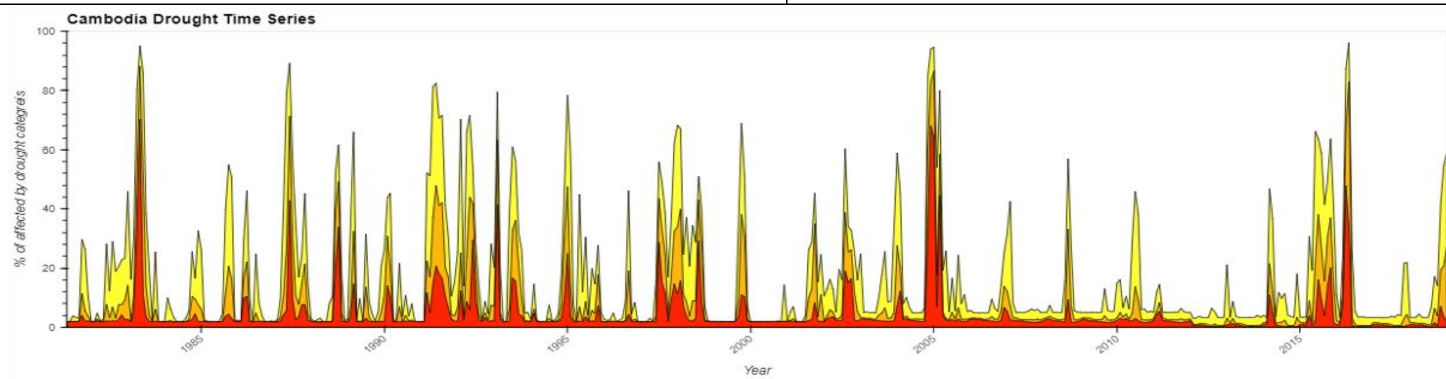
Figure 7 RMSE (Root Mean Square Error)

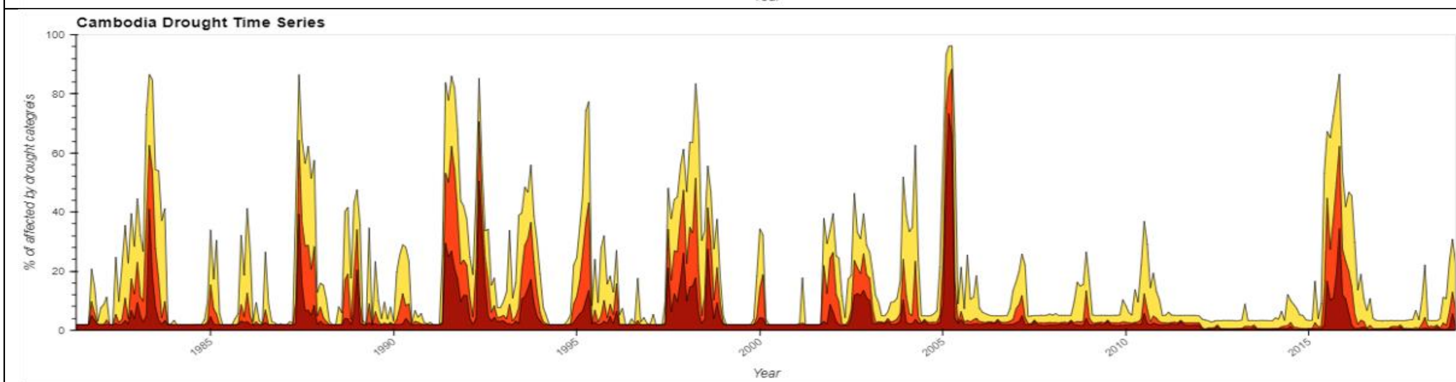
4) RMSE (Root Mean Square Error)

Comparing satellite data with time series by averaging the VIC model nationwide, the model's value was following the trend of satellite data. So, we calculated the RMSE to validate the model (Figure 7 left side). The average RMSE with GLEAM evaporation was 0.7, and Cambodia had the smallest 0.526 and the largest 0.99 in Laos. RMSE of soil moisture was averaged 0.0858 with SMOS and 0.1305 with SMAP (Figure 7 right side), Both SMOS and SMAP showed the smallest RMSE in Thailand. And when we drew the time series plots with the national average, there is a slight difference between the two products, SMOS was always smaller than the model, and SMAP shows higher values than the model. Both use L-band radiometer, but there is differences in processing soil moisture. Further research is expected to be needed to determine which of these products is more accurate.

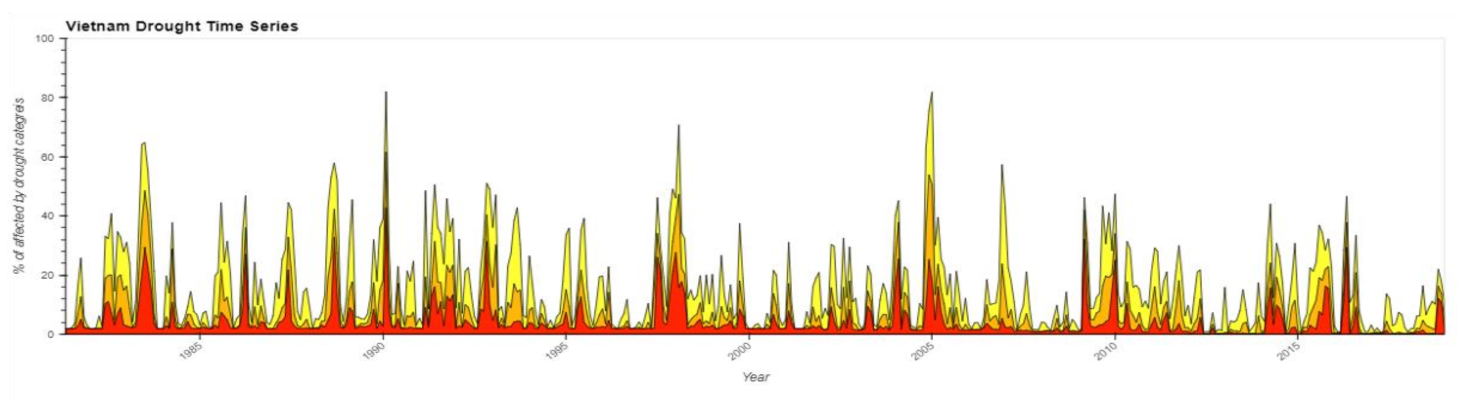
	SPI3	SPI6
	Modreate Drought Severe Drought Extreme Drought	Moderate Drought Severe Drought Extreme Drought

