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Fuzzy AHP for Drought Risk Assessment in Lam Ta Kong Watershed, the North-eastern Region of Thailand

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Abstract

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Droughts occur from a combination of natural factors and human activities rather than just a single natural cause. Spatial factors have also heavily influenced the causes of draught. This study was conducted in the Lam Ta Kong watershed, Thailand. In this study, the Fuzzy Analytic Hierarchy Process (FAHP) method was applied to evaluate the risk of agricultural drought and the GIS technique was employed to give full consideration to the ambiguity and uncertainty of the agricultural drought risk. There are five risk factors to consider in the agricultural drought risk assessment and they are divided in a total of fifteen criteria: physical factors (slope gradient and elevation), climatic (rainfall and aridity index), soil (texture, drainage, fertility, erosion, and soil salinity), land utilization (land use and land cover) and water resources (precipitation days, stream density, distance from an irrigation canal, and groundwater volume). These criteria determine the weight and score used to evaluate their parental risk factors. The Analytic Hierarchy Process (AHP) was applied together with the triangular fuzzy numbers (TFNs) method to assess the data obtained from the criteria to achieve the drought risk assessment. The results indicated that the overall risk of the Lam Ta Kong area was at a moderate risk of agricultural drought (50.45%), of which 15.63% of the total area was at a high risk of agricultural drought. Moreover, 0.40% of the total area located at the central part of the watershed was at a very high risk which was due to its saline soil with > 50% dense salt crust. This research indicated that the major factors causing droughts in the watershed were related to the soil factors, especially soil texture, soil fertility and soil salinity. These soil factors were considered as the driving factors of drought. The results of this study can be used for land use planning and water resource management in order to prepare for droughts in the watershed.

Keywords: agricultural drought; defuzzification; drought index; drought risk; FAHP

Drought is influenced by natural and various anthropogenic factors, and it is a serious factor affecting global water and food security. Therefore, detailed drought risk assessments are crucial, especially in developing countries. The Fuzzy Analytic Hierarchy Process (FAHP) is an advanced mathematical model, it is a tool to analyse the key characteristics and determinants of complex problems and to address the limitations of the conventional Analytic Hierarchy Process (AHP) (Chang 1996; Wang 2009; Tian & Yan 2013). FAHP is a popular approach for multiple criteria decision-making and has been widely used in the literature (e.g. Tuysuz & Kahraman 2006; Wang & Elhag 2007; Tian & Yan 2013; Zou *et al.* 2014). Moreover, FAHP can also be used to predict and prioritise criteria and factors leading to environmental issues in the future (Yang & Zhang 2012; Yang *et al.* 2013; Zhao *et al.* 2013).

Drought is an intrinsically complex multidimensional process which includes both uncertain quantitative and qualitative factors. Therefore, FAHP is deemed to be particularly appropriate for prioritising the factors and criteria into a hierarchical order and analysing the data using the pairwise comparison technique (Tian & Yan 2013). Research has shown that applying FAHP to environmental risk factor analysis and prediction proved effective results (Tuysuz & Kahraman 2006; Yang & Zhang 2012; Yang *et al.* 2013; Zou *et al.* 2014; Radionovs & Užga-Rebrovs 2016).

This study was conducted in the Lam Ta Kong watershed, Thailand, where is a tropical country with the savanna climate (*Aw*). Some areas are dry sub-humid (aridity index, AI 0.51–0.65), which made it a drought-affected country despite its location (Wijitkosum 2014). The area has suffered from droughts for a long period of time. However, studies regarding this issue are limited (Sa-Nguansilp *et al.* 2017). Thus the study aims to employ FAHP, an effective method for drought analysis, to investigate agricultural drought risk factors and the level of the risk. The data and findings were forwarded to relevant agencies in the Lam Ta Kong watershed area providing a database for defining suitable mitigation measures for agricultural and water management based on the spatial data.

