

REMOTE SENSING-BASED ASSESSMENT OF HYDRO-CLIMATIC AND LAND USE CHANGES IN THE KOK RIVER BASIN, NORTHERN THAILAND

ÉVALUATION PAR TÉLÉDÉTECTION DES CHANGEMENTS HYDROCLIMATIQUES ET DES USAGES DES SOLS DANS LE BASSIN VERSANT DE KOK, AU NORD DE LA THAÏLANDE

Kaprom C.^{1,2,3}, Suiadee W.^{2,3}, Prechawit C.^{2,3}, Maneephai S.^{2,3}, Kowsuvon N.^{2,3,4},
Suepsahakarn R.^{2,3}, Maekan E.^{1,3}, Saelo W.³, Noicharoen T.³, Kosinyawong R.³, Siyanan S.³,
Williams J.¹, Sriwongsitanon N.^{1,2,4,*}

ABSTRACT

Thailand is increasingly affected by climate change and land use change, which have significantly altered hydrological processes and increased environmental and disaster risks. The Kok River Basin, a transboundary watershed along the Thailand–Myanmar border, has experienced growing climate variability and environmental pressures.

This study analyzes spatiotemporal changes in the basin during 1994–2024 by integrating remote sensing data with in-situ observations and applying trend analysis using the Mann–Kendall (MK) test and Sen's slope (SS) estimator. The analysis covers four sub-basins (Sai, Ruak, Kham, and Kok) and key variables including rainfall, streamflow, water quality, land surface temperature (LST), land use change, and fire occurrence.

The results indicate a statistically significant increasing trend in land surface temperature, with an overall rise of approximately 0.57–1.05 °C. Land use change analysis shows urban expansion of up to 25%, while agricultural land decreased by 17.9–28.3%, partly due to land conversion, abandonment, and degradation into degraded forest areas. Fire hotspot analysis reveals a slight overall decrease of approximately 2% in annual averages; however, increases are observed in forested (4.9%) and urban (26.7%) areas, indicating shifting fire risk patterns. Rainfall variability has increased, particularly over the last decade, with more frequent extreme wet and dry events based on the Standardized Precipitation Index (SPI). Monthly trend analysis shows a significant decrease in rainfall during May in both the Sai and Ruak sub-basins, suggesting a delayed onset of the rainy season.

The Ruak sub-basin also exhibits decreasing rainfall in July and March, indicating intra-seasonal dry spells and reduced off-season rainfall. Streamflow shows significant decreasing trends, while flood and drought events have become more frequent under increased rainfall variability. Water quality analysis indicates heavy metal contamination, particularly arsenic, with concentrations of 0.027–0.031 mg/L, exceeding national standards and likely associated with upstream mining activities. Overall, the integration of remote sensing and field-based data demonstrates strong capability for monitoring long-term spatiotemporal environmental changes in complex transboundary basins. The findings provide important scientific evidence to support water resources management, disaster risk reduction, and climate change adaptation planning.

¹ Remote Sensing Research Centre for Water Resources Management (SENSWAT), Water Resources Engineering, Faculty of Engineering, Kasetsart University, Bangkok, Thailand

² Thai National Committee on Irrigation and Drainage (THAICID), Bangkok, Thailand

³ Royal Irrigation Department (RID), Bangkok, Thailand

⁴ Asian Regional Working Group (ASRWG), International Commission on Irrigation and Drainage (ICID)

* Corresponding author : fengnns@ku.ac.th

Keywords: Remote sensing; Hydro-climatic variability; Land use and land cover (LULC) change; Climate change; Standardized Precipitation Index (SPI); Mann–Kendall (MK) trend test; Sen's slope (SS) estimator; Kok River Basin.

RESUME

La Thaïlande est de plus en plus touchée par le changement climatique et l'évolution des usages de sol, phénomènes qui ont considérablement modifié les processus hydrologiques et augmenté les risques environnementaux et de catastrophes. Le bassin versant de Kok, un bassin versant transfrontalier, situé le long de la frontière entre la Thaïlande et le Myanmar, connaît une variabilité climatique croissante et subit des pressions environnementales. Cette étude analyse les changements spatio-temporels survenus dans le bassin entre la période 1994–2024 en intégrant les données de télédétection aux observations in situ et en appliquant une analyse des tendances à l'aide du Test de Mann-Kendall (MK) et l'estimateur de la pente de Sen (SS). L'analyse couvre quatre sous-bassins (Sai, Ruak, Kham et Kok) et des variables clés telles que les précipitations, le débit, la qualité de l'eau, la température de surface terrestre (LST), le changement d'usage des sols et la fréquence d'incendies.

