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Research article

Interaction of drought-influencing factors for drought mitigation strategies in Lam Ta Kong Watershed, Khorat Plateau

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ABSTRACT

Generally, drought is influenced by both spatial characteristics and anthropogenic activities within an area. Drought vulnerability assessment is a critical tool that can be effectively used to develop proper drought mitigation strategies to prevent avoidable losses. To develop suitable drought mitigation strategies, the overall drought vulnerability must be assessed, and the interaction among drought-influencing factors in the area should be considered. Consequently, this study aimed to investigate the interactions among critical drought-influencing factors and drought vulnerability in the Lam Ta Kong Watershed via spatial analysis with the analytical hierarchy process (AHP) and geographical information system (GIS) technology. Ten drought-influencing factors were considered in the vulnerability assessment: slope, elevation, soil texture, soil fertility, stream density, precipitation, temperature, precipitation days, evaporation, and land use. The results indicated that the critical drought-influencing factors were precipitation, precipitation days, and land use, resulting in most of the watershed experiencing high drought vulnerability (35.1% of the watershed or 1810.83 km^2). Moreover, this research highlighted the interactions among the critical drought-influencing factors. Precipitation interacted with precipitation days to cause drought vulnerability across the watershed, with a p-value <0.05. Similarly, the interactions between precipitation and land use and between precipitation days and land use, with p-values <0.05, showed that they were associated with and influenced by drought in the Lam Ta Kong Watershed. This study further indicated that appropriate drought mitigation strategies for this watershed must consider the interactions among these drought-influencing factors, as well as their specific interactions across the watershed.

1. Introduction

Drought is a critical natural disaster that widely occurs in various climatic zones, particularly in arid and semi-arid zones, and often occurs repeatedly [1,2]. This phenomenon generally reflects unusual atmospheric circulation patterns and climate change that cause irregular precipitation patterns [3]. Drought profoundly negatively affects ecological, economic, and social systems [4–7]. The magnitude of drought impacts varies depending on the spatial location, local conditions, drought intensity, and duration [8–10], while arid and semi-arid areas are severely affected by the frequency and severity of droughts. The magnitude of the drought severity in these zones is amplified by low annual precipitation, which directly affects water storage in surface water and groundwater sources [11].

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Previous research has indicated that various natural and anthropogenic factors are driving factors that increase the drought frequency and intensity worldwide [8,12], even in humid and subhumid zones [2,13–17]. Similarly, Thailand is located in a tropical climate zone. However, the country has experienced long-lasting drought.

A study by the Department of Disaster Prevention and Mitigation (DDPM) of Thailand [18] indicated that within 21 years (1989–2010), Thailand had suffered drought every year, and more than 80% of the country was affected by drought for 12 years. Moreover, drought events, including El Niño, were linked with natural disasters since El Niño years yielded decreased precipitation in Thailand and caused higher drought intensity and water scarcity in the following years [19]. Most of the affected areas occur in the northeastern region and are influenced by geographical and physical factors. Nakhon Ratchasima Province is the economic center of the northeastern region [20]; however, 85.9% of the provinces regularly experience drought [21]. The Lam Ta Kong Watershed is an important watershed of Nakhon Ratchasima, as it is intentionally and constantly developed with multisectoral development plans, including economic, agricultural, transportation, and tourism development efforts. The watershed occurs on the Khorat Plateau, a vast formation of red-bedded continental sedimentary rock of the Khorat Group formed after the Mesozoic era [22]. The Maha Sarakham Formation is a massive potash deposit on the Khorat Plateau. This area encompasses three rock salt members interbedded with claystones [23]. Development and urbanization within watersheds have also caused rapid changes in land use and human activities, critically affecting water requirements. Moreover, geographical factors contribute to drought vulnerability and increase the drought severity.

A meta-analysis of the literature revealed that various influential factors, including geographical, natural, climatic, and anthropogenic factors, play a critical role in causing drought based on spatial factors. Geographical factors, including slope and elevation, reflect the geographical characteristics and unique natural features of an area and are usually applied to assess drought conditions [20, 24–26]. Several additional factors can also be used and, based on their specific spatial differences, include solar radiation [27], groundwater level ([9,13,28], salt dispersion [16], and lithology [13]. Natural factors describe the natural conditions and compositions within the area that contribute to drought in addition to the geographical characteristics of the area. Soil texture, soil fertility, stream density, soil depth, soil moisture, and distance to rivers/irrigation are universal natural drought indicators used in drought assessment [16,17,29,30]. Climatic factors directly influence the climate of the region [31] and contribute to drought [32,33]. Various climatic factors, including precipitation, temperature, precipitation days, evaporation, and humidity, have been considered in drought assessment studies [2,13,27,34]. Anthropogenic factors have become critical factors contributing to and intensifying drought events. Land use and land cover are key anthropogenic factors considered in drought assessments to reflect both possible human activities and the water demand that influence the drought vulnerability of an area [20,29]. In addition, land use and land cover change can cause negative changes in surface runoff and can interrupt the hydrological cycle [35], further increasing drought vulnerability.

Typically, drought management strategies can be categorized into two approaches: reactive and proactive. Among these, proactive measures are widely favored for their cost-effectiveness. To cultivate effective proactive drought management strategies in drought-affected regions, it is imperative to develop these plans with a thorough understanding of the area's spatial dynamics, encompassing its distinct physical, natural, and climatic conditions. At this juncture, both risk assessment and vulnerability assessment prove to be invaluable. The concepts of risk and vulnerability are extensively discussed across various disciplines, often tailored and applied to their respective fields. Risk and vulnerability are intricately intertwined; in the context of disasters, risk is portrayed as a function of hazard, exposure, and vulnerability [36], or as a function of hazard and vulnerability, where exposure is inherently accounted for within vulnerability [37,38]. In essence, vulnerability constitutes a critical component of disaster risk assessment, elucidating the degree to which a region is susceptible to adverse effects or harm resulting from such natural occurrences [39,40]. In general, the fundamental components of vulnerability encompass exposure, sensitivity, and adaptive capacity [39,41,42]. Assessing drought vulnerability serves as a crucial tool for comprehending and addressing the inherent risks of drought occurrences. Consequently, drought vulnerability assessment has become a critical process and tool for identifying, gathering, and evaluating pertinent drought factors and vulnerability levels. Ultimately, this facilitates the formulation of effective mitigation and adaptation strategies.

