

Integrated assessment of flood and drought hazards for current and future climate in a tributary of the Mekong river basin

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ABSTRACT

Projecting flood and drought characteristics under climate change is important to management plans and enhancement of the resiliency of the society. However, studies that provide the integration of flood–drought hazard events is scarce. This study assessed the flood and drought hazards for future climate in the Mun River basin. A non-modelling approach is used to assess the flood hazard, while a multi-variate approach is used for the drought hazard. The results suggest that areas under ‘high’ and ‘very high’ drought hazard levels will increase from 27 and 4% during the baseline period to 43 and 37%, during the near-future period. Similarly, an increase in the ‘high’ and ‘very high’ flood hazard levels from 11 and 22% during the baseline period to 16 and 24% during the near-future period is projected. When both hazards are considered together, the total hazard is projected to increase by 155% in the near-future period. 76% of the catchment during the near-future period will have a combined hazard level from ‘medium’ to ‘very high’ compared to the 30% during the baseline period. The research presents a grim outlook on future floods and droughts in the basin, with the areas of Nakhon Ratchasima, Rio Et and Si Sa Ket provinces particularly at risk from both hydro-meteorological hazards.

Key words: climate change, combined hazard, droughts, floods, multi-variate approach, Mun River basin

HIGHLIGHTS

- Individual and combined flood and drought hazard assessment for the near-future period.
- Non-modelling approach for flood and a multi-variate approach for drought hazards used.
- Area under high and very high drought hazards up from 30 to 80% in the near future.
- Area under high and very high flood hazards up from 33 to 40% in the near future.
- Area under the combined hazard projected to increase by 155% across the catchment.

1. INTRODUCTION

Hydro-meteorological extremes, either an acute lack of water or excess of it, are characterized by spatial-temporal variability and manifest as droughts or floods, respectively. They have the potential to cause severe damage to the environment (Masud *et al.* 2015), have a significant effect on the hydrology and water resources of watersheds (Aalijahan *et al.* 2021), and cause socio-economic impacts (Marcos-Garcia *et al.* 2017). Between 2005 and 2014, 83% of the recorded disasters, 39% of the recorded human deaths and 70% of the documented damages were linked to weather, water and climate (WMO 2018), respectively. With climate change, hydro-meteorological hazards are likely to be more frequent and severe, and influence a greater area. A warmer climate will intensify the hydrological cycle, resulting in the spatial and temporal redistribution of global water resources (Chen & Sun 2017).

With almost one billion people living in flood-prone areas (Kittipongvises *et al.* 2020), flooding is one of the most destructive natural hazards in the world, affecting 45% of the global population (Hammond *et al.* 2014; Kittipongvises

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et al. 2020) and causing billions of dollars of damage each year (Davenport *et al.* 2021). Several studies have shown that precipitation extremes will increase in the frequency and magnitude in the future (Zhu 2013; Rudra *et al.* 2015; Burke & Stott 2017; Ohba & Sugimoto 2019). An increase in the extreme precipitation will be manifested as an increase in the flood risk.

Problems caused by flooding are increasingly exacerbated by increased water vapour in the atmosphere (Morita 2011; Aalijahan *et al.* 2023), a higher frequency of intense rainfall events (Chitwatulsiri *et al.* 2021) and changes in land use, increasing surface runoff, resulting in greater flood extents and depths (Khan *et al.* 2018; Penny *et al.* 2023). In particular, South Asia is one of the most flood-prone regions in the world due to its natural geography (Shah *et al.* 2020).

On par with flooding, between the 2008 and 2018 period, global drought resulted in economic losses of about 8.42 billion USD (CRED 2018). A study by Lesk *et al.* (2016) showed that between 1964 and 2007, drought resulted in an estimated loss of 1,820 million metric tons of cereal globally. There are several types of droughts: meteorological, agricultural, hydrological, groundwater, ecological, socio-economical, etc. (Mishra & Singh 2010; Zargar *et al.* 2011; Crausbay *et al.* 2018). Under climate change, global agricultural droughts are projected to increase (Zhao & Dai 2017), several studies in Asian river basins have similar conclusions (Nam *et al.* 2015; Lu *et al.* 2016; Li *et al.* 2017; Kwon & Sung 2019).

Floods and droughts are common natural hazards with dire consequences in Thailand. The probability of drought in any given year is 0.45 for Thailand, the highest among Asia-Pacific countries (Pandey *et al.* 2007). While the droughts of 2004–2005 caused an estimated damage of about 220 million USD (Wichitarapongsakun *et al.* 2016), the devastating drought of 2015–2017 resulted in a damage of 3,300 million USD (EM-DAT 2019). On the other hand, flooding is also a serious issue in Thailand, experiencing 69 major floods since 1985 (Singkran 2017). The historic flooding of 2011–2012 affected 16 million people in 64 provinces out of 77 and caused a damage of about 45.7 billion USD (DDPM 2015). The World Bank estimated it to be the fourth most costly natural disaster in the world from 1995 to 2011 (Kittipongvises *et al.* 2020). Other studies in Thailand have shown that extreme precipitation is likely to increase in the future (Singhrattna *et al.* 2012; Komori *et al.* 2018; Igarashi *et al.* 2019), consequently increasing the flood hazard.

There have been many methods that examine flood and drought hazards: hydrologic-hydraulic modelling approach (Vojinovic *et al.* 2016; Jacob *et al.* 2020), hydrographs (Samu & Akıntuğ 2020), frequency ratio (Kongmuang *et al.* 2020), FDD index (Guan *et al.* 2021), NDVI and LSWI (Chandrasekar *et al.* 2010; Navarathinam *et al.* 2015) and the modified Mann-Kendall (MMK) (Gemmer *et al.* 2008; Zhang *et al.* 2015). However, lately Geographical Information Systems (GIS) techniques are increasingly used in flood hazard, with SPI and SPEI used in drought assessments (Nawai *et al.* 2015; Prabnakorn *et al.* 2016, 2020, 2021; Shao & Kam 2020). MCDA-GIS is a combination of GIS with multi-criteria decision analysis (MCDA). GIS-based MCDA is a method increasingly used over the past two decades for flood risk and hazard assessment (Tang *et al.* 2018; Shadmehri Toosi *et al.* 2019, 2020; Kittipongvises *et al.* 2020) that provides a simple, effective and accurate means to investigate spatial distributions and characteristics using basic GIS analysis and mapping (Paquette & Lowry 2012; Samanta *et al.* 2016; Shadmehri Toosi *et al.* 2020). It is especially useful method in areas where there are limited data (Shadmehri Toosi *et al.* 2020). MCDA-GIS provides more flexibility for decision makers to evaluate factors that cause flooding (Nigusse & Adhanom 2019), providing significant advantages over different methods in overcoming decision-making difficulties (Vavatsikos *et al.* 2019).

Modelling multiple climate hazards together is rarely done. However, Ming *et al.* (2015) provided a quantitative approach of multi-hazard risk assessment to assess crop losses caused by high winds and flooding. Typically, droughts and flooding are treated independently due to challenges, associated with their subjective nature and their coupled dynamics. Recently, Brunner *et al.* (2021) have suggested that droughts and floods should be studied in a joint framework to help learn about fast event transitions. For example, Forzieri *et al.* (2016) modelled multiple hazards (flooding, drought, heatwaves) over Europe using the Overall Exposure Index (OEI), which works under the assumption that hazards are mutually non-exclusive and the Change Exposure Index (CEI), which expresses the number of hazards at a given baseline period. In agreement with the above Tabari *et al.* (2021) state that few studies and combined and projected flood and drought risk owing to large uncertainties, non-linearities and complex spatial-temporal dynamics. The study goes on to develop a global framework to encapsulate changes in flood and drought hazards using Extreme Value Distribution (GEV), SPEI and SPI. Nevertheless, both the above studies failed to combine the hazards within one map/entity. More recently, Yang *et al.* (2023) have combined the drought and flood status with crop yield through a correlation approach using SPEI to identify the risk from each hazard through both linear and probabilistic analyses. The study concluded that there were uncertainties within the models used and the level of risk classification.

To conclude, floods and droughts are significant disasters with severe implications to the society. It is important to understand and quantify them, especially with the ever disheartening climate change outlook, so that measures can be designed to mitigate them. Consequently, this study considers the joint spatial patterns of the flood and drought hazards in the Mun River basin, Thailand, for present and future climate scenarios. While previous studies have looked at either flood or drought hazard separately, this study presents its novelty by providing a non-modelling approach to joint hazard analysis considering both flood and drought. The methodology, using MCDA-GIS, is applicable to other studies as it is not limited by detailed data needs as found with hydrological/hydraulic modelling. The study will be useful to identify the areas where both single flood and drought hazards are located, as well as areas at risk from combined hazards, which could be a basis for implementing measures to improve resilience and reduce the associated risk in the future against both hydro-meteorological extremes commonly occurring in basins across the globe.