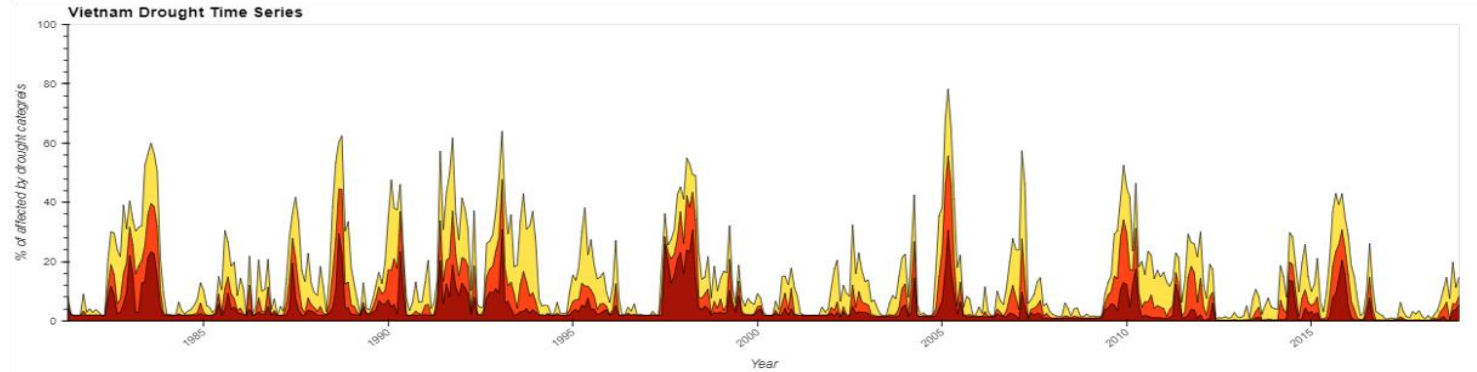
Cambodia



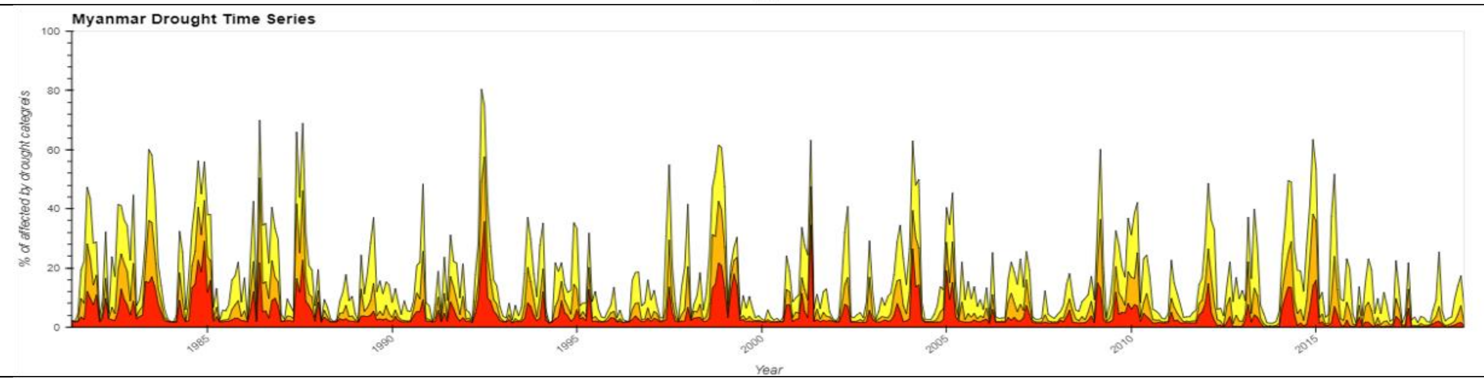


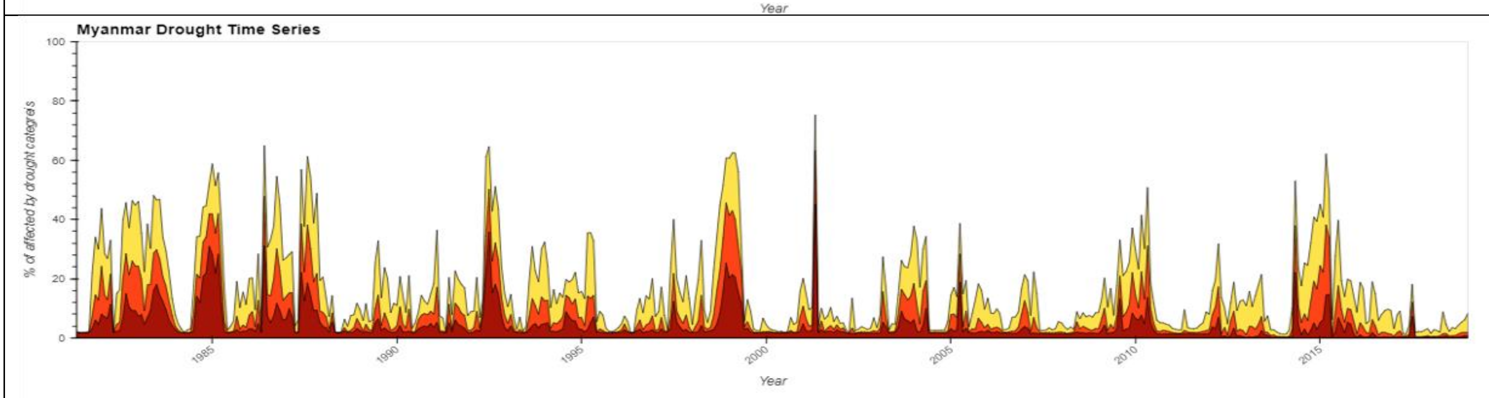
Vietnam



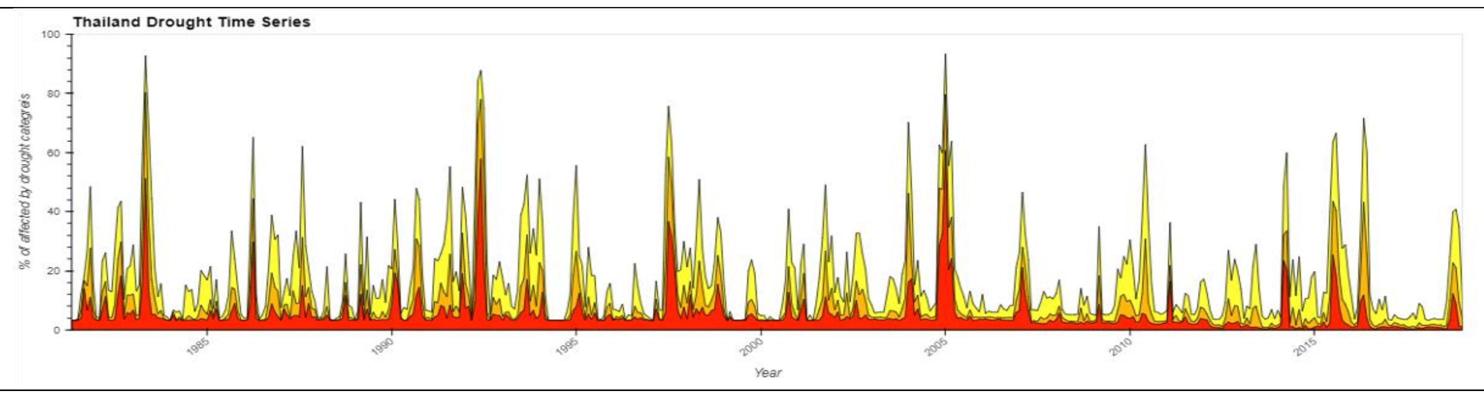


Myanmar





Thailand



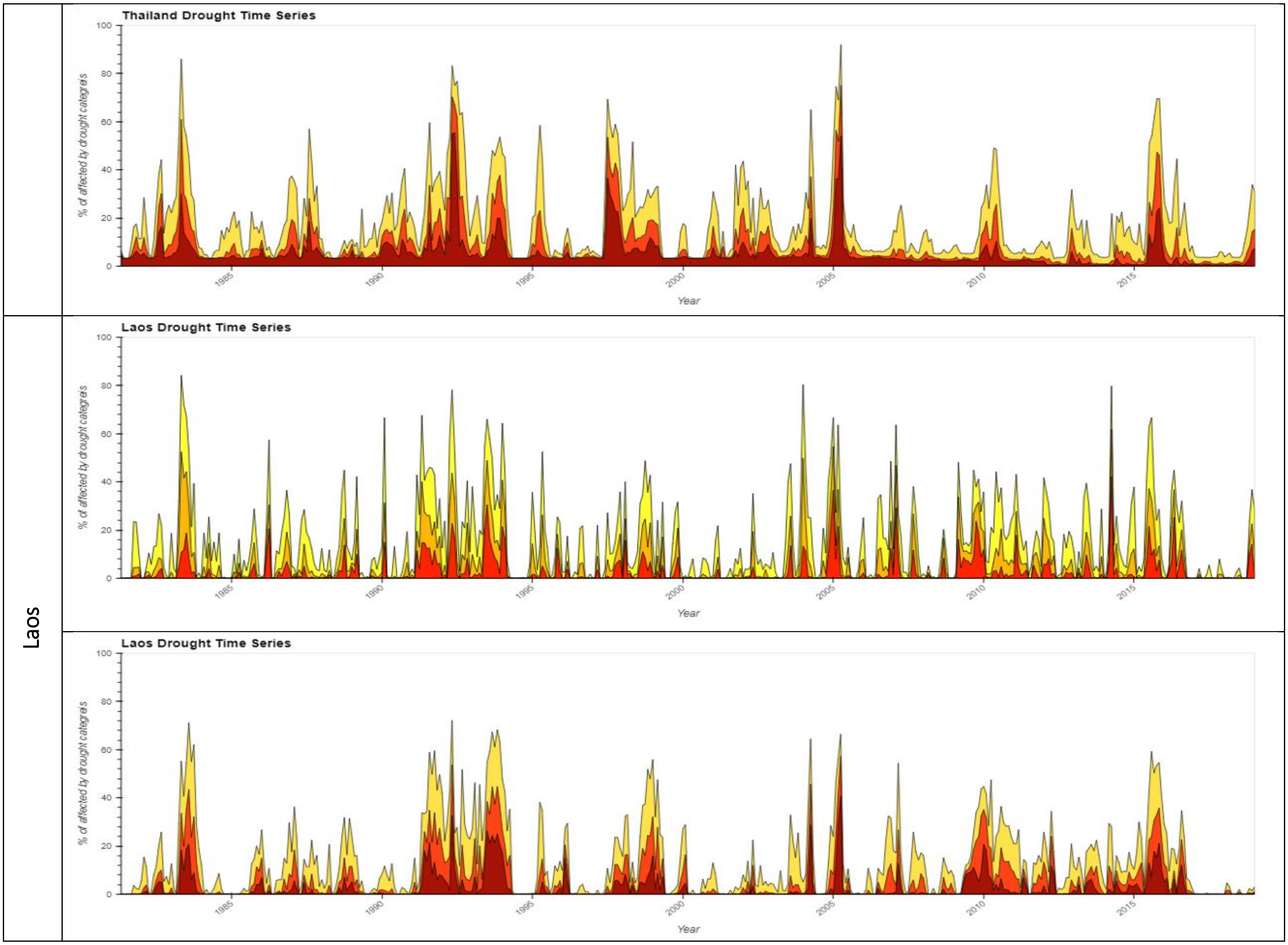


Figure 8 Time series area under Drought

Figure 8 shows the area of the damaged area as a percentage of the entire country according to the level of the drought and the upper graph in each country shows the SPI3 index and the lower graph shows the SPI6 graph. Each color is represented by mild droughts, moderate droughts, and severe drought. If the SPI is less than -1, we called a moderate drought, and if it is less than -1.5, we called a severe drought, and if it is less than -2, it was extreme drought. The drought in Cambodia occurred during the period from January to June 1983, which affected the widest area during the study period, and 70% of the country was under extreme (SPI < -2). The next most widespread event was from September 2004 to March 2005, and 68% of the countries were affected by extreme drought. As such, Cambodia appears to suffer the widest rate of damage when drought occurs compared to other countries, and between 2005 to 2016, meteorological drought (SPI6 <-1) did not occur from 2006 to 2014. Vietnam experienced severe drought in the largest area (42%) in the early 1990s, while over 70% of Thailand experienced severe drought in 1983, 1992, and 2004. Laos appears to have suffered the least rate of drought compared to other countries, but it suffered from continuous drought from 1991 to 1994 and from 2009 to 2010.