Previous studies entailed the application of various models to assess the drought vulnerability and identify critical drought-influencing factors, particularly the analytical hierarchy process (AHP) [43–45] and fuzzy analytical hierarchy process (FAHP), which are popular and widely accepted tools [20,46]. As described in the literature, drought can occur due to many factors. Several studies have focused on the interactions between drought factors and drought evolution [47,48]. However, the interactions among various drought factors have been overlooked in drought assessment research, and research on the relationship between the drought risk and drought factors is rare. The risk factors are interrelated [49], and each factor imposes a certain effect on drought [50]. Several studies have shown that natural factors are interrelated and that human activities can influence natural changes [51–53]. Baudena et al. [54], Molina et al. [55], and Perugini et al. [56] stated that land use and land cover interact and affect precipitation patterns. Understanding these relationships could also enhance the understanding and development of effective drought mitigation plans and strategies. Defining measures on the basis of understanding the causes of this problem could effectively lead to drought mitigation, which could help minimize the impacts of droughts on the environment, society, and economy [2,57,58]. Hence, this study aimed to investigate the interactions among drought-influencing factors in the Lam Ta Kong Watershed via drought vulnerability assessment involving the application of the AHP and GIS techniques. Ultimately, the interaction among drought-influencing factors and generation of drought maps could be beneficial for developing appropriate drought mitigation plans for the Lam Ta Kong Watershed.

2. Study area and data sources

2.1. Study area

The Lam Ta Kong Watershed is located in Nakhon Ratchasima, Thailand, with coordinates of 14° 22′ 59.6964″N - 15° 8′ 25.6596″N and 101° 10′ 51.9276″E – 102° 23′ 46.5216″E. This watershed is an important subwatershed of the Mun River Basin that covers approximately 5161.8 km^2 in 6 districts in Nakhon Ratchasima Province, including Pak Chong, Sikhio, Sung Noen, Kham Thale So, Mueang Nakhon Ratchasima, and Chaleom Phra Kiat. The mainstream watershed (Lam Tam Kong River) originates in Khao Yai, a national park and natural world heritage site, and the river flows from Pak Chong (upstream) to the northeast. This river flows through downstream districts to merge with the Mun River in Chaleom Phra Kiat, as shown in Fig. 1.

The Lam Ta Kong Watershed is located in a tropical climate zone where the average annual rainfall ranges from 1000 to 1100 mm. Watershed areas are utilized for various activities, of which agriculture, communities, and settlements are the major sectors. Agriculture accounts for 86% of the total watershed area, with only 10.4% of the agricultural area irrigated [16].

2.2. Data preparation and curation

Drought vulnerability assessment of the Lam Ta Kong Watershed requires data on various spatially related factors, including meteorological, geographical, physical, and anthropogenic data. The data were aggregated from multiple local and national sources and are summarized in Table 1.

Meteorological data spanning a 30-year period from 1992 to 2021 were obtained from the Thai Meteorological Department (TMD) and DDPM. Daily records of precipitation, temperature, precipitation days, and evaporation were systematically gathered from eleven stations within the watershed. Subsequently, the collected data were subjected to interpolation processes to generate comprehensive maps for each meteorological dataset. Elevation data were directly obtained from the United States Geological Survey (USGS), while slope data were extracted from the digital elevation model (DEM). Soil texture and soil fertility data of the watershed were sourced from the latest survey reports of the Land Development Department (LDD) in 2018. Land use data were extracted and classified from satellite images (Landsat 5) acquired from both the LDD and Geoinformatics and Space Technology Development Agency (GISTDA). Postclassification data were validated against field survey data and reference maps acquired from the LDD to verify the classification accuracy.

This research is subject to certain limitations. For instance, soil data for the cliff area along the border of Pak Chong and Sikhio is currently unavailable, since there were no survey and soil sample collections conducted due to the high elevation and the isolation (absence of road access) of the area. Consequently, this specific area was intentionally excluded from the analysis and drought assessment in this research.

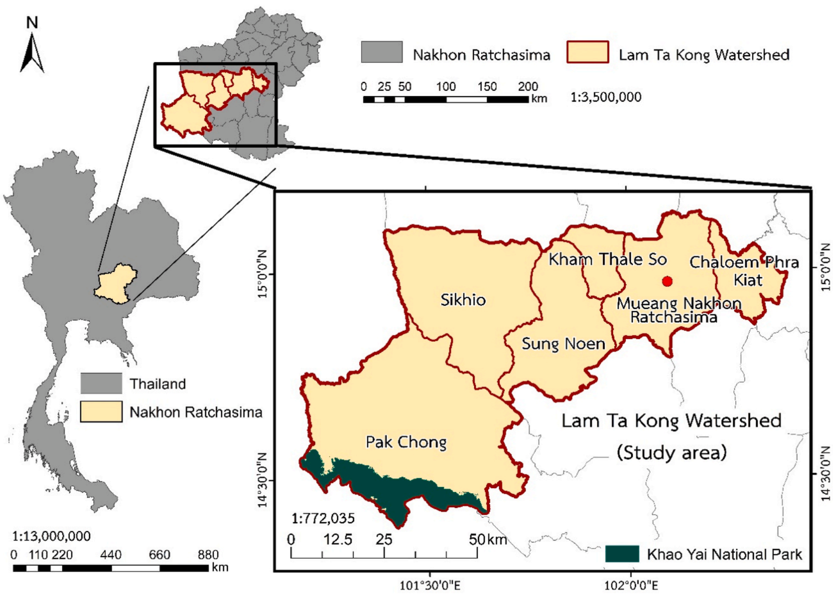

Fig. 1. Lam Ta Kong Watershed (study area) is located in Nakhon Ratchasima Province.

Table 1
Data type and sources used for this drought vulnerability assessment.

Data	type	Source of data	Period
Slope	Shapefile	Extracted from DEM that acquired from USGS	2021
Elevation	DEM (30 m resolution)	Acquired from the USGS	2021
Soil texture	Shapefile	Prepared from soil data provided by LDD	2018
Soil fertility	Shapefile	Prepared from soil data provided by LDD	2018
Stream density	Shapefile	Extracted from DEM that acquired from USGS	2021
Precipitation	Daily precipitation data	TMD and DDPM	1992–2021
Temperature	Daily temperature data	TMD	1992–2021
Precipitation days	Daily precipitation data	TMD and DDPM	1992–2021
Evaporation	Daily evaporation data	TMD	1992–2021
Land use	Shapefile, Satellite Images	Extracted from satellite images acquired from LDD and GISTDA	2019

3. Methods

3.1. Identifying drought-influencing factors and assessing drought vulnerability

A meta-analysis of the literature revealed that the factors influencing drought vulnerability varied based on the spatial content and locality of the study area [16]. As previously discussed, vulnerability comprises three key components; exposure, sensitivity, and adaptive capability. These elements were integrated differently in the drought vulnerability assessment process, influenced by the distinct spatial conditions and techniques of drought analysis. In this drought vulnerability assessment conducted in the Lam Ta Kong Watershed, ten drought-influencing factors were classified into four groups (geographical, natural, climatic, and anthropogenic factors), representing the key components of vulnerability.