The situation of Lam Ta Kong watershed. The Lam Ta Kong watershed covers an area of approximately 3419.9 km^2 across six districts of upstream Pak Chong area and downstream areas of Sikhiu, Sung Neon, Kham Thale Sor, Muang Nakhonratchasima, and Chalearm Prakeate. The major part of the watershed (65.0%) is used for agriculture, of which 10.4% is under irrigation. Its upstream area is facing deforestation and its downstream area is under continuously expanding agricultural utilization and urbanization. The average annual precipitation in the area is 1200.4 mm.

MATERIAL AND METHODS

Identify drought risk factors. Drought risks are monitored and assessed to strengthen the agricultural sector which represents the poorest and most vulnerable member of the community. Many factors affect drought, including precipitation, soil, water resources and human activities (Cox *et al.* 2008; Santos *et al.* 2014; Wijitkosum 2014). It is important to investigate risk factors for each locality (Wessels *et al.* 2004; Wijitkosum 2016). Five main factors (physical, climatic, soil, land utilization and water resources), and fifteen subcriteria were used to analyse the agricultural drought risk level and risk area in the watershed using FAHP.

The physical factors included slope gradient and elevation. The climatic factor was represented by rainfall and AI, derived from climatic data over a 25-year period from eight agrometeorological stations in the watershed. The soil factor was assessed via five indicators: soil texture, drainage, fertility, erosion and salinity. Land utilization was evaluated using two indicators: land use and land cover. The RS and GIS technology were integrated to classify and map the land utilization data (Lillesand *et al.* 2008; Chen *et al.* 2012; Wijitkosum 2012). Landsat and Theos satellite images were processed by the ENVI software (Ver. 4.7, 2009) and the image geo-referencing accuracy was initially cross-checked against a reference map of the area. The last factor is water resources, which was evaluated based on a source of water for planting, and included precipitation days, stream density, distance from an irrigation canal and groundwater volume.

FAHP analysis for drought risk factors. The FAHP is an integrated method which enables handling ambiguity associated with the mapping of drought risk areas (Van Laarhoven & Pedrycz 1983). FAHP was developed from the fuzzy set theory, it is a class of objects with a continuum of grades of membership. Fuzzy membership functions can be any real number in the interval [0, 1] (Wang *et al.* 2006). In FAHP procedure, pairwise comparison was used to replace crisp values in order to eradicate vagueness and uncertainty of the factors. FAHP adopted the hierarchical model by taking into account layers of criteria and subcriteria. Prioritization was carried out by comparing the significance of values of each pair in the hierarchical model (Wang *et al.* 2006; Saaty 2008). Each criterion was given a fuzzy number (FN) (1–9) (Table 1) as part of the fuzzy set, then the scatter of its membership function was identified (An *et al.* 2007). In this study, the triangular fuzzy numbers (TFNs) (Eq. (1)) were determined for constructing drought risk factors (Kaufmann & Gupta 1988).

$$\mu(x_0) = \begin{cases} \dfrac{x-l}{m-l}, & x \epsilon [l,m] \\ \dfrac{x-u}{m-u}, & x \epsilon [m,u] \\ 0, & otherwise \end{cases} \qquad (1)$$

Where $l \leq m \leq u$. If $l = m = u$, the FN gets a crisp number. Following this, respondents could state an area below (l) or above (u), this value (m) can therefore *not* be interpreted as the modal value according to Chang (1996).