2. STUDY AREA AND METHODOLOGY

2.1. Study area

The Mun River basin (as shown in Figure 1) is the largest basin in northeast Thailand and has a catchment area of about 53,800 km². It is one of the major tributaries of the Mekong river. As part of the Korat plateau, the elevation varies between 64 m in the central region to 1,351 m in the south-west area (Khadka *et al.* 2022). The basin comprises four provinces, namely, Nakhon Ratchasima, Buriram, Surin and Si Sa Ket, and partially another four (Roi Et, Maha Sarakham, Khon Khen and Ubon Ratchathani). Even though the basin is one of the most drought prone regions in the country (Khadka *et al.* 2021), it is also an important agricultural region (Penny *et al.* 2021) of the country with rice cultivation occupying approximately

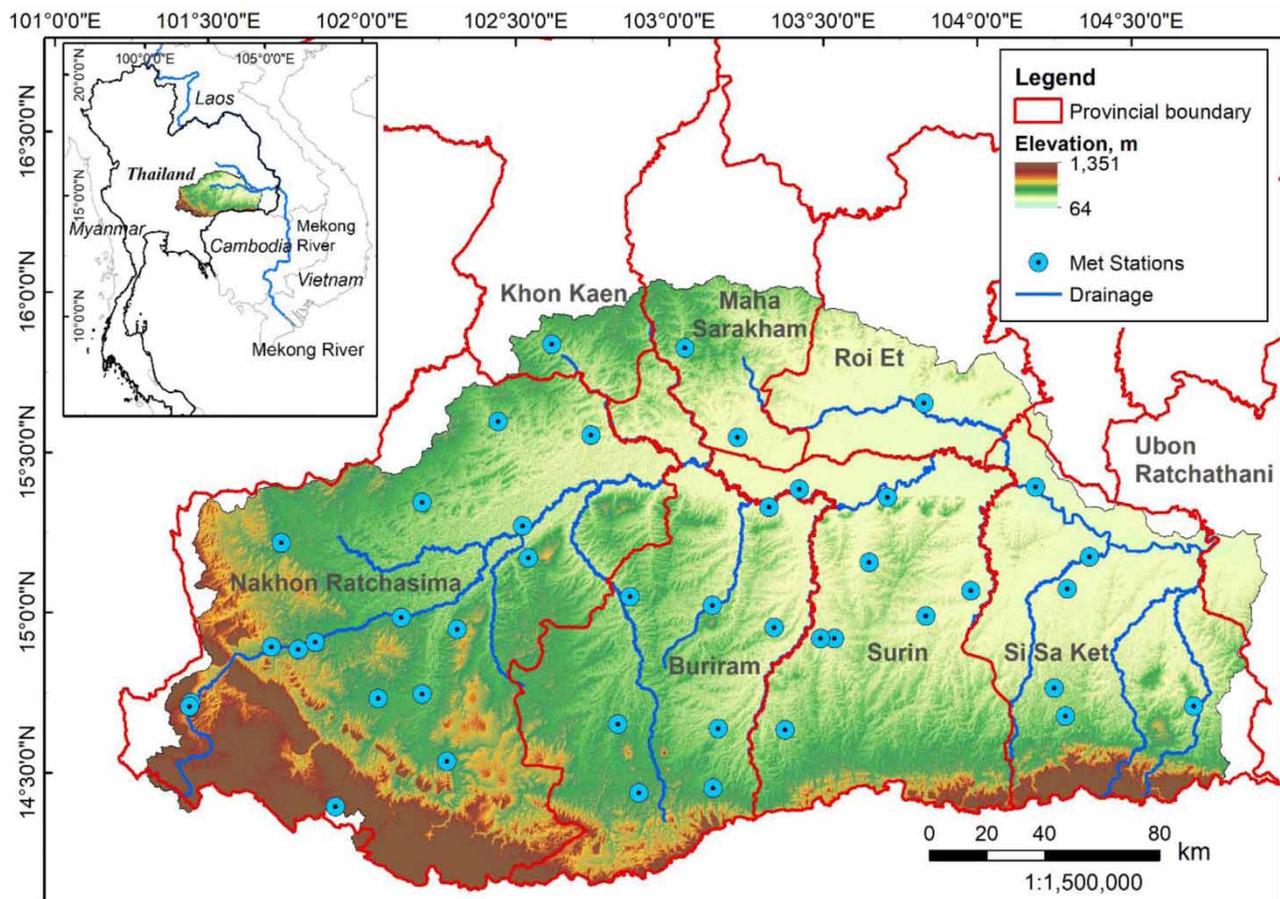


Figure 1 | The study area of the Mun River basin, located in northeast Thailand, hydrological and provincial boundaries.

75% of the agricultural land and 55% of the basin's total area (Penny *et al.* 2021; Prabnakorn *et al.* 2021). The climate of the basin is primarily governed by the south-west monsoonal system, which brings heavy rainfall during mid-May to mid-October (providing about 80% of the annual rainfall). Consequently, the basin is prone to flooding especially within these months (Prabnakorn *et al.* 2019). However, the winter monsoonal system (December to February) is relatively dry, with the summer months extending from March to May. As the basin regularly experiences considerable problems caused by floods in the wet season and droughts in the dry season (Prabnakorn 2020; Prabnakorn *et al.* 2021), it makes an excellent case study.

2.2. Topographic and land use (LU) dataset

Data sources and Geographical Information System (GIS) tools used to create the driving map can be observed in Table 1. Land use types were identified according to the land use maps supplied by the Land Development Department (LDD) of Thailand which were also used in the previous study by Penny *et al.* (2021) paddy fields, field crops, perennials and orchards, other agriculture, forest, water bodies, marsh and swamp, urban and miscellaneous. From land use data using the 'Distance tool', drainage density could also be calculated. Soil data were classified according to the Harmonized World Soil Database, a global soil database framed within a GIS, which contains up-to-date information on world soil resources, classification range from combinations of clay, loam and sand. A slope map was created using the surface toolbox within ArcMap 10.6.1 (ESRI) and an elevation map provided by ALOS-JAXA.

2.3. Observed climatic data

The study utilizes the gridded rainfall and temperature dataset prepared by Khadka *et al.* (2022). The observed rainfall data from 43 stations (acquired from Thai Meteorological Department) were spatially interpolated to 0.25-degree grids using the inverse distance weighting (IDW) method. The maximum and minimum temperature datasets from the Climate Prediction Center (CPC) Global land surface air temperature analysis (Fan & van den Dool 2008) were used after comparison with other data products to ensure accuracy and consistency.

Spatially, both maximum and minimum temperatures show very small variations within the study basin (<1.0 °C); however, considerable spatial variation in the rainfall is observed as it gradually increases from the west towards the east (Figure 2). The Nakhon Ratchasima province in the west receives the least rainfall (about 800 mm/year), while the Si Sa Ket province in the east receives the most rainfall (about 1,600 mm/year).

2.4. Future climate projection dataset

Near-future (2021–2050) climate, projected by Khadka *et al.* (2022), was used in this study. The climate projection (rainfall and temperatures) is based on eight climate models participating in HighResMIPs (Haarsma *et al.* 2016) of CMIP6 (Table 2). The study has assessed the changes in the climate for the near-future (2021–2050) with respect to the baseline period of 1981–2010. The future projections are available for shared socio-economic pathway (SSP) 5–8.5, which represents the high emission scenario (O'Neill *et al.* 2017). Bias correction for raw temperature and rainfall data from climate model is carried out using the quantile mapping method (Ines & Hansen 2006).