The geographical factors included the slope and elevation of the study area, which represented the sensitivity condition. The slope critically affects soil moisture [24], influencing water infiltration and the water-holding capacity [2]. The severity of drought impacts varies across the watershed due to differing slopes, indicating varying levels of sensitivity. The elevation related to the slope indicates the increase in altitude from sea level. This also suggests an increased distance from the groundwater level, the most common and closest water source. These geographical dynamics exert a profound influence on the soil moisture levels of the area, often exacerbating drought conditions.

The natural factors considered in this assessment comprised soil texture, soil fertility, and stream density. Soil texture and soil fertility were indicative of the sensitivity condition, while stream density represented the adaptive capacity condition. The soil texture impacts soil moisture since the soil texture indicates the soil particle content that reflects the water-holding capacity [24,59]. Consequently, the presence of various soil textures across the watershed results in areas being affected variably by drought impacts. Furthermore, the limited water retention capacity resulting from soil characteristics can exacerbate the onset and severity of drought conditions. The stream density also directly influences soil moisture in an area since it reflects the dispersion and distribution of streams within a unit area (km./km^2) [26]. Stream density represents the adaptive capacity condition, as areas with higher stream density are better equipped to minimize the adverse effects of droughts. Additionally, soil fertility emerges as a pivotal determinant in agricultural drought, given its direct influence on vegetation health and land cover within the region. The variation in soil fertility across the watershed also reflects varying degrees of being affected by drought impacts (sensitivity).

The climatic factors considered in the assessment encompassed precipitation, temperature, precipitation days, and evaporation, reflecting the exposure conditions to which the region is vulnerable to drought events. These factors hold particular significance as they directly impact the quantity of water available within the watershed, thereby serving as indicators for potential drought occurrences and severity. Additionally, these climatic variables play a crucial role in determining the availability of water resources that can be sustained and supported within the area [15,43,60].

Furthermore, in this study, the anthropogenic factor of land use, greatly influenced by human activities, was employed to represent the sensitivity condition. Land use encompasses activities and their associated water demands that directly influence an area's vulnerability to drought [25] as different types of land use and activities are variably affected by drought impacts. Moreover, changes in the land surface due to land use change affect water infiltration, potentially leading to drought or flooding during various periods [50,61].

3.2. Analytical hierarchy process (AHP) technique

The analytical hierarchy process (AHP) is a well-known multicriteria decision analysis (MCDA) technique developed by Saaty [62]. It is widely employed for problem-solving and decision-making processes that involve multiple parameters or criteria. The AHP structurally investigates problems and hierarchically evaluates the importance of parameters based on pairwise comparisons that involve a pairwise comparison matrix [63,64]. The evaluation process of the AHP incorporates expert opinions, which assists in determining the relative importance of the criteria.

The initial step of the AHP entails developing the overall study hierarchy, in which the objective, criteria, subcriteria, and alternatives are arranged. Subsequently, a pairwise comparison is executed to assess the relative importance of each pair of criteria and subcriteria. This comparison is based on the fundamental scores (importance scores) established by Saaty [63,65]. The importance score ranges from 1 to 9, and detailed explanations are provided in Table 2. The weight of each study parameter was computed based on the importance score from the comparison matrix using Eq. (1) [43,66]. The consistency ratio (CR) of each matrix was subsequently calculated to ensure consistency between the pairwise comparisons within the comparison matrix. The acceptable CR value is less than 0.1, indicating that the pairwise comparison matrix is reasonably consistent [44]. The CR value was derived from the CI/RI, and the consistency index (CI) was determined by Eq. (2) [44,67].

$$A_{ij} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{12} & \cdots & a_{nn} \end{bmatrix} \tag{1}$$

where (i,j = 1,2, …,n)

$$CI = (\lambda_{max} - n) / (n-1) \tag{2}$$

Where λ_{max} is the largest eigenvalue of the matrix, derived from Eq. (3)

n is the matrix size

$$\lambda_{max} = \sum_{i=1}^{n} \left[\sum_{i=1}^{n} a_{ij} w_j \right] \tag{3}$$

Furthermore, the random index (RI) established by Saaty was adopted as the average random consistency index, which depends on the matrix size, as indicated in Table 3 [62,65].

3.3. Application of the analytical hierarchy process (AHP) in weight evaluation for drought vulnerability assessment

In this drought assessment, the AHP was utilized to evaluate the weights of the drought-influencing factors by analyzing their relative importance based on pairwise comparisons of the criteria and subcriteria. The overall research hierarchy is shown in Fig. 2.

The experts involved in the pairwise comparisons encompassed a diverse range of professionals, including academic experts, government agencies, and local experts. Once the pairwise comparison matrices were developed, the final weights of the individual drought factors and groups of factors were calculated by Eqs. (1)–(3). The highest weight reasonably represents the drought-influencing factor with the greatest impact on drought in the study area. Then, the AHP-derived weights were integrated with GIS data to develop a drought vulnerability map. The overlay technique in ArcGIS software (ArcMap 10.8.1) was used to incorporate the weights with GIS data of the study area and produce the final drought vulnerability map, which visually illustrates the severity of drought vulnerability in the Lam Ta Kong Watershed. Ultimately, a Lam Ta Kong drought vulnerability map was produced, and drought vulnerability was subsequently categorized into five severity levels: very low, low, moderate, high, and very high.

3.4. Evaluating the interactions and correlations among the drought-influencing factors

Pearson correlation analysis was used to evaluate the correlations among the critical drought-influencing factors. Moreover, factorial analysis of variance (ANOVA) was employed to statistically explain the interactions among the variables. Pearson's correlation analysis and factorial ANOVA were used to determine the significance of the observed differences, and a p value < 0.05 was adopted to indicate statistical significance.

4. Results

4.1. Identified drought-influencing factors

The Lam Ta Kong Watershed is a diverse landscape, characterized by a spectrum of slope gradients ranging from a gentle 0% to a steep 242%, and elevations spanning from 122 to 1351 m above sea level (msl) as illustrated in Fig. 3a and b. Notably, a significant portion, around 64.04%, boasts gentle slopes of less than 5%, predominantly forming expansive plains that stretch across both

Table 2
Importance score and definition.

Importance Score	Definition
1	Equally important
3	Weakly important
5	Strongly important
7	Very Strongly important
9	Absolutely more important
2,4,6,8	Intermediate value between the two adjacent judgments

Source: [30,45,62]

Table 3
RI values.

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Source: Adapted from [16,62].