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Table 1. Scale for relative importance used in the pairwise comparison matrix

Intensity of importance	Fuzzy number	Linguistic variables	TFNs (l, m, n)	Reciprocal of fuzzy values $(1/u, 1/m, 1/l)$
1	$\tilde{1}$	equally important	(1, 1, 2)	(0.33, 1.00, 1.00)
3	$\tilde{3}$	weakly important	(2, 3, 4)	(0.20, 0.33, 1.00)
5	$\tilde{5}$	strongly important	(4, 5, 6)	(0.14, 0.20, 0.33)
7	$\tilde{7}$	very strongly important	(6, 7, 8)	(0.11, 0.14, 0.20)
9	$\tilde{9}$	extremely important	(8, 9, 9)	(0.09, 0.11, 0.14)
2, 4, 6, 8		median of the above adjacent judgement	$(x-1, x, x+1)$; $x = 2, 4, 6, 8$	$(1/(x+1), 1/x, 1/(x-1)$; $x = 2, 4, 6, 8$

TFNs – triangular fuzzy numbers; source: Dihn and Duc (2012)

The FAHP process consists of five steps. The first step is to compare the values of each pair in the hierarchical model using the FN. The second step is to create the fuzzy comparison matrix (FCM) (Eq. (2)).

$$\tilde{A} = \left(\tilde{a}_{ij}\right)_{n\times n} = \begin{bmatrix} (1,1,1) & (l_{12},m_{12},u_{12}) & \cdots & (l_{1n},m_{1n},u_{1n}) \\ (l_{21},m_{21},u_{21}) & (1,1,1) & \cdots & (l_{2n},m_{2n},u_{2n}) \\ \vdots & \vdots & \vdots & \vdots \\ (l_{n1},m_{n1},u_{n1}) & (l_{n2},m_{n2},u_{n2}) & \cdots & (1,1,1) \end{bmatrix} \qquad (2)$$

The third step is to calculate and identify the eigenvalue of which $\tilde{A}$ represents a matrix and vector X completes Equation 3:

$$\tilde{A}X = \lambda X \qquad (3)$$

$\tilde{A}$ is an $n \times n$ matrix containing $(\tilde{a}_{ij})$ FNs. X is a non-zero eigenvector, $1 \times n$ in size, and containing X_i fuzzy set numbers. l is a scalar number as the solution of the interval arithmetic equation (Wang & Luoh 2000). The next step is to identify the consistency ratio (CR) of each matrix in comparison with the fuzzy using the equation:

$$(CR = CI/RI) \qquad (4)$$

and given consistency index (CI):

$$CI = (\lambda_{\max} - n)/(n - 1) \qquad (5)$$

$\lambda_{\max}$ represents the hightest result from Eq. (3) and n is the size of the matrix. Random index (RI) represents weights generated by the size of the matrix (n) in comparison with the fuzzy value given the CR is equal to or less than 0.1 (Saaty 1996). The final step is to identify the total weight by analysing the attributes in each hierarchical step and using α to identify the weight of each criterion.

Analysis of drought risk assessment by FAHP. FAHP was used to prioritize drought risk factors. The comparison of the fuzzy values was carried out using FNs 1, 3, 5, 7, and 9 (Table 1). A hierarchical structure of drought risk factors for the watershed was prepared. Fifteen pairwise comparison matrices were developed using equations (1–3). The data was initially analysed by the hierarchical structure analysis using pairwise ratio comparisons as shown in Table 2–3. The calculation using TFNs then followed. CR was calculated by Eq. (4) and (5). FAHP and GIS techniques were employed to analyse drought risk areas. The areas were generated and mapped by the ArcGIS software (Ver. 10.3, 2014) to identify the

Table 2. The pairwise comparison matrix of the drought risk factors with respect to the goal

Factors	Climatic	Physical	Soil	Land utilization	Water resource	Fuzzy synthetic extent
Climatic	(1, 1, 1)	(0.33, 0.50, 1)	(0.25, 0.33, 0.50)	(2, 3, 4)	(2, 3, 4)	(0.10, 0.18, 0.34)
Physical	(1, 2, 3)	(1, 1, 1)	(0.25, 0.33, 0.50)	(2, 3, 4)	(2, 3, 4)	(0.12, 0.23, 0.43)
Soil	(2, 3, 4)	(2, 3, 4)	(1, 1, 1)	(4, 5, 6)	(2, 3, 4)	(0.25, 0.42, 0.72)
Land utilization	(0.25, 0.33, 0.50)	(0.25, 0.33, 0.50)	(0.17, 0.20, 0.25)	(1, 1, 1)	(0.33, 0.50, 1)	(0.04, 0.06, 0.12)
Water resource	(0.25, 0.33, 0.50)	(0.25, 0.33, 0.50)	(0.25, 0.33, 0.50)	(1, 2, 3)	(1, 1, 1)	(0.06, 0.10, 0.19)