Results from Khadka *et al.* (2022) suggest that the maximum and minimum temperature in the study basin will increase by 1.45 °C (0.8–1.9 °C) and 1.54 °C (1.1–1.9 °C) in the near-future compared to the baseline. While there will be no significant

Table 1 | Details of the data type and sources used within flood hazard analysis

Data type	Observation period	Spatial resolution	Organization source	GIS tools used
Land use of northeast Thailand	2016	100 m	Land Development Department (LDD)	Reclass – Reclassify
Drainage density (distance from river)		100 m		Data Management Tool – mosaic to new raster distance – Euclidean Distance
Soil data – lithology type	2008	100 m	Mekong river Commission (MRC)	Reclass – Reclassify
Topographic map – elevation and slope	2019	30 m	ALOS – JAXA	Reclass – Reclassify The Surface Tool – Slope

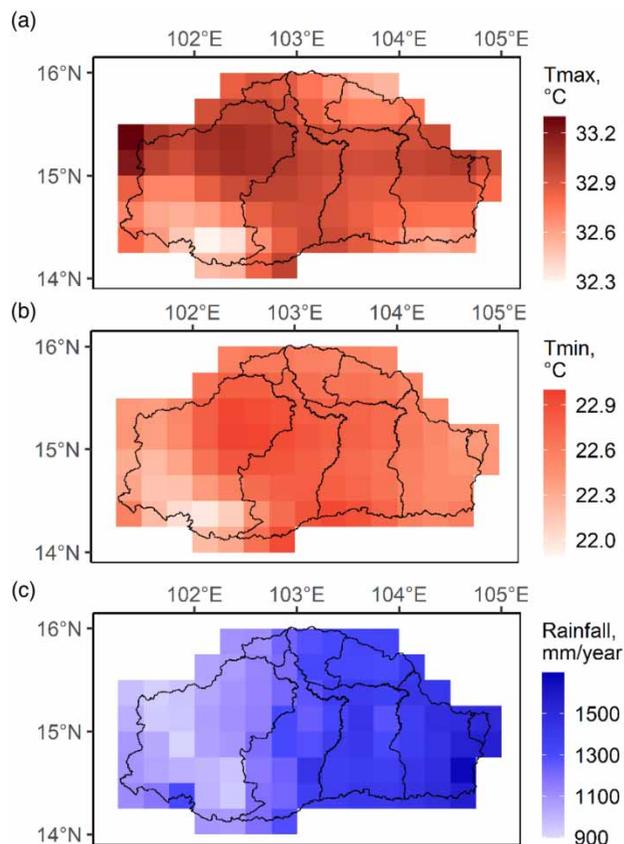


Figure 2 | Observed annual (a) maximum temperature, (b) minimum temperature, and (c) rainfall in the study area for 1981–2010 period.

Table 2 | Details of climate models used for the near-future climate in the Mun River basin (Khadka *et al.* 2022)

S.N.	Model designation	Modelling group	Atmospheric resolution (lat × lon)	Number of vertical levels	Ensemble member
1.	CNRM-CM6-1	Centre National de Recherches Meteorologiques (CNRM)/ Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	1.4° × 1.4°	91	r1i1p1f2
2.	CNRM-CM6-1-HR	Centre National de Recherches Meteorologiques (CNRM)/Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	0.5° × 0.5°	91	r1i1p1f2
3.	EC-Earth3P	EC-EARTH Consortium	0.7° × 0.7°	91	r1i1p2f1
4.	EC-Earth3P-HR	EC-EARTH Consortium	0.35° × 0.35°	91	r1i1p2f1
5.	HadGEM3-GC31-HH	UK Met Office Hadley Centre (MOHC)	0.23° × 0.35°	85	r1i1p1f1
6.	HadGEM3-GC31-HM	UK Met Office Hadley Centre (MOHC)	0.23° × 0.35°	85	r1i1p1f1
7.	HadGEM3-GC31-MM	UK Met Office Hadley Centre (MOHC)	0.55° × 0.83°	85	r1i1p1f1
8.	HadGEM3-GC31-LL	UK Met Office Hadley Centre (MOHC)	1.25° × 1.875°	85	r1i1p1f1

changes (0.5%, between -5 and $+10\%$) in the annual rainfall, temporal variations will increase in the future with projected increase by 6–11% and decrease in the summer by 2–8%. Similarly, the ensemble of the selected climate models indicated that the extreme rainfall events, computed as 10-year return values of 1-day maximum and 5-day consecutive maximum rainfall,

will increase by 23% (9–40%) in the near-future period. The results are suggestive of significant impacts of climate change on the rainfall extremes.

2.5. Methodology

Figure 3 presents the overall methodology used in the study. SPEI is used to characterize droughts in terms of duration, severity and frequency. Multi-variate analysis is then carried out to quantify the drought hazard. Similarly, six physiographic and climatic factors have been utilized to produce the flood hazard maps. Joint flood and drought hazard map is prepared by combining the individual hazard maps in ArcMap 10.6.1 (ESRI). Climate change projections (including the extreme rainfall) are taken from the study by Khadka *et al.* (2022). The detailed methodology is explained in the following sub-sections.

2.6. Current and future flood hazard

The first phase of the methodology was a literature review of papers (2004–2021) covering articles using MCDA-GIS for flood hazard and risk (Figure 4 and Supplementary material, Table S1). This methodology was chosen as it is frequently used within the literature (Tanavud *et al.* 2004; Duan *et al.* 2009; Ozturk & Batuk 2011; Paquette & Lowry 2012; Elsheikh *et al.* 2015; Rahmati *et al.* 2016; Samanta *et al.* 2016; Alves *et al.* 2018; Ghosh & Kar 2018; Tang *et al.* 2018; Liu *et al.* 2019; Nigusse & Adhanom 2019; Shadmehri Toosi *et al.* 2019, 2020; Vavatsikos *et al.* 2019; Ajjur & Mogheir 2020; Kittipongvises *et al.* 2020; Kongmuang *et al.* 2020; Feizizadeh *et al.* 2021) and provides the ability to weight and combine multiple inputs to create an integrated analysis. Using the driving factors that appeared repeatedly within the literature, the top six were selected: slope, elevation, distance from water bodies (drainage density), land use, rainfall and lithology (Figure 4). Other factors that appeared in the literature included distance from urban area, urban drainage network, population and distance from coastal zone; these factors were disregarded from the study as the catchment is primarily agricultural and land locked. Others such as groundwater depth, TWI, PMR and SPI could not be used due to the limited data pool available to the study.

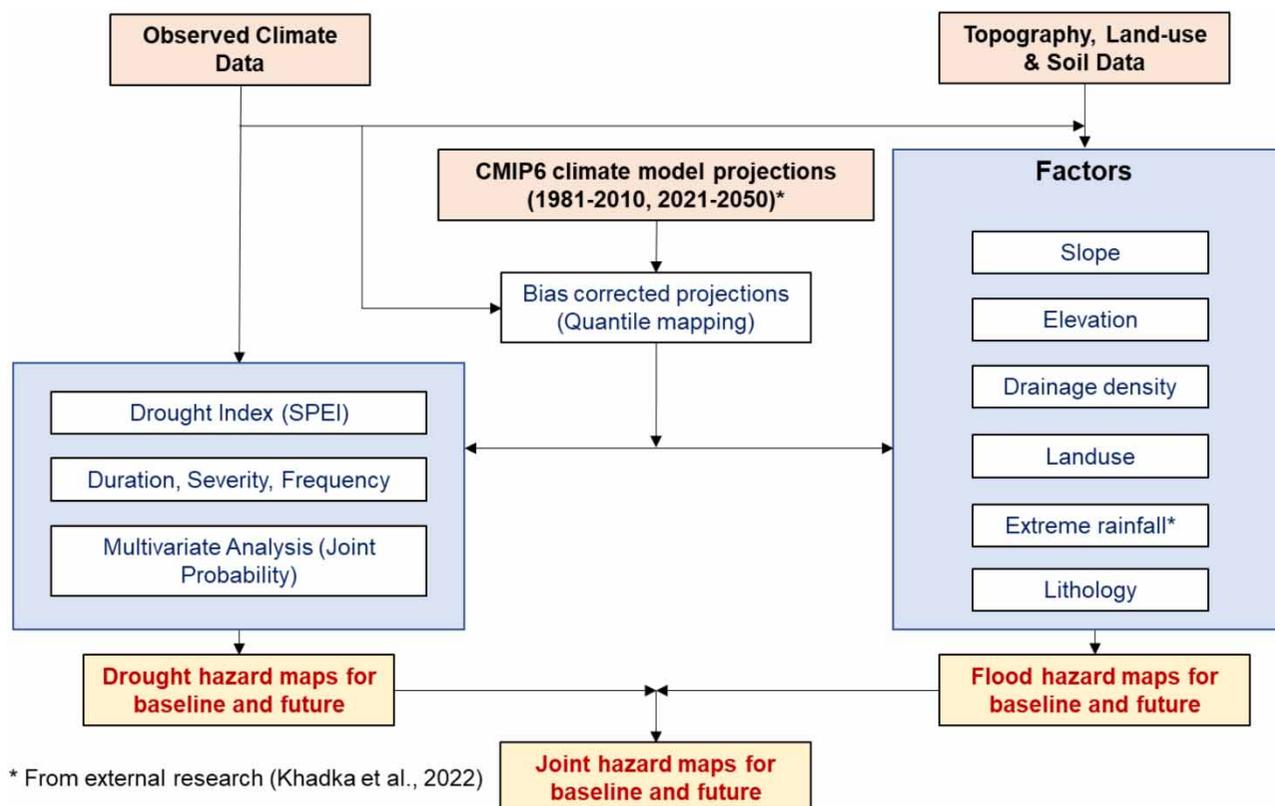


Figure 3 | Overall methodology for preparing the joint hazard maps for observed and climate change scenarios.