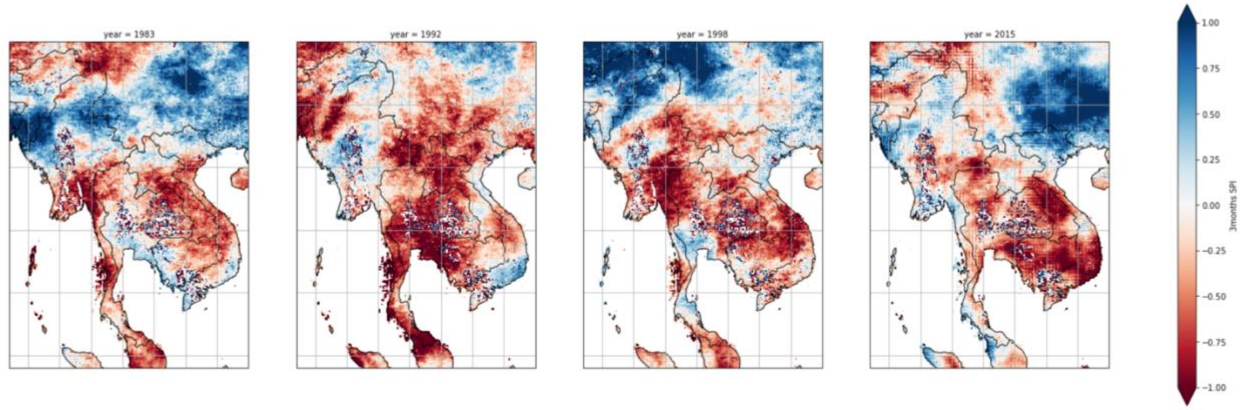


Figure 9 Historical Drought Record with SPI 3

Figure 9 shows the annual average SPI3 index for the year of the drought event. Comparing drought events in 1982–84, 1991–94, 1997–99, 2015–16, Cambodia suffered drought in the northeastern region (Stung Treng, Ratanakiri, Kratie, Mondulkiri, and Preah Vihear) in 1983 and 1998 and the drought index for this region in 1983 was generally around -0.5 to -0.75 but in 1998, the same region had a more severe drought with the SPI3 index below -0.75. And this is the region where the forest has turned into Savannas the most in Cambodia. In 1992 and 1998, Thailand suffered common damage to the Cropland part, and in 1992 the drought affected a larger area. The drought record show more severe drought damage in northeastern Cambodia than in the past, and this is a region that has defrosted in Cambodia.

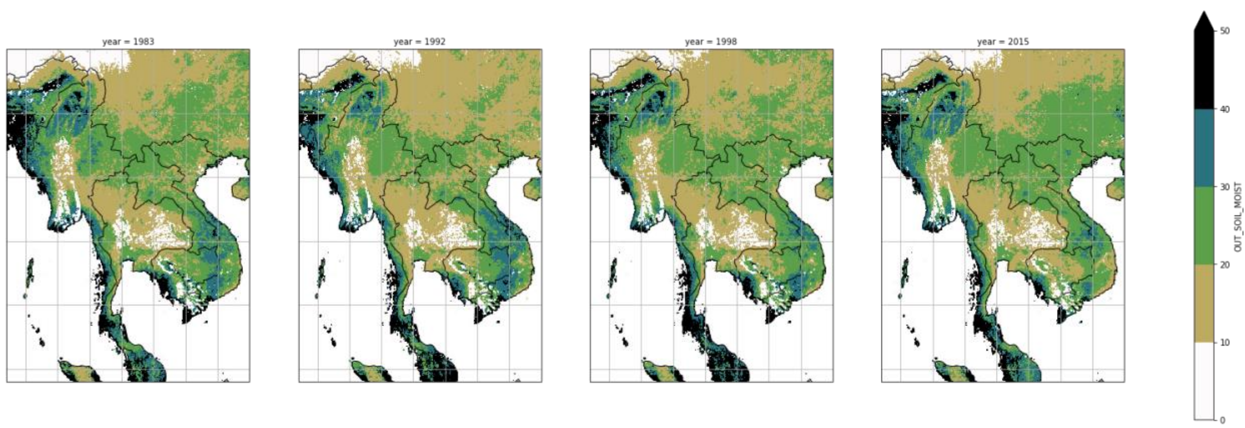


Figure 10 Mean yealy soil moisture on historical drought record

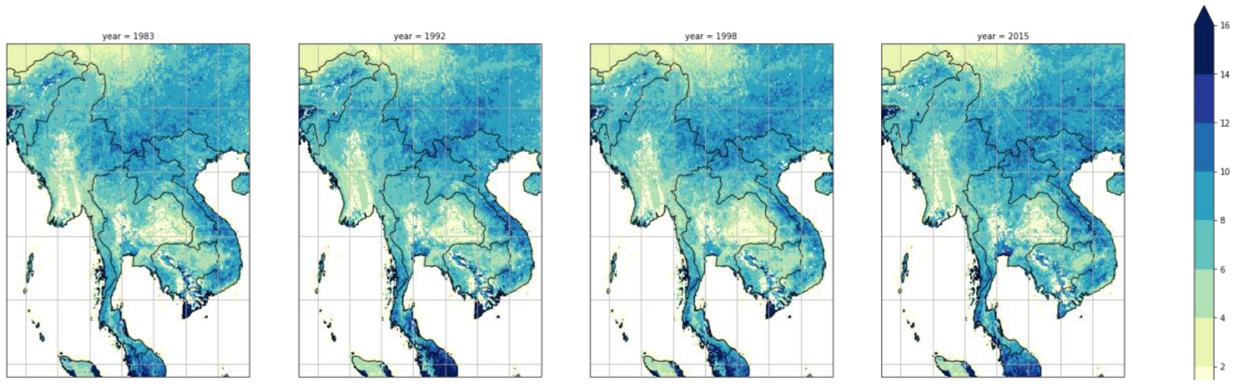


Figure 11 Yearly min soil moisture on historical drought record

Since SPI is an index calculated based on precipitation, it may be difficult to directly correlate with land cover, so we compared drought events with soil moisture data that comes from the VIC model. We used the soil moisture of the topsoil layer. Figure10 shows the annual average moisture content, and Figure 11 shows the minimum moisture content in the year when the drought occurred. Cambodia's 2015 average soil moisture map shows that it is much dry compared to other drought years, but the minimum moisture map is a little wetter. So that means Cambodia in 2015 was a little drier on average, but it had a little more moisture during the drought time. Compared to the drought before the 2000s, Laos shows having more moisture in more areas in 2015. And Vietnam has small minimum moisture in the delta area in 2015 compared to other years, and on both maps, there was no significant change in Myanmar between each drought events.