$\lambda_{\max} = 5.1692$; consistency index $CI = 0.0423$; random index $RI = 1.12$; consistency ratio $CR = 0.03778 \leq 0.10$ hence the matrix is consistent

Table 3. The pairwise comparison matrix of criteria for the risk of drought factor

						Fuzzy synthetic extent
Climatic	rainfall	aridity index				
Rainfall	(1, 1, 1)	(2, 3, 4)				(0.74, 0.75, 0.74)
Aridity index	(0.25, 0.33 ,0.5)	(1, 1, 1)				(0.25, 0.25, 0.26)
Physical	slope	elevation				
Slope	(1, 1, 1)	(1, 2, 3)				(0.64, 0.67, 0.64)
Elevator	(0.33, 0.5, 1)	(1, 1, 1)				(0.35, 0.33, 0.35)
Soil	texture	drainage	fertility	erosion	salinity	
Texture	(1, 1, 1)	(4, 5, 6)	(6, 7, 8)	(3, 4, 5)	(2, 3, 4)	(0.47, 0.47, 0.46)
Drainage	(0.17, 0.20, 0.25)	(1, 1, 1)	(2, 3, 4)	(0.20, 0.25, 0.33)	(0.17, 0.20, 0.25)	(0.07, 0.07, 0.07)
Fertility	(0.13, 0.14, 0.17)	(0.25, 0.33, 0.50)	(1, 1, 1)	(0.20, 0.25, 0.33)	(0.17, 0.20, 0.25)	(0.04, 0.04, 0.04)
Erosion	(0.20, 0.25, 0.33)	(3, 4, 5)	(3, 4, 5)	(1, 1, 1)	(0.50, 1, 1)	(0.17, 0.18, 0.17)
Salinity	(0.25, 0.33, 0.50)	(4, 5, 6)	(4, 5, 6)	(1, 1, 2)	(1, 1, 1)	(0.15, 0.21, 0.35)
Land utilization	land use	land cover				
Land use	(1, 1, 1)	(1, 1, 2)				(0.58, 0.50, 0.58)
Land cover	(0.50, 1, 1)	(1, 1, 1)				(0.41, 0.50, 0.41)
Water resource	precipitation days	stream density	distance from irrigation canal	ground water volume		
Precipitation days	(6, 7, 8)	(3, 4, 5)	(1, 1, 1)	(4, 5, 6)		(0.60, 0.58, 0.56)
Stream density	(1, 1, 1)	(0.20, 0.25, 0.33)	(0.13, 0.14, 0.17)	(0.25, 0.33, 0.50)		(0.06, 0.05, 0.05)
Distance from irrigation canal	(3, 4, 5)	(1, 1, 1)	(0.20, 0.25, 0.33)	(2, 3, 4)		(0.21, 0.23, 0.24)
Ground water volume	(2, 3, 4)	(0.25, 0.33, 0.50)	(0.17, 0.20, 0.25)	(1, 1, 1)		(0.11, 0.12, 0.13)

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affected areas into five different levels: very high, high, moderate, low, and very low.