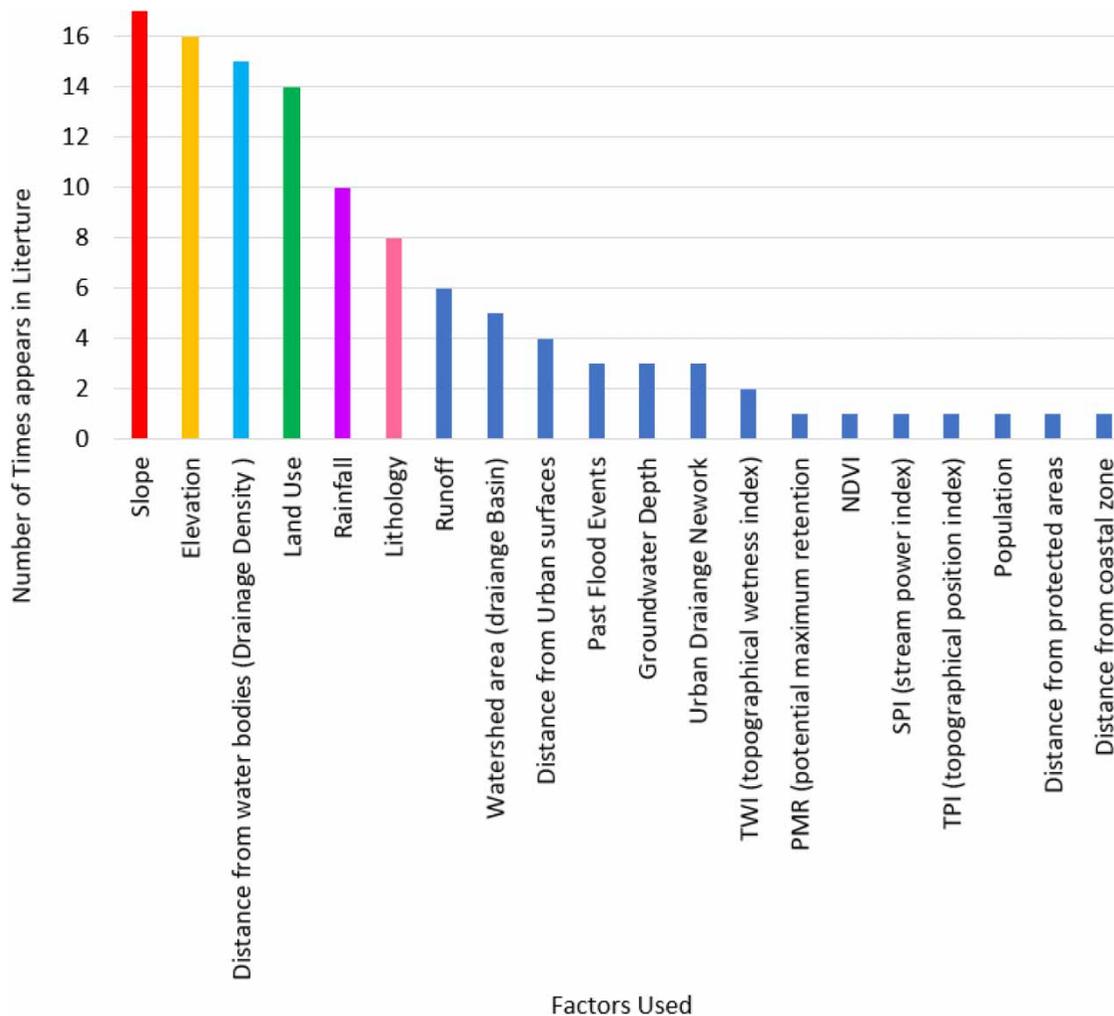


Figure 4 | Factors used within the MCDA-GIS literature for flood-related risk or hazard analysis. The first six driving factors used were slope, elevation, distance from water bodies (drainage density), land use, rainfall, and lithology.

The weighting for driving factors can be decided via questioning from a series of experts or stakeholders (Alves *et al.* 2021); however, for this case study, the six chosen driving factors were considered equal weights (Januadi & Nabila 2020).

The ArcMap spatial analysis weighted sum tool was used to overlay several raster layers of factors presented in Figure 3. By multiplying each by a given weight and summing them together so the sum of all weights equalled 100%, a single flood hazard map was created. Each raster map within the analysis was reassigned a reclassified to identify the preference for the class relative to the criterion in the overlay analysis (Table 3). Topographic maps were reclassified from 1 to 5 according to the Jenks natural break method (Vojinovic *et al.* 2016; Shadmehri Toosi *et al.* 2019, 2020; Kongmuang *et al.* 2020). Rainfall extremes are the main driver of flooding events. In this study, 10-year return values of annual maximum consecutive 5-day rainfall (RX5day) are used as a climatic factor for assessing future flood hazards. It is one of the extreme rainfall indices recommended by ‘The Expert Team on Climate Change Detection and Indices’ (ETCCDI) (Peterson 2005). As shown in Figure 5, the extreme rainfall represented by RX5day is projected to increase under climate change scenarios. CNRM-CM6-1 projects a least increase in RX5day (6%), while the highest increases are projected by HadGEM3-GC31-HH (51%) and HadGEM3-GC31-LL (34%) in the near-future. Rainfall maps were created using Empirical Bayesian kriging (EBK). A study by Ali *et al.* (2021) assessed the optimal spatial distribution and rainfall characterization of 27 interpolation techniques from geo-statistical and deterministic categories and concluded that EBK was a robust and straightforward interpolation technique that requires minimal interactive modelling. Subsequently, EBK was used as the interpolation technique for the rainfall maps.

Table 3 | Classification of flood hazard levels based on normalized values for topographic factors – reclassified via the Jenks natural break method

Thematic layer	Classified value	Reclassified value	Level of hazard
Elevation	64–140	5	Very high hazard
	140–160	4	High hazard
	160–186	3	Medium
	186–241	2	Low hazard
	241–1,356	1	Very low hazard
Slope	0–0.0755	1	Very low hazard
	0.0755–0.2266	2	Low hazard
	0.2266–0.4533	3	Medium
	0.4533–1.0577	4	High hazard
	1.0577–19.264	5	Very high hazard
Drainage density (distance from river)	0–2,105	5	Very high hazard
	2,105–4,975	4	High hazard
	4,975–8,803	3	Medium
	8,803–14,352	2	Low hazard
	14,352–48,800	1	Very low hazard
Land use	Forest/Miscellaneous	1	Very low hazard
	Perennial and orchard	2	Low hazard
	Field crops	3	Medium
	Paddy field	4	High hazard
	Water bodies, Marshland, urban	5	Very high hazard
Soil types	Sand	1	Very low hazard
	Sandy loam	2	Low hazard
	Sandy loam/clay loam	3	Medium
	Loam	3	Medium
	Clay loam/loam	4	High hazard
	Clay loam	4	High hazard
	Clay	5	Very high hazard

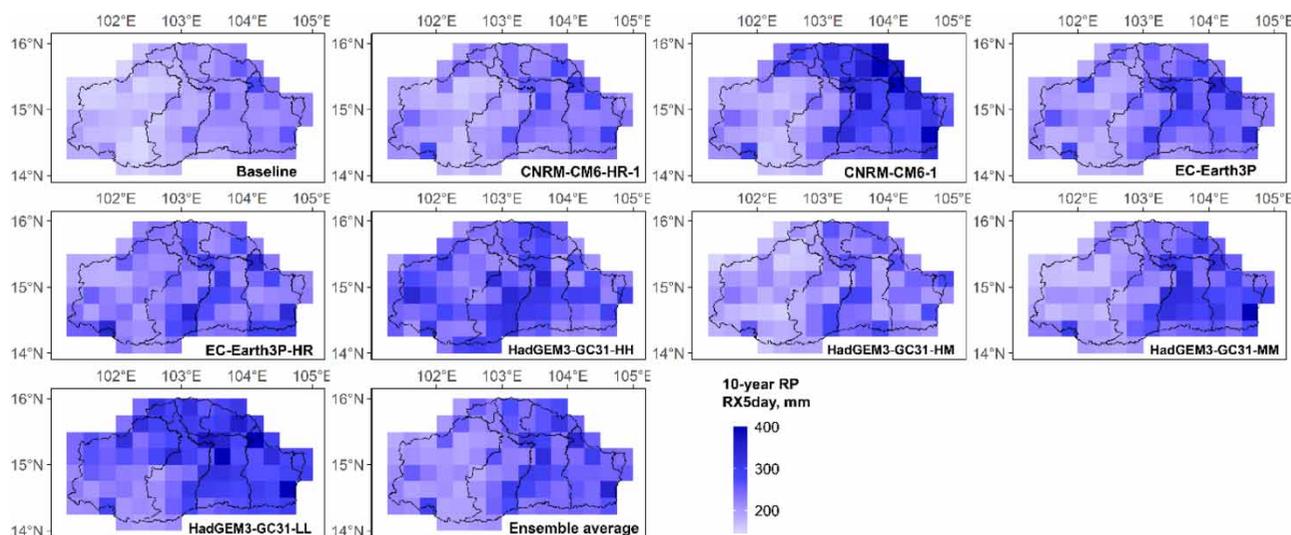


Figure 5 | 10-year return values (RP) of annual maximum consecutive 5-day rainfall (RX5day) for the baseline period and for the near-future period using eight climate models and the ensemble average.