Les résultats indiquent une tendance à l'augmentation statistiquement significative de la température de la surface des sols, avec une hausse globale d'environ 0,57–1,05 °C. L'analyse du changement d'usage des sols montre une expansion urbaine allant jusqu'à 25%, tandis que les terres agricoles ont diminué de 17,9–28,3%, en partie en raison de la conversion des terres, l'abandon et la dégradation des zones forestières dégradées. L'analyse des points chauds d'incendie révèle une légère diminution globale d'environ 2% des moyennes annuelles; cependant, des augmentations sont observées dans les zones forestières (4,9%) et urbaines (26,7%), ce qui indique des tendances changeantes en matière de risque d'incendie. La variabilité des précipitations a augmenté, en particulier au cours de la dernière décennie, avec une fréquence accrue des événements extrêmes humides et secs selon l'indice de précipitations normalisé (SPI). L'analyse des tendances mensuelles montre une diminution significative des précipitations en mai dans les sous-bassins de Sai et de Ruak, ce qui suggère un début tardif de la saison des pluies.

Le sous-bassin de Ruak constate également une baisse des précipitations en juillet et mars, indiquant des périodes sèches intra-saisonnières et une réduction des précipitations hors saison. Le débit des cours d'eau montre des tendances significatives à la baisse, tandis que les inondations et les sécheresses sont devenues plus fréquentes en raison de la variabilité accrue des précipitations. L'analyse de la qualité de l'eau indique une contamination par des métaux lourds, en particulier l'arsenic, avec des concentrations de 0,027–0,031 mg/L, dépassant les normes nationales et probablement associées aux activités minières en amont. Dans l'ensemble, l'intégration de la télédétection et des données recueillies sur le terrain montre qu'il est possible de suivre les changements environnementaux spatiotemporels à long terme dans les bassins transfrontaliers complexes. Les résultats fournissent des preuves scientifiques importantes pour soutenir la gestion des ressources en eau, la réduction des risques de catastrophes et la planification de l'adaptation au changement climatique.

Mots-clés : Télédétection; Variabilité hydro-climatique; Changements de l'usage des sols/de la couverture terrestre (LULC); Changement climatique; Indice de précipitation normalisé (SPI); Test de tendance de Mann-Kendall (MK); Estimateur de la pente de Sen (SS); Bassin versant de Kok.

1. INTRODUCTION

Climate change and land use change have become major drivers affecting hydrological processes and environmental conditions worldwide. In Southeast Asia, increasing temperatures and greater rainfall variability have led to more frequent and severe extreme events, including floods and droughts (IPCC, 2021; Hirabayashi et al., 2013). These changes directly influence watershed dynamics, ecosystem functions, and water security, creating significant challenges for sustainable water resources management. Transboundary river basins are particularly vulnerable to such changes because environmental and hydrological conditions in upstream areas can directly affect downstream regions

across national boundaries (Zeitoun & Warner, 2006). As a result, understanding the interactions among climate variability, land use change, hydrological responses, and environmental conditions is essential for supporting effective watershed management and disaster risk reduction. The Kok River Basin, located in northern Thailand and originating in Myanmar, is one of the important transboundary river basins in the Mekong region. In recent years, the basin has experienced increasing environmental pressures, including floods, droughts, forest fires, water quality degradation, and rapid land use changes. These challenges are believed to be associated with both climate change and human-induced activities occurring within the watershed. Therefore, comprehensive assessments are needed to better understand the magnitude and direction of environmental changes occurring throughout the basin.

Remote sensing technology has become an important tool for monitoring environmental changes across spatial and temporal scales. Satellite-based products provide continuous observations over large areas and are particularly useful in regions where ground-based observations are limited. Products such as MODIS and CHIRPS have been widely applied to investigate key environmental variables, including land surface temperature (LST), land use and land cover (LULC), active fires, and rainfall distribution patterns (Didan, 2015; Funk et al., 2015). Moreover, integrating remote sensing products with field observations can improve the reliability and effectiveness of watershed-scale assessments (Wulder et al., 2018). Although numerous studies have investigated climate and environmental changes, most have focused on individual variables such as rainfall, temperature, land use, or hydrological conditions. Integrated studies that simultaneously assess multiple environmental indicators remain limited, particularly in transboundary river basins where environmental processes are highly interconnected. A comprehensive assessment framework is therefore required to better understand the relationships among climate change, land use change, hydrological processes, and environmental degradation.