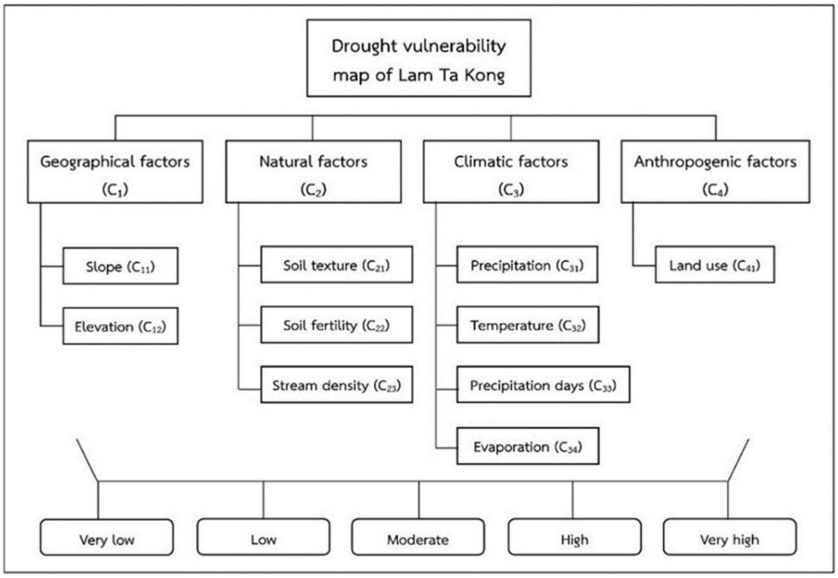

Fig. 2. Hierarchical structure of drought vulnerability assessment of the Lam Ta Kong Watershed.

upstream and downstream regions. In contrast, a mere 4.08% of the watershed exhibits steep gradients exceeding the slope gradients of 36%, predominantly clustered amidst the forested domains of the upstream areas. Similarly, areas of elevated terrain, encompassing 25% of the total area and rising above 401 msl, are primarily concentrated upstream, nestled around the Khao Yai National Forest. The soil properties within the watershed are distinguished by the distinctive rock formations of the Khorat Plateau, imparting unique textures and compositions. Soil texture is characterized by a blend of sand, silt, and clay, resulting in a spectrum of fine, moderate, and coarse textures (Fig. 3c).

Predominantly, coarse soil texture prevails across the watershed, encompassing approximately 59.2% of the area, with moderate texture comprising 22.31%, and fine texture representing 18.5%. Notably, coarse soil extends extensively throughout both upstream and downstream regions, while fine soil predominates primarily in the upstream areas. Furthermore, the watershed predominantly resides on soil with low fertility, encompassing 61.7% of the total area (2870.69 km^2), with a significant 83.37% of the downstream regions covered by this low fertility soil as shown in Fig. 3d. In contrast, areas of high soil fertility are confined to the upstream regions, constituting approximately 258.6 km^2 or 5.56% of the watershed. The stream density across the watershed exhibits a varied pattern, ranging from 0 to 4.9 km/km^2 (Fig. 3e). A substantial portion, comprising 39.6% of the total area (2043.1 km^2), experiences low stream density. Conversely, only 15% of the watershed (774.1 km^2) encounters high stream density, surpassing 1 km/km^2.

The average annual precipitation throughout the watershed stands at approximately 1040 mm, with an average of 84 precipitation days annually, as illustrated in Figs. 3f and 4b. However, the majority of the area, accounting for approximately 42.84% of the watershed (221.69 km^2), receives annual precipitation below 1050 mm. In the upstream areas, the average annual precipitation escalates to 1536 mm, occurring over 101 precipitation days. Conversely, downstream regions experience a comparatively lower average annual precipitation of 941 mm, distributed across 81 precipitation days. The average annual temperature across the watershed hovers around 26.9 °C, with temperatures exhibiting an upward trend towards the downstream areas (Fig. 4a). Conversely, the average annual evaporation, approximately 154.49 mm, follows a contrasting pattern, intensifying towards the upstream regions and reaching its peak within the forested areas in Pak Chong (Fig. 4c). In the watershed, agriculture dominates 57.12% of the area, spread across both upstream and downstream regions as shown in Fig. 4d. Forests cover 1331.65 km^2, comprising 25.8% of the watershed, mainly in the upstream. Urban settlements span 728.63 km^2, making up 14.12% of the watershed, with major developments in Pak Chong and Mueang Nakhon Ratchasima.

4.2. Drought vulnerability

As mentioned, drought vulnerability was analyzed at five severity levels, and Table 4 provides a summary of the drought