2.7. Current and future drought hazard

To characterize the drought events in the basin, SPEI (Vicente-Serrano *et al.* 2010) has been used. It is a multi-scalar meteorological drought index, which considers climatic water balance [i.e., difference between precipitation (P) and potential evapotranspiration (PET)]. Since it considers both temperature and precipitation, it is suitable for climate change analysis. PET is estimated using the Hargreaves–Samani (Hargreaves & Samani 1982) method. Although the SPEI can be calculated at different timescales, a 12-month timescale is more relevant for climate change studies (Ahmadalipour *et al.* 2017; Lee *et al.* 2019) so that short-term rainfall variabilities can be avoided. SPEI is calculated by fitting the data in GEV distribution (Stagge *et al.* 2015; Khadka *et al.* 2021).

Droughts are characterized in terms of duration, severity and frequency. In order to avoid the minor drought events, a SPEI threshold method suggested by Khadka *et al.* (2021) has been used. This method uses two criteria to define droughts: (a) a certain length of consecutive period has SPEI less than zero, and (b) the maximum intensity during that period is ≤ -0.5 . The method will omit minor events while preserving the duration and severity characteristics. Univariate analysis of drought duration and severity is widely practiced (Liu *et al.* 2011; Chen *et al.* 2013; Sun *et al.* 2019), but since duration and severity are highly correlated (Masud *et al.* 2015; Khadka *et al.* 2021), it is often prudent to consider them together. In this study, a multi-variate approach using the copula function (Sklar 1959) is used to determine the drought hazard. The joint return period of drought events with severity (S) exceeding ' s ' and duration (D) exceeding ' d ' is given by the following equation (Shiau 2006):

$$T_{s,d} = \frac{E(L)}{1 - F(s) - F(d) + C(s, d)} \quad (1)$$

The denominator represents the joint occurrence probability $P(D > d \text{ and } S > s)$, with chosen thresholds of duration (d) and severity (s) taken as the median values of univariate frequency analysis; $F(s)$ and $F(d)$ are the cumulative probability of the drought event exceeding severity of ' s ' and duration of ' d '; $E(L)$ is the average or expected drought interval. Following Nelson 2006, the empirical copula function $[C(s, d)]$ of two random variables, x and y , is derived as

$$C\left(\frac{i}{n}, \frac{j}{n}\right) = \frac{\#(x \leq x_{(i)}, y \leq y_{(j)})}{n} = \frac{m}{n} \quad (2)$$

where x_i and y_j are the order statistics of the samples of size n and m is the number of observations satisfying $x \leq x_i$ and $y \leq y_j$, with $1 \leq i, j \leq n$. The joint probability of the 10-year joint return drought event is considered to define the drought hazard.

2.8. Normalization and categorization

Computed factors for the flood hazard and the joint probability for the drought hazard are normalized between 0 and 1 before the hazards are classified into five equal-spaced categories (Table 4),

$$X_{(i)} \text{ normalized} = \frac{(X_i - X_{\min})}{(X_{\max} - X_{\min})} \quad (3)$$

Table 4 | Classification of flood/drought hazard levels based on normalized values

Normalized value	Class	Level of hazard
<0.2	1	Very low hazard
0.2–0.4	2	Low hazard
0.41–0.6	3	Medium hazard
0.61–0.8	4	High hazard
>0.8	5	Very high hazard

where X_i is the factor/joint probability for grid i , and X_{\min} and X_{\max} are the minimum and maximum values among all grids, respectively. Normalization for the climate change scenario is carried out with respect to the baseline period.

2.9. Combined flood and drought hazards

The hazard score was calculated by combining the previous normalized flood and drought hazard maps using the ArcMap 10.6.1 mosaic to the new raster tool. As illustrated in Figure 6, each square represents a different level of hazard whether this be a single hazard (flood or drought) or a combined hazard (flood and drought), where the drought hazard was on the y -axis and the flood hazard was on the x -axis. The hazard level was determined based on these categories and given a colour code. Combined hazard maps were created for the baseline period, the CMIP6 models and a multi-model ensemble defined as the average of the chosen eight models in Table 2.

3. RESULTS AND DISCUSSION

3.1. Current and future flood hazard

There is a limited spatial variation in the locations of the flood hazard within the basin between the baseline period and future hazard (Figure 7) with CNRM-CM6-1, EC-Earth3P and HadGEM3-GC31-MM having the greatest resemblance to the multi-model ensemble. Overall, there is a low/very low flood hazard seen in the west (Nakhon Ratchasima) of the catchment and in the very south locations associated with increased elevations and degree of the slope level. Main areas of 'very high' to high flood hazards are seen in the east (Si Sa Ket) and north-eastern areas (Roi Et and Maha Sarakham), locations where elevations are the lowest, the slope is the steepest, and the distance from the river tributaries is smaller. It is well documented that an increase in the elevation reduces flooding propensity (Khalequzzaman 1994), whereas the slope influences the direction of and amount of surface runoff or subsurface drainage, having a dominant effect on the contribution of rainfall to stream flow. Consequently, steeper slopes are more susceptible to surface runoff, while flat terrains are susceptible to water logging (Ouma & Tateishi 2014).

For the near-future period, the majority of climate models suggest the increased 'very high' flood hazard area compared to the observed period with 11% classified as 'high' flood hazard (Figures 7 and 8). In particular, climate models HadGEM3-GC31-LL (19%) and HadGEM3-GC31-HH (17%) predicted the greatest increase in the 'very high' flood hazard area, whereas HadGEM3-GC31-HM (9%) predicted the least and less than the observed period. Areas of 'high' and 'medium' hazards have also increased, but this is less extreme varying from 22 to 24% and 26 to 28%, respectively, for the near-future period compared to the 22 and 27% for the observed period (Figure 8). Flood hazard increases are observed in the east of the basin especially in Rio Et and Si Sa Ket, correlating to areas where increasing rainfall was observed and along Mun tributaries within Nakhon Ratchasima and Buri Ram. This concurs with findings from Khadka *et al.* (2021) that the magnitude of extreme rainfall will increase in the future within all models except HadGem3-GC31-HM. In addition, areas of very low hazard and low flood hazard have decrease in the future compared to the observed period (18%), and especially for climate models HadGEM3-GC31-LL (11%) and HadGEM3-GC31-HH (12%), locations for this decrease in the flood hazard are observed in the south catchments Buri Ram and Surin (Figures 7 and 8).

While the higher resolution version of CNRM-CM6-1-HR shows a reduced flood hazard (Figure 8) compared to the multi-model ensemble, both models agreed that the flood hazard will increase in the basin. This corresponds to where the projected increase in the rainfall is 10%. The results from the two models from EC-Earth Consortium are dissimilar, with Earth3P-HR

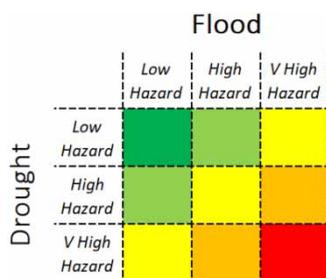


Figure 6 | Combined hazard matrix for flood and drought.