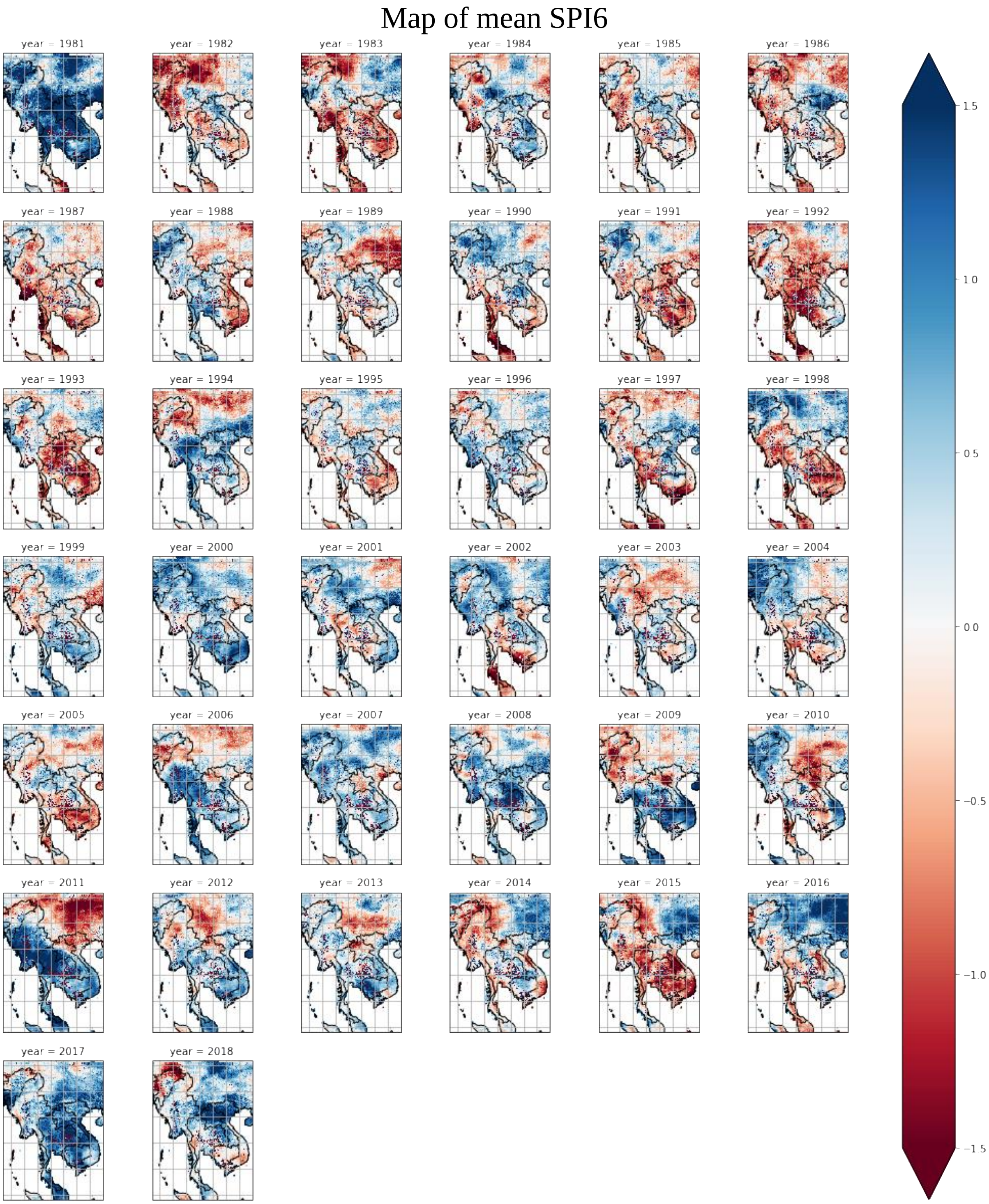


Figure 12 Map of Yearly mean of Lower Mekong River Basin 6 months SPI

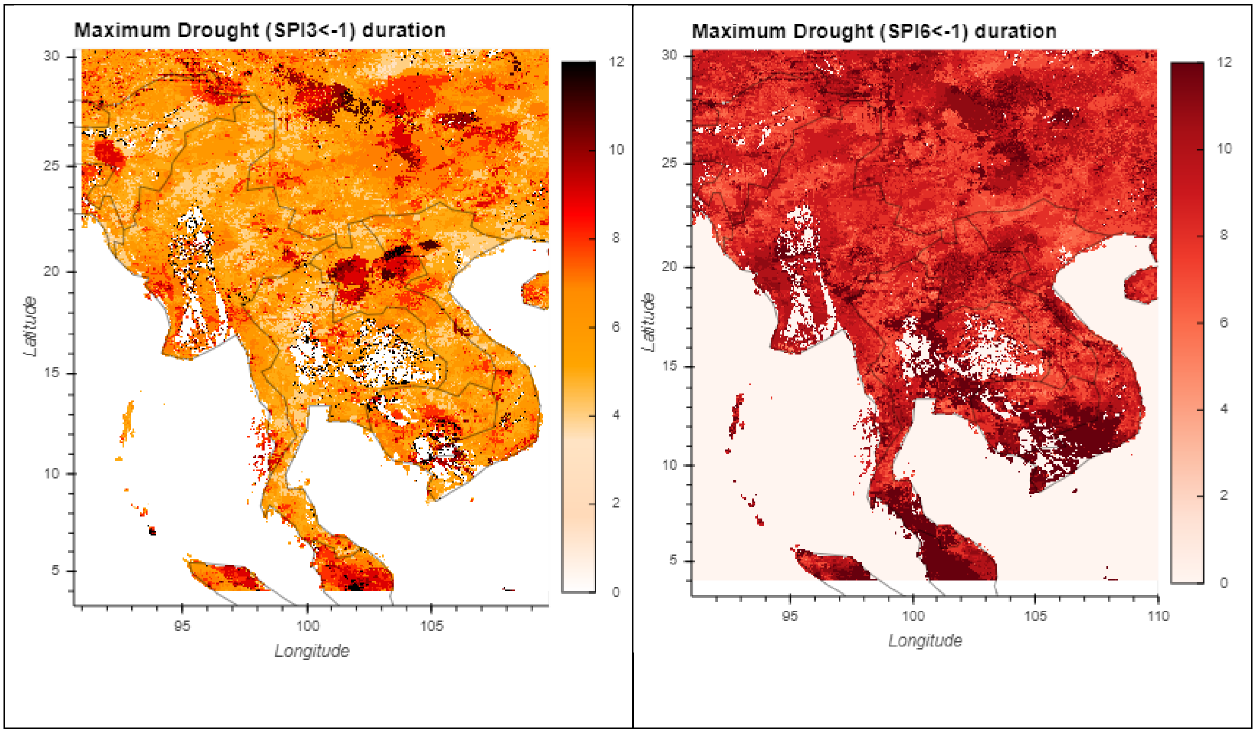
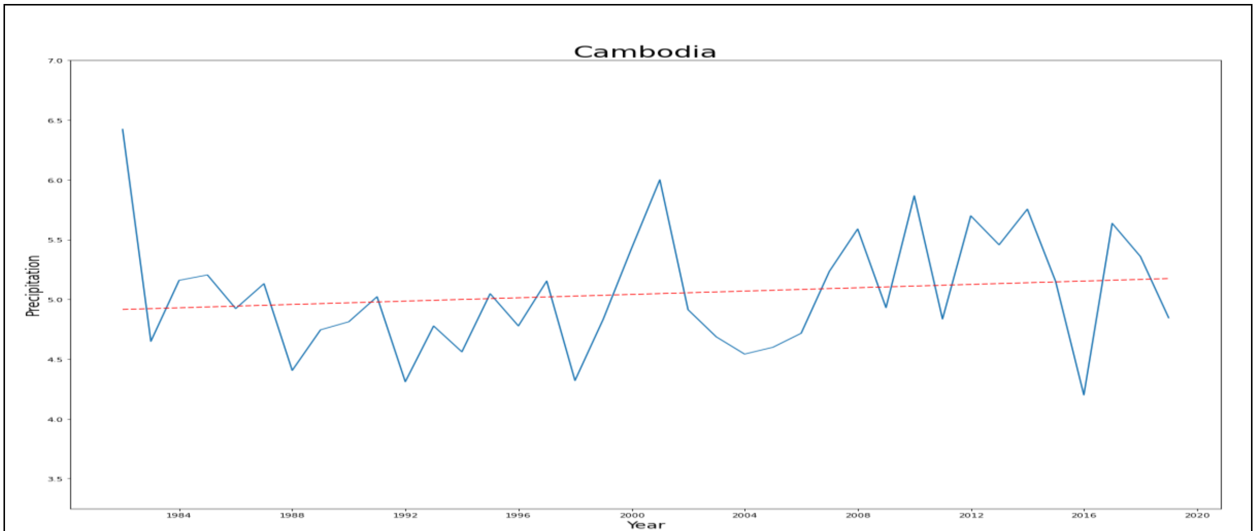
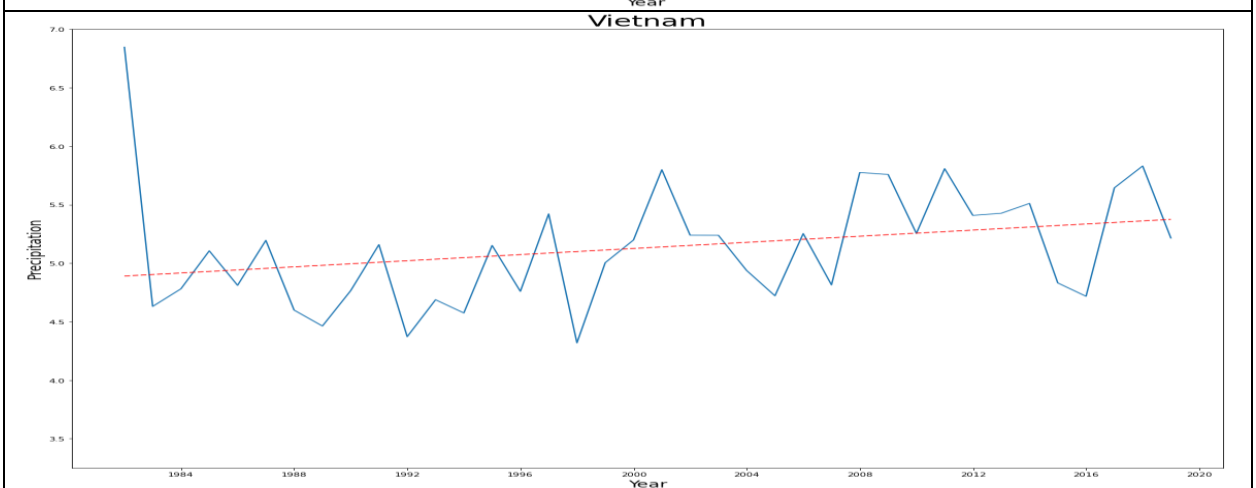