RESULTS

Factors affecting the agricultural drought in the Lam Ta Kong watershed. Of all the 3419.9 km^2, 77.50% of the area has a slope lower than 2% covering the central part of the watershed and 68.84% was used for agricultural purposes. The vegetative cover reached approximately 68.20% with 24.12% forest coverage in Khao Yai National Park and in a small area in the mountain range in the upstream area. 57.38% of the area had an average rainfall of 1000–1050 mm/year and 74.36% had an AI between 0.50 and 0.65. Moreover, there are 93 precipitation days/year. 63.98% of the area was a long distance (> 6000 m) away from the irrigation canal. The majority of the agricultural area has suffered severely from the adverse impacts of droughts. Regarding soil factors, the main type of soil texture in the area was loamy soil covering 31.03% of the watershed and 59.46% was classified as having very low fertility. Soil drainage in most of the area (67.79%) was very poor and 43.26% had a low soil erosion level. 13.64% of the area, mainly in the central part of the watershed, was affected by salt. Dense salt crust areas (> 50%) were mostly found in Kham Thale Sor where the soils were deep and generally infertile. The water resource factors also affected the drought risk of the area. Groundwater volume at 2–20 cm^3/h covered 46.83% of the area whilst 42.98% received a groundwater volume lower than 2 cm^3/h. The stream density of the watershed was 1.0 km/km^2. The stream is narrow and shoal at some parts, the flow is uneven due to water scarcity. The map shows fifteen risk factors influencing agricultural drought risk in the watershed as shown in Figure S1 in Electronic Supplementary Material.

Drought risk factors. The results also showed that (Table 4) the soil factors had the highest impact (W = 0.4532) on drought in the area, followed by physical factors (W = 0.2416), climatic factors (W = 0.1950), water resources (W = 0.1089), and land utilization (W = 0.0736). The subcriteria that had the highest influence were soil texture (soil factor); rainfall (climatic factor); precipitation days (water resources), and slope gradient (physical factors). The results showed consistency since the *CR* of all the matrices was below 0.1 (*CR* = 0.0378).

Agricultural drought risk assessment of the Lam Ta Kong watershed. The total of 1785.46 km^2 or 50.45% of the areas were at the moderate agricultural drought risk. A high risk of drought occupied up to 15.63% of the total area while only 0.40% was categorized as being at a very high risk of drought. Areas experiencing the highest drought risk were located in some parts of Kham Thale Sor where the average rainfall was less than 1000 cm^3/year. The area was also critically affected by salinity, especially in the northern parts where dense salt crusts (> 50%) were distributed widely on the soil surface. Moreover, the soil was sandy soil with very low fertility

Table 4. The factors that affect drought risk in the Lam Ta Kong watershed by using FAHP

Factors	Relative weight	Criterion	Relative weight	Final weight
Climatic	0.1950	rainfall	0.7833	0.1527
		aridity index	0.2633	0.0513
Physical	0.2416	slope	0.6508	0.1572
		elevator	0.3492	0.0843
Soil	0.4532	texture	0.4700	0.2130
		drainage	0.0789	0.0357
		fertility	0.0451	0.204
		erosion	0.1787	0.0809
		salinity	0.2274	0.1030
Land utilization	0.0736	land use	0.5588	0.0411
		land cover	0.4412	0.0324
Water resource	0.1089	precipitation days	0.5860	0.0638
		stream density	0.0604	0.0065
		distance from irrigation canal	0.2300	0.0250
		ground water volume	0.1235	0.0134