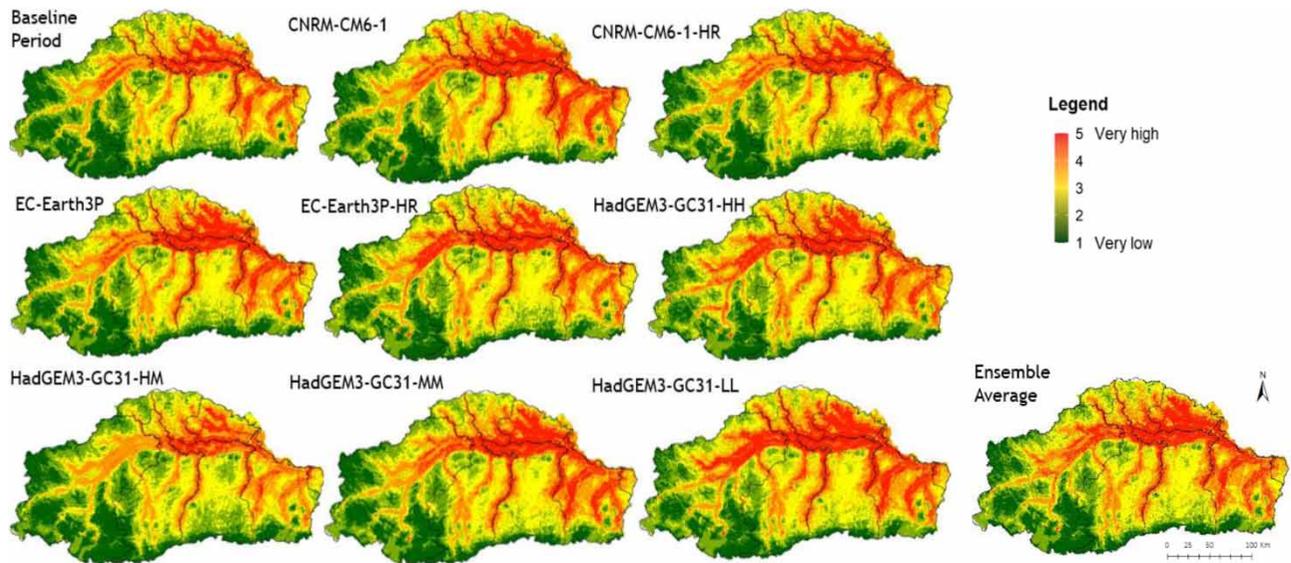


Figure 7 | Flood hazard map of the Mun River basin for the baseline period (1981–2010) and near-future period (2021–2050) using eight climate models and their ensemble. Hazards are classified into five classes: very low (1), low (2), medium (3), high (4), and very high (5).

finding an increase in the ‘very high’ flood hazard area in Nakhon Ratchasima compared to EC-Earth3P. Nevertheless, percentage-wise (Figure 8) the two models have similar results, although the high-resolution version of the model does find a slight increase in the % area covered by ‘very high’, ‘medium’ and ‘low’ flood hazards (Figure 8).

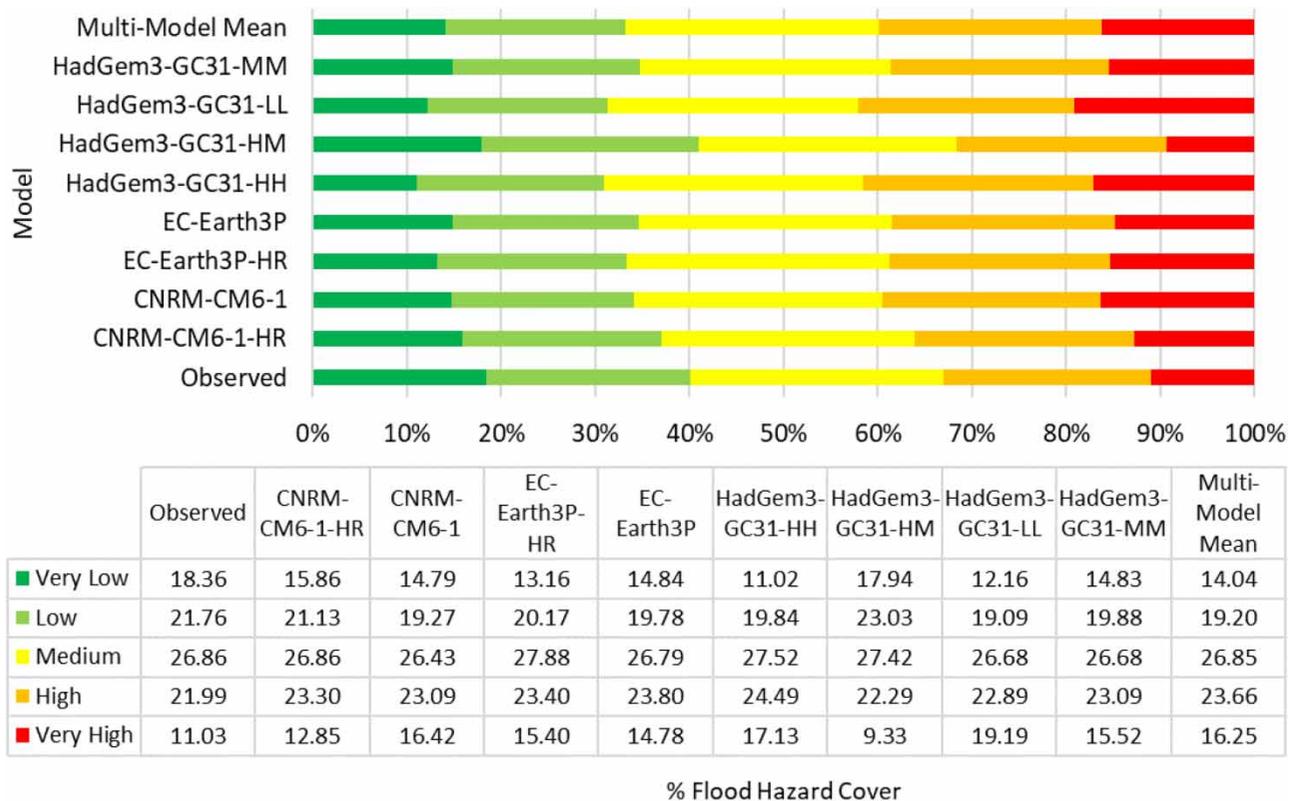


Figure 8 | Percentage area (%) under different hazard levels for the observed period (1981–2010) and near-future period (2021–2050) using eight climate models and their ensemble.

3.2. Current and future drought hazard

Drought hazard maps of the study area are created for the baseline period (1981–2010) as well as for the near-future period (2021–2050) using the multi-variate approach are shown in (Figure 9). While the results on drought hazard only are presented here, the detailed analyses of the observed droughts are discussed in a study by Khadka *et al.* (2021).

There is a significant variation in the drought hazard level within the basin during the baseline period [Figure 9(a)]. Nakhon Ratchasima (western part) has the higher area under the ‘very high’ hazard category, while Nakhon Ratchasima, Si Sa Ket (eastern part) and Roi Et (north-eastern part) have a significant area under the ‘high’ drought hazard category. Buriram, Surin and Maha Sarakham provinces have a relatively ‘low’ drought hazard in the basin. Overall, it can be observed that the drought hazard in the basin is irrespective of the annual rainfall received by the area. For example, Si Sa Ket receives the highest annual rainfall, but a significant area is under ‘high’ and ‘very high’ drought hazard levels. Drought characteristics and, hence, drought hazards are more affected by the temporal variability of the climatic parameters.

For the near-future period, most of the climate models (except CNRM-CM6-1-HR and HadGEM3-GC31-LL) have consensus that the ‘high’ and ‘very high’ hazards area will significantly increase and mostly concentrate on the western part of the basin. The multi-model ensemble also indicates the dire scenario where hazard levels have increased significantly throughout the basin. Table 5 shows that the area under high and ‘very high’ drought hazard levels will increase from 27 and 4% during the baseline period to 43 and 37% during the near-future period (multi-model ensemble average), respectively. All of the climate models (except CNRM-CM6-1-HR) suggest that the area with ‘low’ and ‘very low’ drought hazards will decrease in the near-future. High-resolution version of climate models from Met Office Hadley Centre (MOHC) and EC-Earth Consortium projected a significant increase in the area with a ‘very high’ drought hazard level, while the model from CNRM projected least increase. Spatially, the high-resolution version of the model from CNRM shows a reduced hazard in the eastern part of the basin (where the projected increase in the annual rainfall is 10%); both versions agree that the drought hazard will increase in the western part. The results from two models from EC-Earth Consortium are similar, even though the low-resolution version shows a low hazard in the south-east part. Except the low-resolution version of the model from the MOHC, three models project a considerable increase in the drought hazard in the basin.