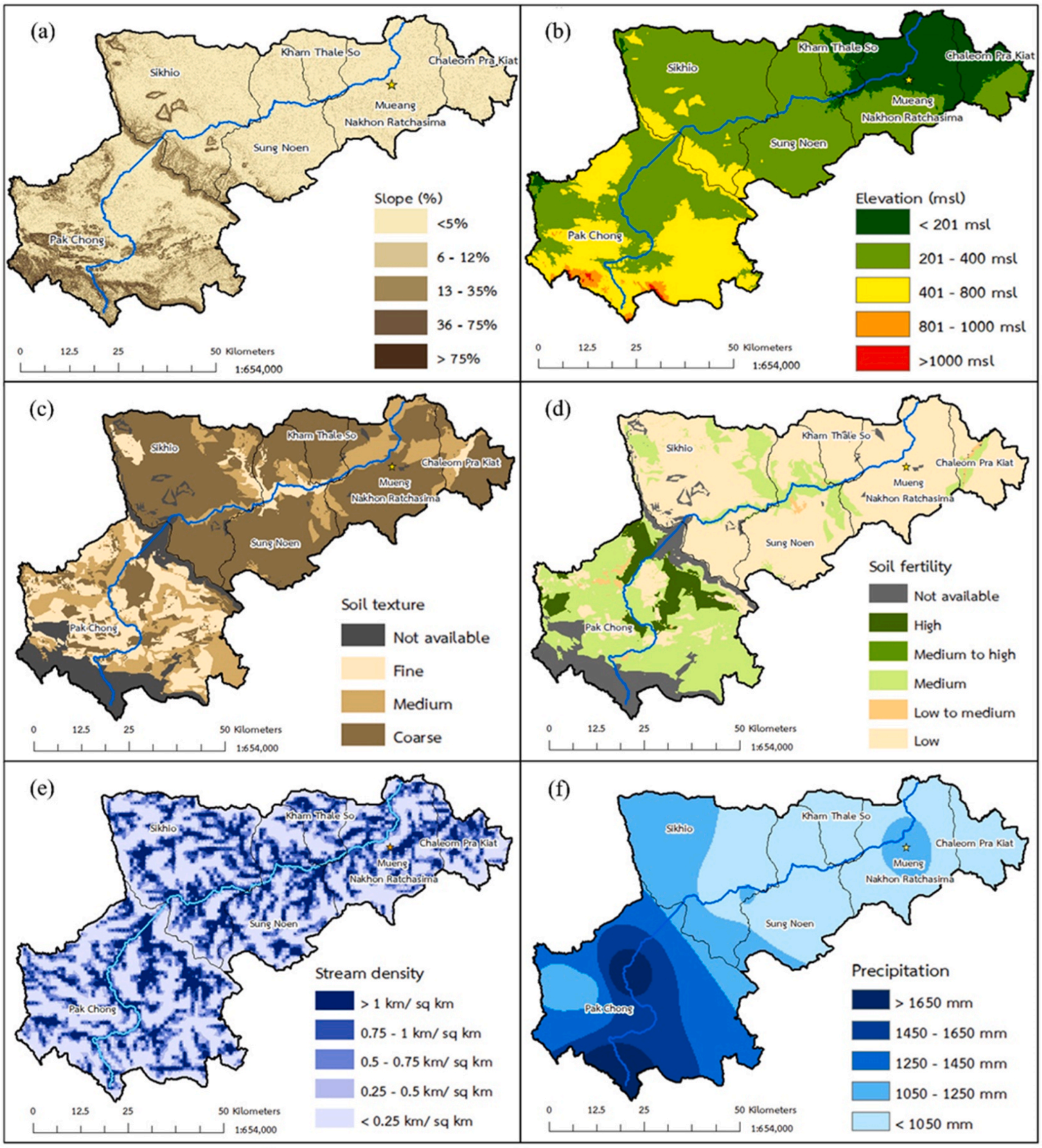

Fig. 3. Identified drought-influencing factors: (a) slope, (b) elevation, (c) soil texture, (d) soil fertility, (e) stream density and (f) precipitation.

vulnerability assessment results. The assessment revealed that 35.1% of the Lam Ta Kong Watershed (1810.83 km^2) exhibited high vulnerability, which was predominantly concentrated in the central region and areas northeast of the watershed, especially most of Sikhio, Sung Noen, Kham Thale So, and Mueang Nakhon Ratchasima, as shown in Fig. 5. Approximately 30.3% of the watershed (1565.93 km^2) experienced moderate drought vulnerability, and was scattered in both upstream and downstream areas. Approximately 15.6% of the study area (804.95 km^2) experienced low vulnerability, mostly located in the Pak Chong areas and near the Khoa Yai National Park. In contrast, 10.9% of the Lam Ta Kong Watershed (564.76 km^2) exhibited very high vulnerability, covering several scattered portions of the upstream area and multiple clustered portions in downstream areas. Furthermore, only 8% of the watershed (413.79 km^2) was classified as indicating a very low drought vulnerability. The zones with a very low vulnerability were mostly scattered in the upstream areas and near the Khao Yai National Park.

4.3. Weighting of the factors influencing drought

Weights were determined through AHP analysis based on a total of 51 pairwise comparisons, and all pairwise comparison matrices had consistency ratios less than 0.1, indicating that the pairwise comparisons were reasonably consistent.

According to Table 5 and Fig. 6, the climatic factors primarily affected the drought vulnerability of the Lam Ta Kong Watershed (weight = 0.36), followed by geographical factors (weight = 0.24), anthropogenic factors (weight = 0.21) and natural factors (weight

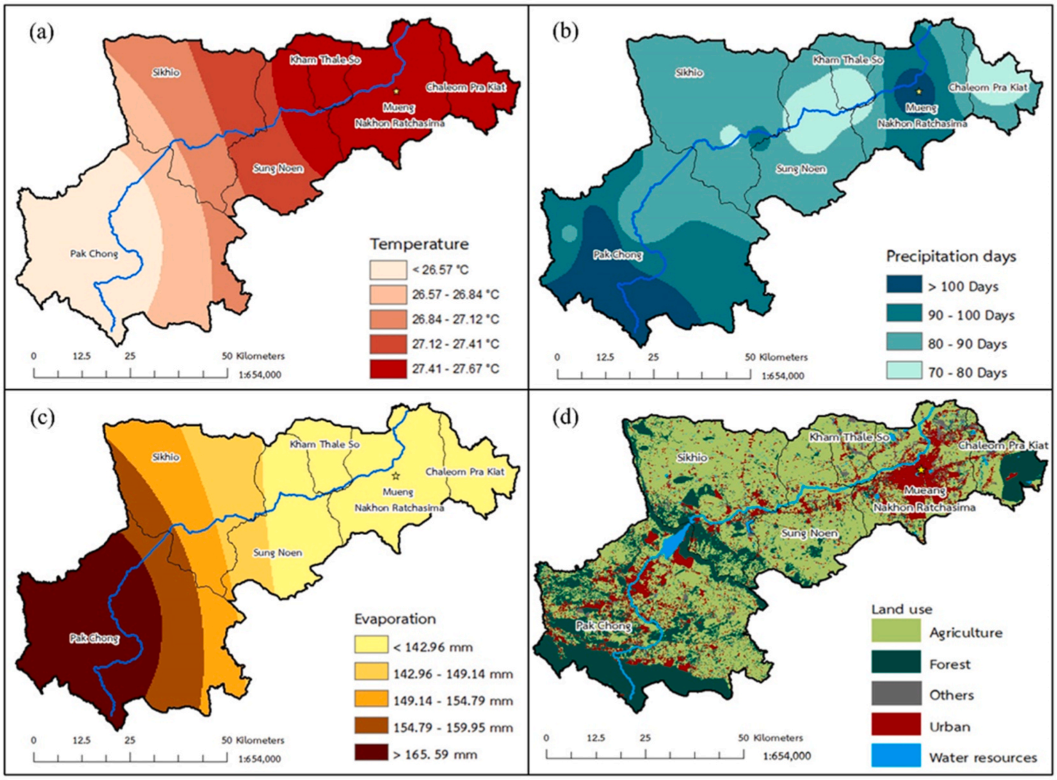

Fig. 4. Identified drought-influencing factors: (a) temperature, (b) precipitation days, (c) evaporation and (d) land use.

Table 4
Results of drought vulnerability of the Lam Ta Kong watershed by area.

Drought vulnerability	Area (km^2)	Percentage
Very Low vulnerability	413.79	8.02%
Low vulnerability	804.95	15.60%
Moderate vulnerability	1565.93	30.35%
High vulnerability	1810.83	35.09%
Very high vulnerability	564.76	10.94%

= 0.19). Among all the climatic factors, precipitation significantly contributed to the drought vulnerability of the watershed, as indicated by the highest weight of 0.37, followed by precipitation days (weight = 0.32), evaporation (weight = 0.17), and temperature (weight = 0.14). Additionally, based on the final weights, precipitation, precipitation days, and land use emerged as the critical drought factors in the area, with weights of 0.19, 0.16, and 0.15, respectively.