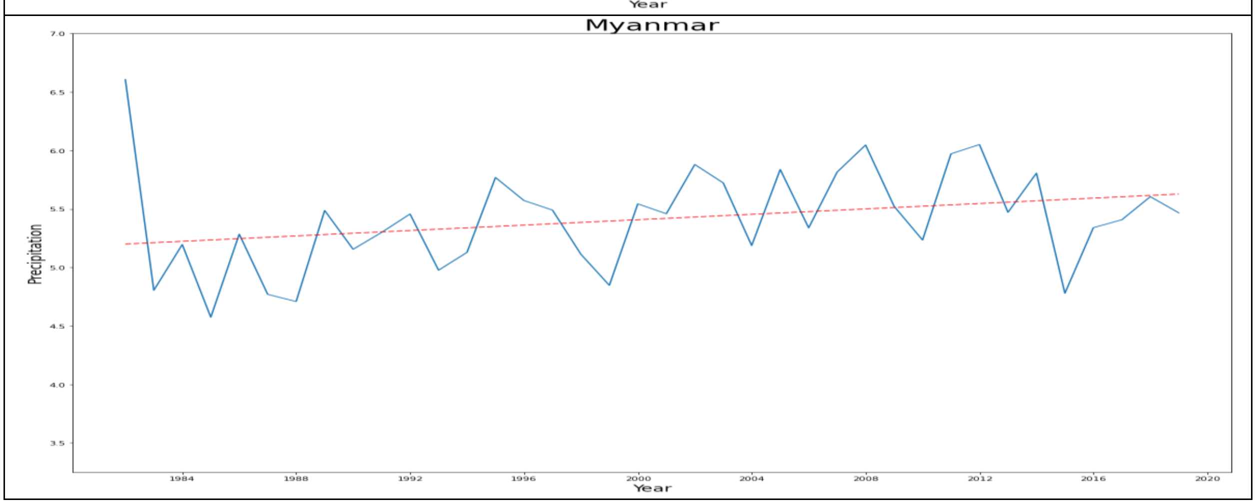
Figure 13 Maximum drought duration for 37 years

Figure 13 represents the maximum drought period each pixel had during the study period. In the left of Figure 13, most of the study area seems to have a maximum continuous drought for about six months in general, and what appears to be black means that there has been a drought for more than a year. So, compared to other places, the longer drought parts appear near the middle of Myanmar and southeast Cambodia. Unlike SPI3, the SPI6 map showed that the southernmost part of Vietnam suffered drought for more than a year, which means that this Vietnam Delta region suffered from an agricultural drought rather than a meteorological drought. In addition, all three regions mentioned above are in cropland land, and the Vietnam Delta region is a key region for rice production in the Mekong Basin, and the damage to crops due to such drought can be expected.

5. Discussion


Cambodia
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
Precipitation
1984
1988
1992
1996
2000
2004
2008
2012
2016
2020
Year


Vietnam
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
Precipitation
1984
1988
1992
1996
2000
2004
2008
2012
2016
2020
Year


Myanmar
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
Precipitation
1984
1988
1992
1996
2000
2004
2008
2012
2016
2020
Year