Under a climate change scenario, future droughts are projected to be longer (increase of 22%) and severe (increase of 63%), while the joint occurrence probability of the drought event, which exceeds the 10-year return period threshold of duration and severity, is also projected to increase by 37% (Khadka *et al.* 2022). These are mainly driven by an increase in evapotranspiration (by approximately 5%) and higher temporal variability of the rainfall (increase by approximately 35%). Consequently, areas under ‘high’ and very high drought hazards are projected to increase in the basin. The results concur with the findings

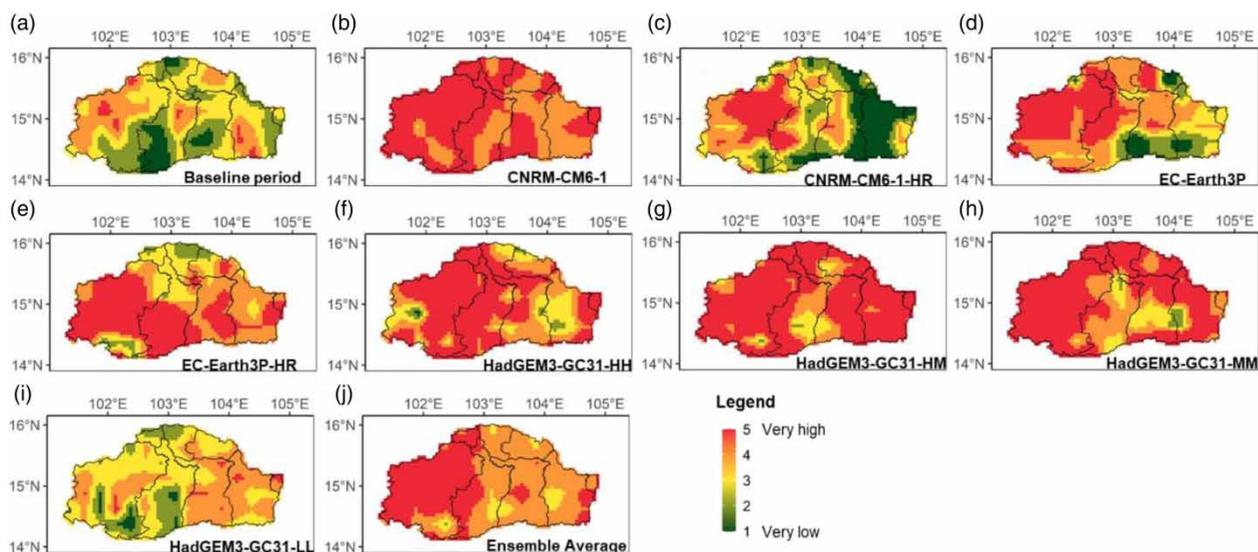


Figure 9 | Drought hazard map of the Mun River basin for the baseline period (1981–2010) and near-future period (2021–2050) using eight climate models and their ensemble. Hazards are classified into five classes: very low (1), low (2), medium (3), high (4), and very high (5).

Table 5 | Projected area of the Mun River basin (in %) under different drought hazard levels during observed and near-future period

Hazard level		Very low	Low	Medium	High	Very high
Area under different hazard levels (%)	Observed period	8	26	36	27	4
	Near-future period (2021–2050)					
	CNRM-CM6-1-HR	23	15	17	11	34
	CNRM-CM6-1	0	17	17	8	57
	EC-Earth3P-HR	0	1	11	18	70
	EC-Earth3P	6	9	12	18	55
	HadGem3-GC31-HH	0	2	9	20	68
	HadGem3-GC31-HM	0	0	4	17	79
	HadGem3-GC31-LL	0	2	35	41	22
	HadGem3-GC31-MM	3	14	32	30	21
	Ensemble average	0	2	18	43	37

by Khadka *et al.* (2022), which shows that the increase in the magnitude of the extreme events will be much higher than the increase in the average climate.

3.3. Current and future combined hazards

Floods and droughts are the two major natural hazards that create significant impacts on people lives and their well-being; it is already well established that the Mun River basin suffers from both at different periods (Prabnakorn 2020). Single hazard areas from the observed period to the near-future decrease dramatically and increase depending on the climate model (Figure 10), decreasing from 40% for the observed to 4% for the multi-model ensemble. Furthermore, areas classified as a low combined hazard have also decreased from 30% of the catchment to 20% of the catchment for the observed and ensemble mean, respectively. However, more harrowing findings are that areas of the combined hazard of medium and above have increased significantly, especially for ‘medium’ and ‘high’ rising from 20 and 9% to 51 and 20% for the observed period and multi-model ensemble, respectively. Overall, this means that over 75% (76%) of that catchment will be covered by combined hazards from ‘medium’ to ‘very high’ hazard levels compared to the 30% in the observed period. This is a percentage increase in the area of 155%.

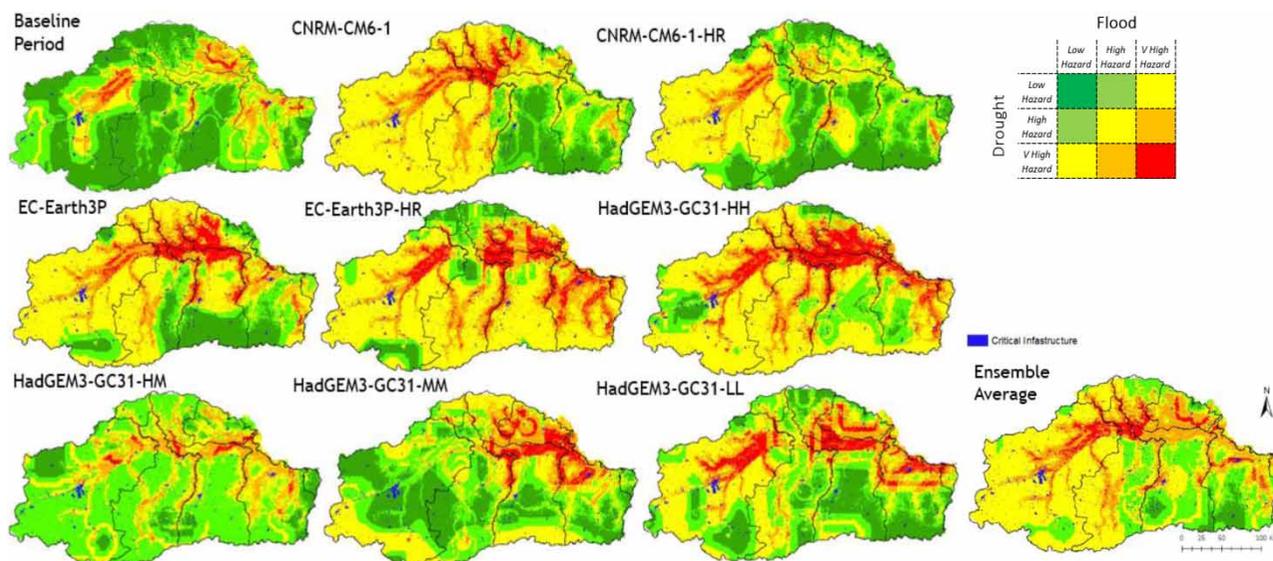


Figure 10 | Combined flood and drought hazard maps of the Mun River basin for the baseline period (1981–2010) and near-future period (2021–2050) using eight climate models and their ensemble. Hazard maps also display locations of the critical infrastructure identified as cities, communications, utilities, and industrial and institutional lands by the Land Development Department of Thailand for the years 2016–2017.

Results found that in the near-future period, ‘very high’ combined hazards will be located in Nakhon Ratchasima and in the north provinces of Rio Et, Khon Kean and Maha Sarakham. The greatest ‘very high’ and ‘high’ combined hazard is seen in HadGEM3-GC31-HH (13% + 20%) and the two models from EC-Earth Consortium: Earth3P-HR (10 and 21%) and Earth3P (8 and 18%) (Figures 10 and 11). Generally, the combined hazards will be worst in the west (Nakhon Ratchasima), and this is the area where drought hazards increase (Figure 9); however, HadGem3-GC31-HM and HadGem3-GC31-MM exclude this reasoning finding hazard reduced in the west compared to the observed period. The models HadGem3-GC31-HM and CNRM-CM6-1-HR display the least increase in the combined hazard area and actually found a decrease in the ‘very high’ combined hazard (1.2 and 1.3% areas, respectively) compared to that observed at 1.4% (Figure 11). Areas of ‘very high’ combined hazards are in locations that follow the river route or are in close proximity to the river, where flood hazards were observed (Figures 1 and 10). Compared to the baseline period, the near-future multi-model ensemble finds an increase in the overall hazard across the catchment of at least one level (Figure 11); this is most prominent in the west – Nakhon Ratchasima and Buri Ram, and north-eastern provinces – Khon Kean, Roi Et and Maha Sarakham (Figure 10). On the other hand, Si Sa Ket finds a similar combined hazard to the baseline period.