This study aims to analyze spatial and temporal changes in the Kok River Basin through the integration of remote sensing products and field observations. The assessment focuses on four major sub-basins, namely the Sai, Ruak, Kham, and Kok sub-basins, and incorporates seven key indicators: rainfall, streamflow, land surface temperature, land use change, flood occurrence, forest fires, and water quality.

Long-term trends and rates of change were evaluated using the Mann–Kendall trend test and Sen's slope estimator. By integrating multiple environmental and hydrological variables within a single analytical framework, this study provides a comprehensive understanding of watershed dynamics under changing climatic and environmental conditions. The findings are expected to support sustainable water resources management, disaster risk reduction, and climate adaptation strategies in the Kok River Basin and other transboundary watersheds.

2. STUDY AREA

The Kok River Basin is located in northern Thailand, covering a large portion of Chiang Rai Province, with its headwaters originating in the Republic of the Union of Myanmar. It is an important transboundary river basin that plays a significant role in regional water resources. The basin is characterized by mountainous terrain in the upstream areas and lowland plains in the downstream areas before the Kok River eventually flows into the Mekong River. This study focuses on four major sub-basins, namely the Sai, Ruak, Kham, and Kok sub-basins, as shown in **Figure 1**. The Sai and Ruak sub-basins originate in Myanmar and flow into Thailand, making these areas particularly sensitive to land use changes and human activities occurring in upstream transboundary regions. In contrast, the Kham and Kok sub-basins are located primarily within Thailand, although they are still influenced by upstream watershed conditions.

The study area is strongly influenced by the tropical monsoon climate, resulting in pronounced rainfall variability throughout the year. Combined with the steep topography of the upstream mountainous regions, these conditions make the Kok River Basin highly vulnerable to both floods and droughts. In addition, water quality issues have become an increasing concern, particularly those associated with land use changes and human activities in the upstream areas along the Thailand–Myanmar border.