4.4. Interaction and correlation among the critical drought-influencing factors

The AHP weights (Table 5) indicated that the critical drought-influencing factors were precipitation, precipitation days, and land use. Moreover, statistical analysis revealed that these critical factors significantly influence the drought vulnerability of the watershed. The analysis of precipitation and land use showed that both factors imposed a statistically significant influence on drought vulnerability, with a p-value <0.05. Moreover, there was a statistically significant interaction effect between precipitation and land use, with a p-value <0.05 and a Pearson correlation coefficient of $r = -0.92$ ($y = -1.1063x + 16{,}336$, $R^2 = 0.84$). Table 6 further verifies the significant correlation between vegetation (including forest and agriculture) and precipitation. The data suggested that vegetation plays a crucial role in influencing the drought vulnerability, as reflected by the substantial impact on increasing the vulnerability level. Specifically, a drastic shift in the precipitation intensity only slightly affected the drought vulnerability of built-up and bare land areas. In contrast, notable increases in drought vulnerability were observed in vegetated areas, highlighting the sensitivity of these regions to changes in precipitation.

The analysis of precipitation days and land use revealed that these factors significantly influenced the drought vulnerability of the area, with a p-value <0.05. The analysis also indicated that the interaction between precipitation days and land use was statistically

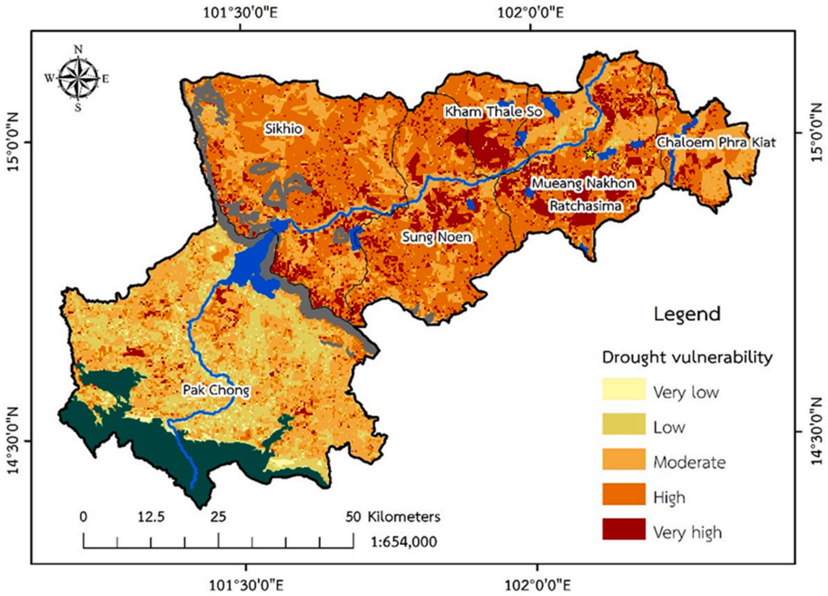

Fig. 5. Drought vulnerability map of the Lam Ta Kong Watershed.

Table 5
Weights achieved from AHP.

	Weight (Criteria)		Weight (Sub-criteria)	Final weight
Geographical	0.24	Slope	0.58	0.07
		Elevation	0.42	0.05
Natural	0.19	Soil texture	0.26	0.06
		Soil fertility	0.32	0.07
		Stream density	0.42	0.1
Climatic	0.36	Precipitation	0.37	0.19
		Temperature	0.14	0.07
		Precipitation days	0.32	0.16
		Evaporation	0.17	0.08
Anthropogenic	0.21	Land use	1	0.15

significant at a p-value <0.05, with a negative Pearson correlation coefficient of $r = -0.98$ ($y = -0.1298x + 1878.7$; $R2 = 0.96$). Moreover, Table 7 highlights the substantial influence of land use on the drought vulnerability of the watershed. Specifically, an increase in the precipitation frequency marginally mitigated the drought vulnerability in built-up areas (including other and urban areas).

Moreover, the analysis between precipitation and precipitation days revealed that both exerted a statistically significant effect on the drought vulnerability of the Lam Ta Kong watershed, with a p-value <0.05. The analysis further revealed a statistically significant interaction effect between precipitation and precipitation days, with a p-value of 0.034 and a high positive Pearson correlation coefficient of $r = 0.98$ ($y = 0.1071\times - 27.346$, $R2 = 0.95$). Table 8 illustrates the influences of precipitation and precipitation days on drought vulnerability. The results showed that days with very low precipitation and low precipitation levels resulted in very high drought vulnerability.

5. Discussion

5.1. Drought vulnerability

Drought in the Lam Ta Kong Watershed has emerged as a significant concern, prompting purposeful evaluation of various factors to identify the critical influence of recurring drought events. Notably, aligning with numerous global drought assessments, this research emphasizes that climatic factors are the most critical factors shaping the occurrence of drought [27,34]. In general, precipitation, temperature, precipitation days, and evaporation directly impact the water availability and water balance [31]. Research has shown that precipitation, precipitation days, and land use are the critical drought factors in the area. Precipitation emerged as the most influential factor in the watershed, as evidenced by its highest weight in the AHP. This finding conforms with numerous studies [27,43,44], emphasizing that, according to expert perspectives, precipitation plays a pivotal role as the key drought-influencing factor in the