Although we present how agriculture faces multiple challenges in terms of floods and droughts, we also want to point challenges for the critical infrastructure (CI) (Kumar *et al.* 2021a). The IPCC states that climate change unequivocally impacts various aspects of the built environment: transport, energy, water/wastewater and communications (Hawchar *et al.* 2020). Therefore, we argue that it is also essential to gain an understanding of CI vulnerability to climate-related threats (current and future), in order to develop effective strategies to enhance the resilience of CI (Hawchar *et al.* 2020; Schipper 2020). Floods and droughts can cause both direct (direct damage to physical infrastructure) and indirect effects (hindering supply chains and raw material production) (Kumar *et al.* 2021a). The current CI within the Mun River basin for the baseline period is situated in ‘high’ multi-hazardous areas, for example, Nakhon Ratchasima, Surin and Si Sa Ket (Figure 10). It is likely in the future with land use changes, CI development (cities, communications, utilities, and industrial and institutional lands) will increase across the catchment (Penny *et al.* 2021). Steps towards mitigating hydro-meteorological hazards could

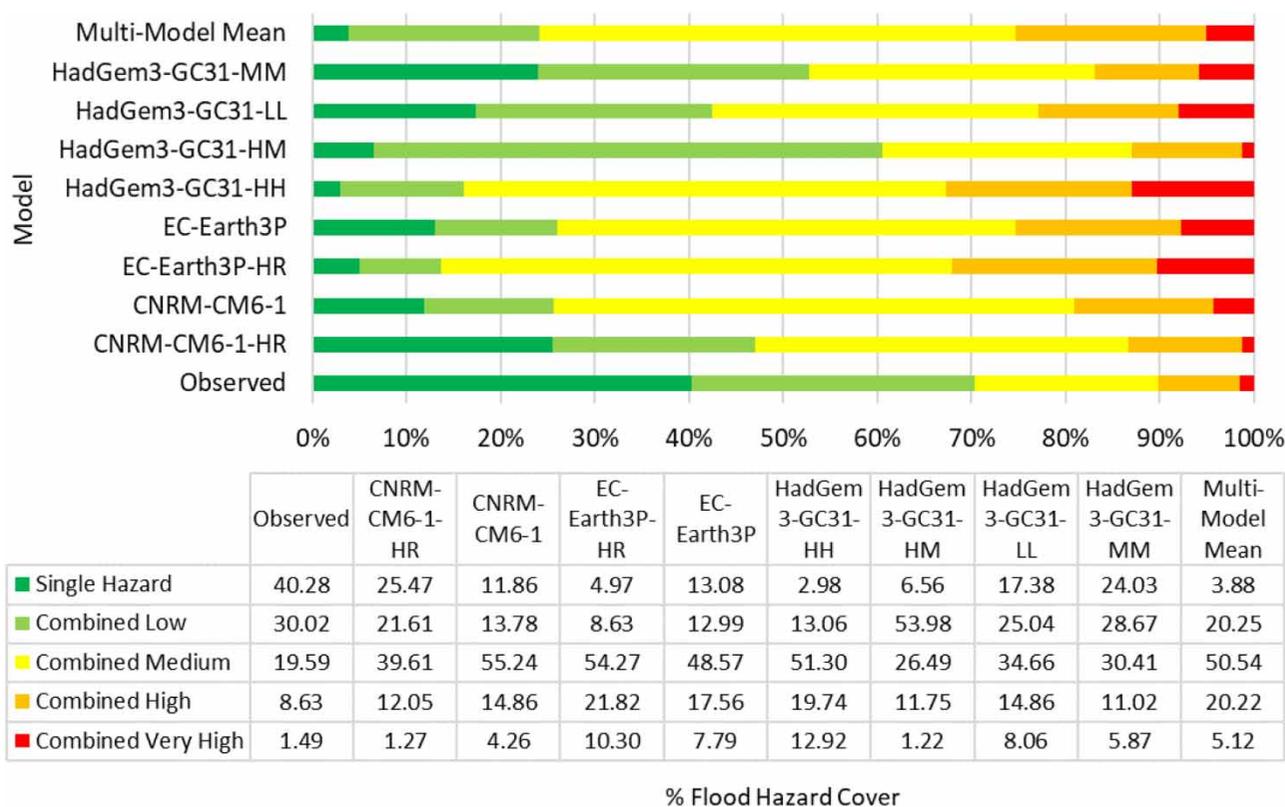


Figure 11 | Percentage combined hazard cover for flood and drought hazard maps of the Mun River basin for the observed period (1981–2010) and near-future period (2021–2050) using eight climate models and the multi-ensemble mean.

include nature-based solutions (Majidi *et al.* 2019; Kumar *et al.* 2021b; Vojinovic *et al.* 2021). A study by Penny *et al.* (2023) provides an extension of this research, which looks into NBS for the Mun River basin. Nevertheless, caution must be taken as though adaptation to climate change is necessary, if adaptation strategies fail, this can worsen situations, leading to maladaptation (Schipper 2020).

4. RECOMMENDATIONS AND FUTURE STUDY

We recommend that a future study may also consider (i) using additional indices, (ii) different weights' allocation for the hazard indexes, and (iii) other methods such as NDVI and LSWI, or (iv) investigating the role of antecedent rainfall and soil moisture conditions (Ávila 2015; Navarathinam *et al.* 2015) in flood hazards. Currently, the present work only considers physiographic variables at a certain point, focusing more on local flooding. However, we also see that the work could be improved by including variables that affect the flood hazard originating from upstream, localized flooding, i.e., flood waters that occur upstream of the catchment but, in fact, affect the flood hazard within the catchment area, for example, stream flow. For this, we recommend to consider studies that have included flow accumulation within their MCDA-GIS methodologies for assessing flood hazard and/or risk, including Nandi *et al.* 2016; Ozkan & Tarhan 2016; Kabenge *et al.* 2017; Dash & Sar 2020; Dung *et al.* 2022; and Baykal *et al.* 2023. In addition to the above, the work could be taken further by using a hydrologic-hydrodynamic model and or 'Bluespot' analysis (Balstrøm 2022; Penny *et al.* 2023).

We acknowledge that this study could be enhanced by using methodologies such as Saaty AHP and ANP (de Brito *et al.* 2018), and rather than using equal weights (used in this study), individual weighting or proportional scoring for MCDA-GIS variables should be used. Nevertheless, when compared to outcomes from other researchers, Khadka *et al.* (2021, 2022) and Prabnakorn (2020), both flood and drought are in agreement with similar studies/forecasts carried out in the Mun River basin. This consolidates/validates the methodology used here.

Formulation and implementation of necessary drought and flood adaptation plans in the basin has paramount importance in making the society more resilient. Provision of high efficiency irrigation systems by the integrative use of surface and groundwater resources could be a major step to combat the negative impacts of droughts in the near-future. Combining temporary storage solutions for excess flood waters in the open fields and increasing swamp/wetland areas could help store flood waters and recharge groundwater aquifers, in turn, combating drought.

5. CONCLUSION

The study has assessed individual and joint hazard levels of floods and droughts in the Mun River basin, Thailand, for baseline (1981–2010) and the near-future period (2021–2050). The flood hazard is computed using six physiographic and climatic factors. The method used for the flood hazard is useful for data-scarce regions, particularly when hydrologic and hydraulic modelling is not available and when rapid assessment is required. Similarly, the spatial drought hazard was assessed using the multi-variate approach that combines three drought characteristics (duration, severity and frequency). A joint hazard map is created by combining the information of drought and flood hazards.

Overall, there is a limited variation in the locations of flood hazard; however, between the baseline and near-future period, the majority of climate models suggest an increase in the 'high' and 'very high' flood areas. The area under 'high' and 'very high' flood hazard levels increases from 11 and 22% during the baseline period (1981–2010) to 16 and 24% during the near-future period (2021–2050), respectively. Flood hazard increases are observed in lower elevations in the east of the basin especially in Roi Et and Si Sa Ket, correlating to areas where increased extreme rainfall is predicted and along Mun River and its tributaries within Nakhon Ratchasima and Buri Ram.

Drought hazard during the baseline period shows an uneven spatial distribution within the basin. While majority of Nakhon Ratchasima and Si Sa Ket have the 'high' drought hazard, Buriram, Surin and Maha Sarakham have low levels, not following the average rainfall trends, which decrease from east towards west. This shows that the drought hazards are more defined by the temporal variability of the climatic parameter (particularly rainfall) than the spatial variability. Results clearly show that the drought hazard levels as well as their spatial extents will increase in the near-future period. The ensemble of climate models suggests that area under 'high' and 'very high' drought hazard levels will increase from 27 and 4% during the baseline period (1981–2010) to 43 and 37% during the near-future period (2021–2050), respectively.

When combining flood and drought hazards together, compared to the baseline period, the multi-model ensemble finds an increased area of 155% in the overall hazard across the catchment, this is most prominent in the west – Nakhon Ratchasima

and Buri Ram, and north-eastern provinces – Khon Kean, Roi Et and Maha Sarakham. In addition, the CI in the basin, particularly situated in Nakhon Ratchasima, Surin and Si Sa Ket, is also at risk from hydro-meteorological hazards. Thus, adaptation for multi-hazard within multiland uses, potentially in the form of NBS, is needed across the catchment not just for the primarily agricultural regions but for areas where the CI is located. Findings present a grim outlook on future floods and droughts in the basin, and this is particularly important as the majority of the population and land area are tied to agriculture, which at present are mostly rainfed cultivation systems. Thus, the results show that the agriculture sector in the basin is highly vulnerable.

To summarize, our research delivers an integrated assessment of flood and drought hazards within the Mun River basin, providing an important step in mitigating risks in multi-hazard environments, the results of which can be employed to test scenarios of measures to reduce the impacts of drought and flooding, and the purpose of which can not only improve predictions but also help inform decision-making. We have reaffirmed that multi-criteria analysis in the GIS environment can be extremely useful in real-world water-related applications.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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