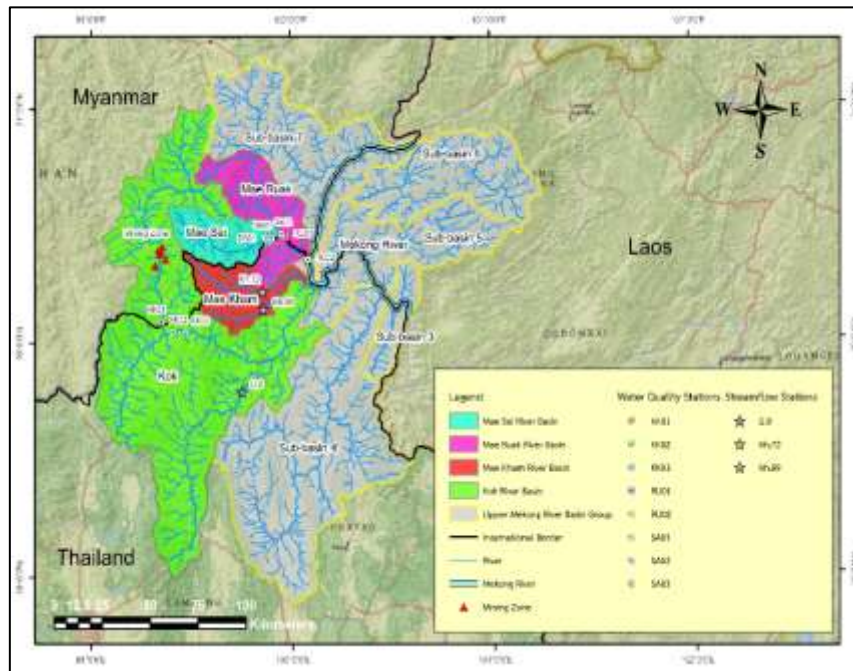


Figure 1. Study area

3. METHODOLOGY

3.1 Data collection

This study utilized multiple datasets to analyze spatial and temporal changes within the Kok River Basin. Six key variables were considered, including rainfall, temperature, streamflow, water quality, land use, and Active fires, representing major hydrological, climatic, and environmental components of the watershed. The analysis was based on the integration of two primary data sources: (1) ground-based observations, including streamflow and water quality measurements, which provide high temporal accuracy and long-term monitoring records; and (2) remote sensing products, including land surface temperature, land use and land cover, rainfall, and active fire occurrences, which offer extensive spatial coverage and enable monitoring of remote and inaccessible areas. The integration of these complementary datasets enhances both the spatial representativeness and reliability of watershed-scale assessments. Since the datasets differ in observation periods, temporal coverage, and spatial resolution, appropriate time periods were selected to ensure consistency in trend analysis. A summary of the datasets used in this study, including the analyzed variables, data sources, study periods, and temporal and spatial resolutions, is presented in **Table 1**.

Table 1. Summary of datasets used for spatial and temporal change analysis in the Kok River Basin

Variable	Dataset	Period	Temporal Resolution	Spatial Resolution	Data Source
1) Rainfall	CHIRPS	1994–2024	Monthly	0.05°	www.chc.ucsb.edu/data/chirps
2) LST	MOD11A2	2001–2024	8-day	1 km	www.earthdata.nasa.gov
3) Streamflow	RID	1994–2023	Annual	Station	www.hydro-1.net
4) Water Quality	PCD	2024	Annual	Station	www.pcd.go.th
5) Land Use	MCD12Q1	2001–2024	Annual	500 m	www.earthdata.nasa.gov
6) Active Fire	MOD14A2	2001–2024	8-day	1 km	www.earthdata.nasa.gov

Note: RID refers to the Royal Irrigation Department, and PCD refers to the Pollution Control Department.

3.2 Standardized Precipitation Index (SPI) Analysis

The Standardized Precipitation Index (SPI) was applied to assess rainfall variability in the Kok River Basin using monthly rainfall data from 1994–2024. SPI is a widely used indicator for monitoring drought and wetness conditions in meteorological and hydrological studies (McKee et al., 1993). The index is calculated by transforming accumulated precipitation over a selected time scale into standardized values, allowing precipitation anomalies to be compared across different periods and locations. One advantage of SPI is its applicability to multiple time scales, making it suitable for evaluating both short-term and long-term climate variability (Guttman, 1999; Hayes et al., 1999). In this study, SPI was used to analyze the frequency of wet and dry events and to identify long-term changes in rainfall conditions within the basin. The classification of drought and wetness severity followed the criteria proposed by McKee et al. (1993)

3.3 Trend Analysis

Long-term trends in hydrological and environmental variables were evaluated using the Mann–Kendall (MK) trend test and Sen's slope (SS) estimator. The MK test is a widely used non-parametric statistical method for detecting the presence and direction of monotonic trends in time-series data, while Sen's slope provides an estimate of the magnitude of change over time (Mann, 1945; Kendall, 1975; Sen, 1968). These methods are particularly suitable for environmental datasets because they do not require a normal data distribution and are less sensitive to outliers. In this study, the MK test was used to determine the statistical significance of increasing or decreasing trends, whereas Sen's slope was applied to quantify the rate of change. The combined use of these methods enables a comprehensive assessment of both the direction and magnitude of long-term environmental changes.

3.3.1 Mann–Kendall Trend Test (MK)

The Mann–Kendall trend test (MK) is a widely used non-parametric statistical method for detecting trends in time-series data, particularly in hydrological and environmental studies (Kaprom et al., 2025). One of its main advantages is that it does not require the data to follow a normal distribution and is relatively insensitive to outliers (Mann, 1945; Kendall, 1975). The MK test is used to determine whether a statistically significant increasing or decreasing trend exists in a dataset by evaluating the relative ordering of observations over time. If later observations tend to be consistently greater than earlier observations, an increasing trend is indicated; conversely, a decreasing trend is identified when later observations tend to be lower than earlier observations. The Mann–Kendall test statistic (S) is calculated as **equation (1)**.

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (1)$$

where x_j and x_k represent observations at time periods j and k , respectively. The sign function is defined as **equation (2)**:

$$\text{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{cases} \quad (2)$$

For large sample sizes ($n > 10$), the statistic S approaches a normal distribution. The standardized test statistic Z can then be calculated as **equation (3)**:

$$Z = \begin{cases} \frac{S-1}{\sqrt{S(S+1)/n}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{S(S+1)/n}} & \text{if } S < 0 \end{cases} \quad (3)$$

where $Var(S)$ is the variance of the statistic S , which depends on the sample size and the presence of tied values within the dataset. The calculated Z -value is compared with the corresponding critical value to determine statistical significance at a specified confidence level. In this study, a significance level of 95% ($p < 0.05$) was adopted. A positive Z -value indicates an increasing trend, whereas a negative Z -value indicates a decreasing trend.