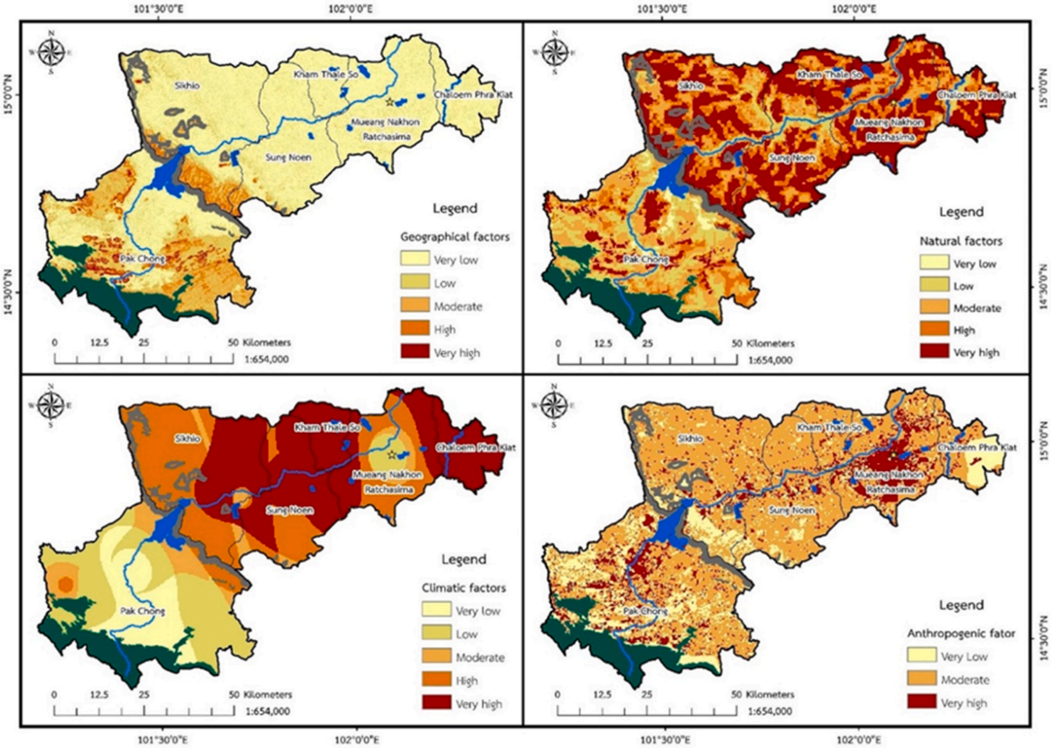

Fig. 6. Four groups of drought-influencing factors.

Table 6
Influences of precipitation and land use on drought vulnerability.

		Precipitation Very low	Low	Moderate	High	Very high
Land use	Forest	4	3	3	2	2
	Agriculture	4	3	3	3	2
	Others	4	3	3	3	3
	Urban	5	5	5	4	4

Remarks: 5 indicates very high drought vulnerability, 4 indicates high drought vulnerability, 3 indicates moderate drought vulnerability, 2 indicates low drought vulnerability and 1 indicates very low drought vulnerability. * Water bodies were not considered in drought vulnerability assessment.

Table 7
Influences of precipitation days and land use on drought vulnerability.

		Precipitation days			
		Low	Moderate	High	Very high
Land use	Forest	3	4	2	2
	Agriculture	4	4	4	3
	Others	4	3	3	3
	Urban	5	5	5	4

Remarks: 5 indicates very high drought vulnerability, 4 indicates high drought vulnerability, 3 indicates moderate drought vulnerability, 2 indicates low drought vulnerability and 1 indicates very low drought vulnerability. * Water bodies were not considered in drought vulnerability assessment.

Lam Ta Kong Watershed. Precipitation and precipitation days significantly influence drought vulnerability since they directly affect the water availability in the watershed. Precipitation is the most important factor in the area since it indicates the amount of water supplied for anthropogenic activities and the natural ecosystem in the watershed. A low precipitation intensity leads to insufficient water availability for natural activities, including evapotranspiration, local climatic activities, and hydrological balance [48], eventually resulting in drought. Precipitation days varied across the watershed due to seasonal variations in the local climate and topography of the area. The number of days when the soil is moist can reflect the availability of moisture for local vegetation and local

Table 8
Influence of precipitation and precipitation days on drought vulnerability.

		Precipitation				
		Very low	Low	Moderate	High	Very high
Precipitation days	Forest	5	4	4	3	2
	Agriculture	4	4	3	3	2
	Others	4	4	2	2	3
	Urban	3	4	3	2	1

Remarks: 5 indicates very high drought vulnerability, 4 indicates high drought vulnerability, 3 indicates moderate drought vulnerability, 2 indicates low drought vulnerability and 1 indicates very low drought vulnerability. * Water bodies were not considered in drought vulnerability assessment.

climatic activities [32].

Moreover, precipitation days significantly influence the drought intensity in the area since the latter is also influenced by extended periods with no precipitation (precipitation <1 mm) [33]. Abundant precipitation, frequent rainfall, and extensive forest coverage fulfill pivotal roles in maintaining a low vulnerability in the upstream and adjacent areas of the Khao Yai National Park. These sections of the watershed remain relatively moist, highlighting the significance of forested areas in retaining and dispersing moisture. Unfortunately, only 25.8% of the watershed is covered with forest areas, and the majority of the watershed is covered with forest conservation areas. However, a major portion of the watershed, specifically 10.9%, was classified as exhibiting a very high drought vulnerability, while 35.1% was classified as exhibiting a high drought vulnerability. This phenomenon is particularly pronounced in the northeastern region of the watershed, which is attributable to the fact that approximately 43.8% of this area (encompassing the downstream areas extending toward the northeast) received an annual precipitation of less than 1050 mm. Land use is one of the critical factors that greatly impacts drought vulnerability, as it reflects the various activities on land and their corresponding water demands. Land use with vegetation coverage, such as forestland areas, helps capture soil moisture and facilitates hydrological cycling [35]. In contrast, built-up areas, including urban settlements, industrial infrastructures, and commercial areas, interrupt the normal hydrological cycle of transpiration and infiltration [35]. Consequently, these areas exhibit higher vulnerability to drought. Notably, clusters of very high vulnerability in the watershed are concentrated around densely urbanized and community settlements in each district, except for Kha Thale, where zones with a very high vulnerability extend across the entire district.

Coincidentally, Wijitkosum [16] revealed that Kham Thale So was one of the areas that experienced the highest drought risk in the Lam Ta Kong Watershed. Kham Thale So faces multiple challenges contributing to its critically high drought vulnerability. In addition to experiencing an average rainfall below 1050 mm and only 90 rainy days per year, the area predominantly features a sandy soil texture. This combination of factors indicates that soil characteristics pose additional threats to the region, intensifying concerns in an area where meteorological factors are already considered significant. This finding is consistent with the findings of Wijitkosum [17] and Sivakumar et al. [15], who indicated that soil factors exerted the greatest impact on drought vulnerability in their respective study areas. Notably, both study areas occurred in subhumid climatic zones, suggesting that precipitation was not the primary factor causing droughts. These observations and results underscore the variability in prioritizing drought-influencing factors, emphasizing the importance of considering spatial and temporal characteristics specific to each study area.

Moreover, highly vulnerable areas occur at a notable distance from irrigation canals and exhibit a low stream density. Conversely, areas characterized by a moderate vulnerability benefit from a certain level of accessibility to irrigation canals, thereby alleviating stress resulting from drought conditions in the region.