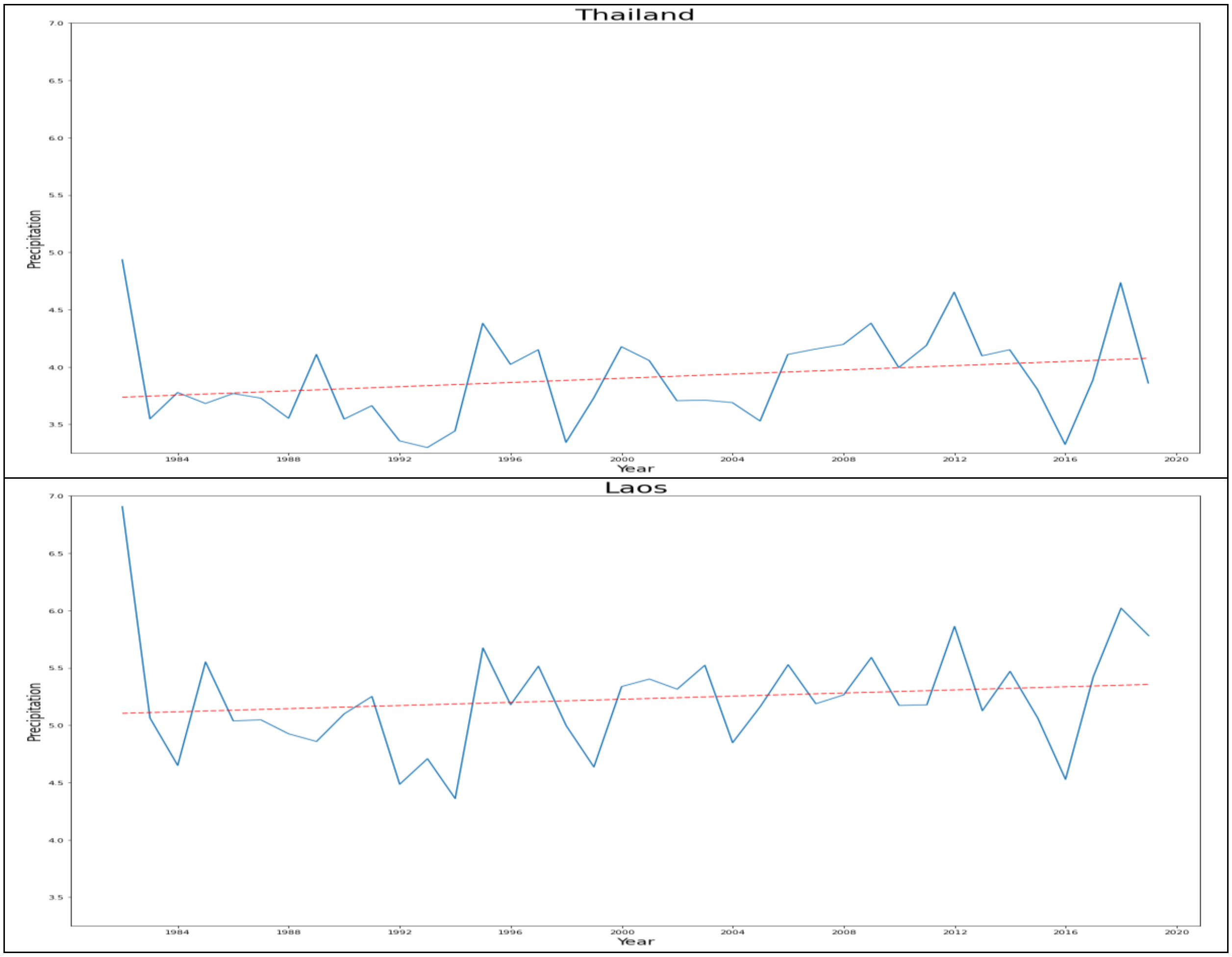


Figure 14 Annual precipitation trends

Through this study, we identified the changes in land cover over 17 years in the Mekong River basin and put land cover data for 2001, 2006,2011, 2018 to the VIC model, and looked for hydrological changes. The drought index of the Mekong River basin, also calculated with the Hydrologic output, and the drought event with these indexes was consistent with the result of the previous study (November 1982 to February 1984, June 1991 to May 1994, September 1997 to April 1999, and April 2015 to Julie 2016). In the historical drought record, northeastern Cambodia had more extreme drought damage in the past than the recent record, and this region has deforested. Also, Thailand has seen a steady decline in forest area until 2002 but has since increased again so there were no significant changes in forest area in 2001 and 2018. As an additional process, it seems necessary whether these changes brought drought to Thailand only to 1998. In addition, major damage was reported in 2015 in the Delta region of Vietnam, and this area is a representative agricultural development area in the Mekong Basin region. So, this damage in the region is expected to cause serious damage to crops.

During the study, we found changes in land cover, but after the 2000s, there was some weak drought event such as moderate drought in southern Cambodia in 2002 and Cambodia in 2005, the only drought in the basin was a year in 2015, like this the drought trend in the Mekong River basin, has been more frequent and affected in the past than in the present and these make it difficult to find a link between land cover and drought. According to a paper that studied Amazon, Amazon increased its deforestation rate by 0.13% each year, which caused a dryness of 4%. In the same study, deforestation results in cumulative deforestation, which leads to less evapotranspiration and less precipitation, which finally brings more deforestation in the study area. (Staal et al. 2020). The Amazon lost 13% of its forest area in 2003 alone, and landcover changes in this area reduced precipitation by 5.45% and ET by 4.61% in dry seasons (Bagley et al. 2014). As such, we expected that there will be a change in drought due to deforestation in the Mekong region, but since 2002 (Figure 12), when the land cover data was changed, the record drought occurred only once in 2015, which had limitations in comparing it to drought events with respect to landcover. In addition, the area and degree of damage were less than in the past drought. As you can see in the figure14, the average annual precipitation in each country is increasing. This is showing a different aspect from other case studies in Amazon. Unlike the Amazon, the speed and area of the deforestation in the Mekong region were not fast and concentrated, so these differences brought different results here. For this reason, further research is needed to find out the impact of land cover on drought in the Mekong basin. Additional research is to use landcover before 2001 to identify the link between landcover and before 2000s drought events. Also, the impact of dams located upstream of rivers should also be considered in future studies. And, it might be necessary to run a model to predict landcover data from the 1940s to the 1960s and look at some causes of the extremely increased drought damage and frequency between these periods.

6. Conclusions

In this study, it was possible to find changes in land cover for 17 years and to obtain a certain degree of accuracy of the model. Study have shown that five countries located in the Mekong River basin have changed 25% over the past 17 years. When the Landcover category was reduced from 25 to 8, the change % was decreased to 20 but it was still high. And the results from this model were compared to other satellite data, the correlation with GLEAM evaporation data was 0.6, and the correlation with SMOS soil moisture data was 0.3, and SMAP was 0.679. In this study, we tried to see the impact of land cover on drought and changed land cover data from 2002 because the landcover data was available since 2001. But since 2002, the drought has only occurred once, and even the drought has a smaller damage area and less intensity than in the past. So, it was not easy to find the relationship between drought and land cover. It is expected that further research will be needed with a longer study period with data.

References

Bagley, Justin E. et al. 2014. “Drought and Deforestation: Has Land Cover Change Influenced Recent Precipitation Extremes in the Amazon?” *Journal of Climate* 27(1): 345–61.

Cherkauer, Keith A., Laura C. Bowling, and Dennis P. Lettenmaier. 2003. “Variable Infiltration Capacity Cold Land Process Model Updates.” *Global and Planetary Change* 38(1–2): 151–59.