3.3.1 Sen's Slope Estimator (SS)

The Sen's slope estimator (SS) is a non-parametric statistical method used to quantify the magnitude of change in time-series data and is commonly applied together with the Mann–Kendall trend test to describe both the direction and rate of change of a trend (Sen, 1968). The method calculates the slope between all possible pairs of observations within a time series and then determines the median of these slopes as the representative estimate of the overall trend. Because it is based on median values, the method is robust against outliers and does not require any assumptions regarding the distribution of the data. The slope between two observations is calculated as **equation (4)**.

$$Q_i = \frac{x_j - x_k}{j - k} \quad (4)$$

where x_j and x_k are the observed values at time periods j and k , respectively, and $j > k$. The Sen's slope estimate is then obtained as the median of all calculated Q_i values. The resulting Sen's slope value represents the rate of change of the variable over the study period. A positive value indicates an increasing trend, whereas a negative value indicates a decreasing trend. Larger absolute values reflect a more rapid rate of change. In this study, Sen's slope was applied in conjunction with the Mann–Kendall trend test to evaluate hydrological and environmental variables in the Kok River Basin, enabling a comprehensive assessment of both trend direction and magnitude.

4. RESULTS AND DISCUSSION

4.1 Analysis of Rainfall Changes

The analysis of rainfall changes in the Kok River Basin using monthly rainfall data from 1994–2024 revealed substantial temporal and spatial variability, particularly during the last 10–15 years, when the occurrence of extreme rainfall events increased noticeably. The results of the Standardized Precipitation Index (SPI) analysis indicate that the frequency of both wet and dry conditions has increased in recent years, reflecting greater climate variability. In particular, moderate-to-severe drought events ($SPI < -1.0$) and unusually wet conditions ($SPI > 1.0$) occurred more frequently compared to earlier periods, as shown in **Figure 2**. During the most recent decade (2015–2024), the Ruak sub-basin exhibited the highest frequency of moderate-to-severe wet events, with 31 occurrences (58%), and drought events, with 28 occurrences (46%). Similar patterns were observed in the Sai sub-basin, which recorded 28 wet events (54%) and 23 drought events (43%).

The Kham sub-basin experienced 28 wet events (58%) and 20 drought events (45%), while the Kok sub-basin recorded 29 wet events (55%) and 17 drought events (53%). These findings suggest that although the annual rainfall totals may not have changed substantially, the frequency of both abnormally wet and abnormally dry conditions has increased over time, indicating a growing tendency toward climatic extremes. Spatially, the Sai and Ruak sub-basins, whose headwaters originate in mountainous areas along the Thailand–Myanmar border, exhibited greater rainfall variability than the downstream areas. This pattern is likely associated with topographic influences, particularly the orographic effect, which enhances localized rainfall formation and results in uneven rainfall distribution. Consequently, these areas are more susceptible to localized heavy rainfall events. In contrast, the Kham and lower Kok sub-basins, characterized by relatively flat terrain, showed more uniform rainfall distributions and rainfall patterns that were generally consistent with the overall basin-wide trend.