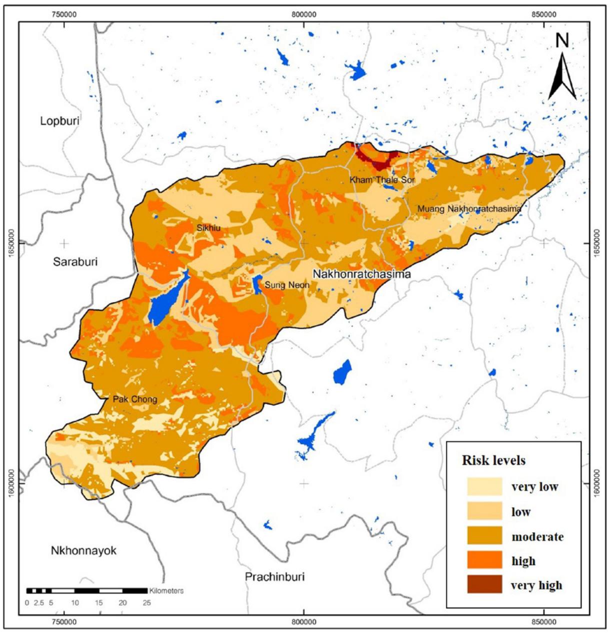

Figure 1. Map of the agricultural drought risk in the Lam Ta Kong watershed

and located far from the nearest irrigation canal (> 6000 m) (Figure 1).

DISCUSSION

The results revealed that a very high drought risk in the watershed occurred in the non-irrigated area with low rainfall volume, very high soil drainage, and very poor soil fertility. Sandy soil with poor drought resistance resulted in low water holding capacity, low nutrients, high erosion and high degradation (Zhang 2006; Wijitkosum 2016) which affected productivity and growth (Whitmore & Whalley 2009; Lal & Stewart 2013). The sandy texture of soil was the main factor influencing the land susceptibility to desertification and drought (Hou *et al.* 2013; Zhao *et al.* 2013; Wijitkosum 2016) because of its significant impact on ecological and hydrological processes. Droughts tend to be a dominant problem of land utilization for agriculture. A previous study (Wijitkosum & Sriburi 2016) showed that this area had strongly alkaline soil (pH 10.3–11.0) making the areas difficult to cultivate and remained deserted. The sedimentary rock, Maha Sarakham Formation, contributed to the amount of salt found in groundwater and surface soil in the area. The alkaline soils have a significant impact on droughts and reduce crop productivity because most crops are sensitive to high concentrations of salt (Biazin & Sterk 2013; Bagley *et al.* 2014). The alkaline soil in this watershed also suffered from low precipitation which hampered the leaching of salt ions from upper to lower soil horizons allowing the salt to accumulate (Blaylock 1994). Once deserted, further reduction in vegetative cover occurred resulting in an accelerated loss of topsoil, soil erosion (Wijitkosum 2012), an increase in soil evaporation and a decrease in soil fertility. These accumulated issues led to an increased drought risk. Moreover, the land with low vegetative cover showed a higher drought risk than that with more coverage (Peng *et al.* 2016). On the other hand, some upstream areas are at a high risk level of drought. Soils found in the areas were composed of sandy soils and sandy loams with very high soil drainage and very low fertility. The area received low levels of precipitation, especially in the dry season, and remained dry despite being located near water sources. Therefore, the watershed was at risk of drought influenced by natural and human factors. The issues are becoming more complicated (Cox *et al.* 2008; Wijitkosum 2014)

Droughts are also heavily influenced by spatial factors. The results from this study revealed different results from Sa-Nguansilp *et al.* (2017), indicated that the majority of the area (46.3%) was prone to a very high drought risk. Rainfall had a high effect on the drought risk in the study area followed by land cover and soil texture. This study gave different results in comparison with the aforementioned even though the factors and the subcriteria were quite similar. This was due to the results from the hierarchical structure and its prioritizing property of the fuzzy set number together with AHP which allowed a more detailed analysis than in AHP. Fuzzy theory can reduce vagueness and uncertainty that are inherent in the problem. The results were consistent with many studies (Tuysuz & Kahraman 2006; Tian & Yang 2013; Yang *et al.* 2013; Radionovs & Užga-Rebrovs 2016) indicating that FAHP is an approach to solving the complicated problems and prioritizing the factors that exceed the limited ability of AHP (Chang 1996; Wang 2009; Yang & Zhang 2012; Yang *et al.* 2013; Zhao *et al.* 2014).

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