Cui, Chenyang et al. 2018. “Soil Moisture Mapping from Satellites: An Intercomparison of SMAP, SMOS, FY3B, AMSR2, and ESA CCI over Two Dense Network Regions at Different Spatial Scales.” *Remote Sensing* 10(1).

Edwards, Daniel C.; McKee, Thomas B.; 1997. “CHARACTERISTICS OF 20TH CENTURY DROUGHT IN THE UNITED STATES AT MULTD7LE TIME SCALES.” 298(0704).

Entekhabi, Dara et al. 2010. “The Soil Moisture Active Passive (SMAP) Mission.” *Proceedings of the IEEE* 98(5): 704–16.

Guo, Hao et al. 2017. “Meteorological Drought Analysis in the Lower Mekong Basin Using Satellite-Based Long-Term CHIRPS Product.” *Sustainability (Switzerland)* 9(6).

Koneti, Sunitha, Sri Sunkara, and Parth Roy. 2018. “Hydrological Modeling with Respect to Impact of Land-Use and Land-Cover Change on the Runoff Dynamics in Godavari River Basin Using the HEC-HMS Model.” *ISPRS International Journal of Geo-Information* 7(6): 206. http://www.mdpi.com/2220-9964/7/6/206 (June 29, 2020).

Kummu, Matti, and Olli Varis. 2007. “Sediment-Related Impacts Due to Upstream Reservoir Trapping, the Lower Mekong River.” *Geomorphology* 85(3–4): 275–93.

Lee, Jung Eun, Benjamin R. Lintner, C. Kevin Boyce, and Peter J. Lawrence. 2011. “Land Use Change Exacerbates Tropical South American Drought by Sea Surface Temperature Variability.” *Geophysical Research Letters* 38(19): 1–6.

Lee, Seung Kyu, and Truong An Dang. 2019. “Spatio-Temporal Variations in Meteorology Drought over the Mekong River Delta of Vietnam in the Recent Decades.” *Paddy and Water Environment* 17(1): 35–44. https://doi.org/10.1007/s10333-018-0681-8.

Leinenkugel, Patrick, Natascha Oppelt, and Claudia Kuenzer. 2014. “A New Land Cover Map for the Mekong : Southeast Asia ’ s Largest Transboundary River Basin.” *Pacific Geographies* 41(February): 10–14.

Mainuddin, Mohammed, Mac Kirby, and Chu Thai Hoanh. 2011. “Adaptation to Climate Change for Food Security in the Lower Mekong Basin.” *Food Security* 3(4): 433–50.

———. 2013. “Impact of Climate Change on Rainfed Rice and Options for Adaptation in the Lower Mekong Basin.” *Natural Hazards* 66(2): 905–38.

McKee, Thomas B., and Nolan J. Doesken and John Kleist. 1993. “THE RELATIONSHIP OF DROUGHT FREQUENCY AND DURATION TO TIME SCALES.” *Journal of Climateology* 105(8): 818–24.

Mishra, Ashok K., and Vijay P. Singh. 2010. “A Review of Drought Concepts.” *Journal of Hydrology* 391(1–2): 202–16. http://dx.doi.org/10.1016/j.jhydrol.2010.07.012.

Mishra, Ashok, Tue Vu, Anoop Valiya Veettil, and Dara Entekhabi. 2017. “Drought Monitoring with Soil Moisture Active Passive (SMAP) Measurements.” *Journal of Hydrology* 552(January 2015): 620–32. http://dx.doi.org/10.1016/j.jhydrol.2017.07.033.

MRC. 2005. “Hydrology of the Mekong Basin, Mekong River Commission, Vientiane.” (November).

Pech, Sokhem, and Kengo Sunada. 2008. “Population Growth and Natural-Resources Pressures in the Mekong River Basin.” *AMBIO: A Journal of the Human Environment* 37(3): 219–24.

Petchprayoon, Pakorn, Peter D. Blanken, Chaiwat Ekkawatpanit, and Khalid Hussein. 2010. “Hydrological Impacts of Land Use/Land Cover Change in a Large River Basin in Central-Northern Thailand.” *International Journal of Climatology* 30(13): 1917–30.

Räsänen, T. A. et al. 2013. “Palaeoclimatological Perspective on River Basin Hydrometeorology: Case of the Mekong Basin.” *Hydrology and Earth System Sciences* 17(5): 2069–81.

Sam, Truong Thao et al. 2019. “Impact of Climate Change on Meteorological, Hydrological and Agricultural Droughts in the Lower Mekong River Basin: A Case Study of the Srepok Basin, Vietnam.” *Water and Environment Journal* 33(4): 547–59.

Schilling, Keith E. et al. 2008. “Impact of Land Use and Land Cover Change on the Water Balance of a Large Agricultural Watershed: Historical Effects and Future Directions.” *Water Resources Research* 45(7): 1–12.

Sona, N. T. et al. 2012. “Monitoring Agricultural Drought in the Lower Mekong Basin Using MODIS NDVI and Land Surface Temperature Data.” *International Journal of Applied Earth Observation and Geoinformation* 18(1): 417–27. http://dx.doi.org/10.1016/j.jag.2012.03.014.

Staal, Arie et al. 2020. “Feedback between Drought and Deforestation in the Amazon.” *Environmental Research Letters* 15(4).

Sterling, Shannon M, Agnès Ducharne, and Jan Polcher. 2013. “The Impact of Global Land-Cover Change on the Terrestrial Water Cycle.” www.nature.com/natureclimatechange (May 16, 2020).

Thilakarathne, Madusanka, and Venkataramana Sridhar. 2017a. “Characterization of Future Drought Conditions in the Lower Mekong River Basin.” *Weather and Climate Extremes* 17(June): 47–58. http://dx.doi.org/10.1016/j.wace.2017.07.004.

———. 2017b. “Characterization of Future Drought Conditions in the Lower Mekong River Basin.” *Weather and Climate Extremes* 17(July): 47–58. http://dx.doi.org/10.1016/j.wace.2017.07.004.

Trisurat, Yongyut, Aekkapol Aekakkararungroj, Hwan ok Ma, and John M. Johnston. 2018. “Basin-Wide Impacts of Climate Change on Ecosystem Services in the Lower Mekong Basin.” *Ecological Research* 33(1): 73–86.

Yamauchi, Katsuhiko. 2014. “Climate Change Impacts on Agriculture and Irrigation in the Lower Mekong Basin.” *Paddy and Water Environment* 12(2): 227–40.

van Zalingen, N et al. 2003. “The Mekong River System.” *FAO Coop. Doc. Repos.* (February): 11–14. http://www.fao.org/docrep/007/ad525e/ad525e0l.htm.

Ziv, Guy et al. 2012. “Trading-off Fish Biodiversity, Food Security, and Hydropower in the Mekong River Basin.” *Source* 109(15): 5609–14.