5.2. Interactions and correlations among the critical drought-influencing factors

This research has shown that precipitation and precipitation days are positively related (p-value = 0.034), which is consistent with the findings of McErlich et al. [51], who revealed a strong positive correlation between precipitation (intensity) and precipitation days (wet-day frequency), suggesting that a region with a higher rainfall frequency is more likely to experience more intensive rainfall. Similarly, Pathak and Dodammani [52] confirmed a robust correlation between precipitation and precipitation days in the semiarid zone of India. The findings of this research, along with prior studies, underscored that a rise in the frequency of precipitation days correlates with a significant uptick in total rainfall within the region. In contrast, Shahid [53] revealed that an increase in the average annual precipitation stimulated an increase in the number of precipitation days in the subtropical humid region of Bangladesh. This highlights the complex and interdependent nature of the interaction and correlation between precipitation and precipitation days. In our investigation, the Khao Yai National Forest emerged as a compelling case study, showcasing a significant surge in annual average precipitation. This surge is primarily propelled by an uptick in the frequency of precipitation days within the region, thereby mitigating drought vulnerability to a considerable extent. However, our analysis also unveiled crucial insights into the nuanced dynamics of vulnerability across different areas. Notably, regions like Kham Thale So, Sung Noen, and segments of Mueang Nakhon Ratchasima stood out with high to very high vulnerability, primarily due to the scarcity of precipitation days leading to diminished rainfall. This emphasizes the complex interplay among precipitation patterns, the frequency of precipitation days, and their direct implications for drought vulnerability.

Moreover, the interaction between land use and precipitation (p-value <0.05), as well as the interaction between land use and precipitation days (p-value <0.05), suggested that changes in land use directly impact the precipitation pattern. Likewise, the results of various studies have consistently indicated a significant correlation between land use and precipitation patterns. Consequently, changes in land use and land cover can influence precipitation patterns globally [10,49,54] since land use changes ultimately lead to land cover changes and significantly impact the regional temperature and precipitation [56]. Spatial analysis of the watershed revealed a notable association between land use and precipitation. Specifically, the intact Khao Yai National Forest exhibited the highest precipitation. Conversely, areas characterized by low precipitation predominantly occurred around urban settlements and agricultural zones, where the forest had been invaded, fragmented, and inadequately maintained. This pattern elucidates the role of forest activities in influencing the transportation of atmospheric moisture, impacting the precipitation distribution in the region [55] since, in tropical climatic zones, precipitation is primarily driven by recycled moisture generated by evapotranspiration from forests [56]. Furthermore, even though the urban area of Mueang Nakhon Ratchasima frequently received regular and substantial precipitation, its vulnerability to drought remained relatively high. In contrast, frequent precipitation in the Pak Chong area maintained a lower drought vulnerability. This resilience is largely attributed to the presence of protective forest cover, which fosters essential processes such as evapotranspiration and infiltration.

The analysis of these critical drought-influencing factors and their interactions emphasizes the considerable impacts of land use, topography, and geographical location on both precipitation patterns and the overall drought vulnerability of the watershed. Many external factors and interactions influence precipitation and precipitation days in the area. However, it is crucial to acknowledge that among these influences, land use is the sole factor directly shaped by human activities. Recognizing this mechanism, extensive efforts to manage and affect precipitation and precipitation days on a large scale would be inherently challenging and impractical. Therefore, land use emerges as a pertinent factor influencing drought amenable to control and management. Furthermore, the observed interactions suggested that adopting appropriate measures to manage land use could effectively improve not only drought conditions but also precipitation patterns.

5.3. Potential mitigation strategies for the Lam Ta Kong watershed

Implementing of land use policies holds significant potential for mitigating drought in the Lam Ta Kong Watershed. These policies serve as key catalysts, driving changes in land use and land cover. Recognizing their significance underscores their potential effectiveness in shaping and addressing the complex challenges posed by drought within the watershed. Land use policy-makers should note that effective land use management in upstream areas should prioritize forest preservation. This is particularly crucial, as evidenced by the observed impact of the forest areas around the Khao Yai National Park, which has the potential to induce precipitation. Such strategic land use practices could contribute to enhanced water availability in reservoirs before water moves downstream. Forest conservation and restoration can further improve soil properties and fertility, benefiting the vegetation cover and positively impacting the local climate [57]. Moreover, maintaining and expanding forest areas upstream, midstream, and downstream could help preserve and disperse humidity, reducing drought vulnerability. Zoning policies could be applied to prevent deforestation, land fragmentation, and urban sprawl in watersheds. In addition, managing urban sprawl is crucial not only for preserving of the city's green spaces but also as a significant step toward mitigating the risk of drought in urban areas. These strategies underscore the potential of implementing zoning and planning land use policies as proactive management tools to mitigate the vulnerability of watersheds to drought. By effectively integrating these measures, they can significantly alleviate the impacts of drought. Moreover, the execution of these drought mitigation strategies can be orchestrated through collaborative efforts across various administrative levels, encompassing districts, provinces, and the watershed, ensuring comprehensive action and sustainable resilience.

6. Limitation and recommendation for future research

Currently, precipitation factors used in this drought assessment primarily considered the average annual precipitation; however, it is acknowledged that incorporating seasonal precipitation data could offer a more distinct understanding of the temporal drought vulnerability in the area. Therefore, future research should assess precipitation during both wet and dry periods to discern variations in the seasonal drought vulnerability of the watershed. In addition, land use change has become a concern for the environment. The findings of this study highlight the critical role of land use in influencing watershed drought, suggesting that effective land use management is a practical measure to mitigate drought impacts. Future research should consider projections of land-use changes to assess future drought risk trends in the watershed. This approach may also identify specific regions that warrant stringent control over land use to address potential impacts effectively.

7. Conclusions

In conclusion, this study provides a comprehensive understanding of the drought vulnerability in the Lam Ta Kong Watershed. The weights determined by the AHP assisted in evaluating the relative importance of various drought-influencing factors and indicated that climatic factors most notably impacted drought vulnerability. A drought vulnerability assessment of the watershed revealed that the majority of the Lam Ta Kong Watershed experienced high drought vulnerability, especially in the middle and northeastern parts of the watershed. The interactions among three critical drought-influencing factors, namely, precipitation, precipitation days, and land use, were assessed. The interaction between land use and precipitation, along with that between land use and precipitation days, highlighted the direct impact of land use changes on precipitation patterns. Recognizing the significance of land use, it emerged as a factor directly influenced by human activities and a key determinant of drought vulnerability. The findings of this research showed that land use policies are practical measures for alleviating drought vulnerability in this watershed. This highlights three cornerstone practices: forest conservation, forest restoration, and forest zoning policies. Conservation policies focus on preserving existing forest areas within the watershed, notably the Khao Yai National Park Forest. Concurrently, forest restoration policies aim to revitalize the watershed by reintroducing a flourishing ecosystem, rejuvenating fragmented forests and vegetated areas. Furthermore, promoting forest zoning policies across all districts within the watershed is essential to designate appropriate territorial portions for forested areas.

Data availability

All the relevant data has been included in the manuscript.

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CRediT authorship contribution statement

Nontaporn Kukuntod: Writing – original draft, Validation, Resources, Methodology, Formal analysis, Data curation. **Saowanee Wijitkosum:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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