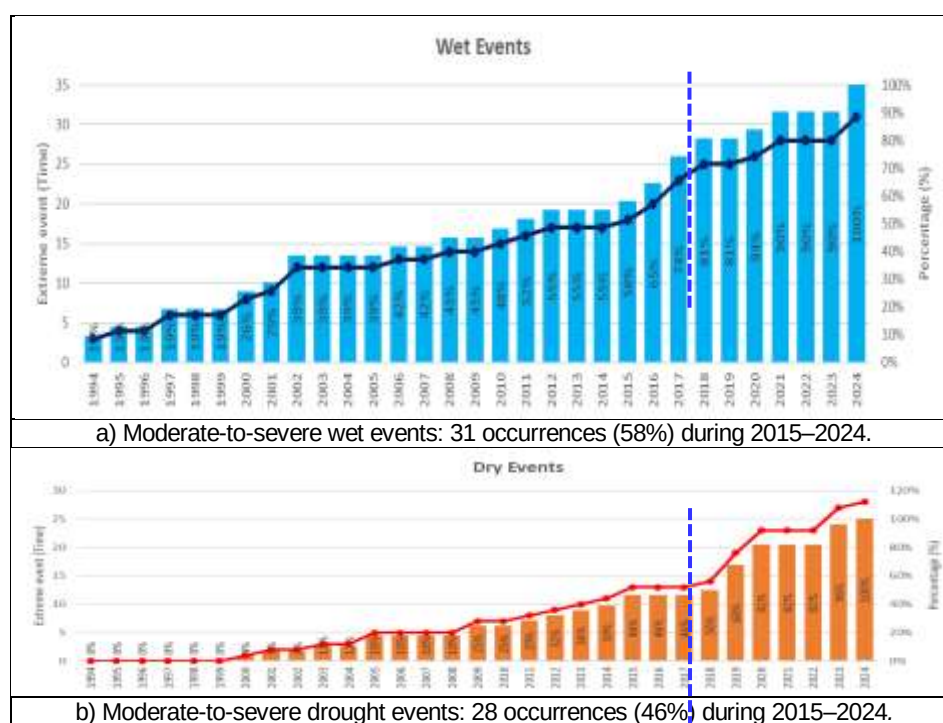


Figure 2. Cumulative frequency and percentage occurrence of moderate-to-severe wet and drought events in the Ruak Sub-basin during 1994–2024, based on the Standardized Precipitation Index (SPI).

In addition, monthly trend analysis using the Mann–Kendall (MK) test and Sen's Slope (SS) estimator, as presented in **Table 2**, revealed statistically significant decreases in rainfall during May in both the Sai and Ruak sub-basins. Since May generally marks the onset of the rainy season, this result suggests a tendency toward a delayed start of the rainy season compared with historical conditions. Furthermore, the Ruak sub-basin showed significant decreasing trends in rainfall during July, which corresponds to the middle of the rainy season, as well as in March, which falls within the late dry season. These findings indicate an increasing likelihood of mid-season dry spells and a reduction in off-season rainfall, both of which may have important implications for agricultural activities, water resources management, and future water security in the study area.

Table 2 Monthly rainfall trend analysis using the Mann–Kendall (MK) test and Sen's Slope (SS) estimator in the Kok River Basin.

Sub-Basin	Rates of change (mm/year)											
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Sai	-	▼2.8	-	-	-	-	-	-	-	-	-	-
Ruak	-	▼3.0	-	▼2.7	-	-	-	-	-	-	-	▼0.5
Kham	-	-	-	-	-	-	-	-	-	-	-	-
Kok	-	-	-	-	-	-	-	-	-	-	-	-

Note: “–” indicates no significant trend, and ▼ indicates a significant decreasing trend ($p < 0.05$). Blue and orange shading denote the rainy and dry seasons, respectively.

Overall, the results suggest that the Kok River Basin is experiencing a transition from relatively stable rainfall patterns toward a more variable climate characterized by increasingly frequent extreme events, including both excessive rainfall and prolonged dry periods. These changes are expected to directly

influence flood and drought occurrences, as well as broader hydrological processes within the basin, and may serve as key drivers of the environmental changes discussed in the following sections.

4.2 Analysis of Land Surface Temperature (LST) Changes

The analysis of Land Surface Temperature (LST) in the Kok River Basin using MODIS data during 2001–2024 revealed significant spatial and temporal changes. The trend analysis based on the Mann–Kendall (MK) test and Sen's Slope (SS) estimator, as shown in **Figure 3**, indicated statistically significant increasing trends ($p < 0.05$) in LST across all sub-basins. The estimated rates of increase ranged from approximately 0.02 to 0.05 °C/year, corresponding to a cumulative increase of about 0.57–1.05 °C over the 24-year study period. Among the sub-basins, the Sai Sub-basin exhibited the highest rate of temperature increase, which is consistent with the continuous expansion of urban areas and associated land-use changes in the region.

To further assess changes in extreme heat conditions, a Hot Threshold was calculated using the Mean+1Standard Deviation (Mean+1SD) of the 8-day LST observations over the entire study period (2001–2024). Annual frequencies of LST values exceeding this threshold were then determined for each year. The results, presented in **Table 3**, show a marked increase in the occurrence of high-temperature events during the most recent decade (2015–2024) compared with the earlier period (2001–2014). On average, the frequency of temperatures exceeding the Hot Threshold increased by approximately 40% across the basin.

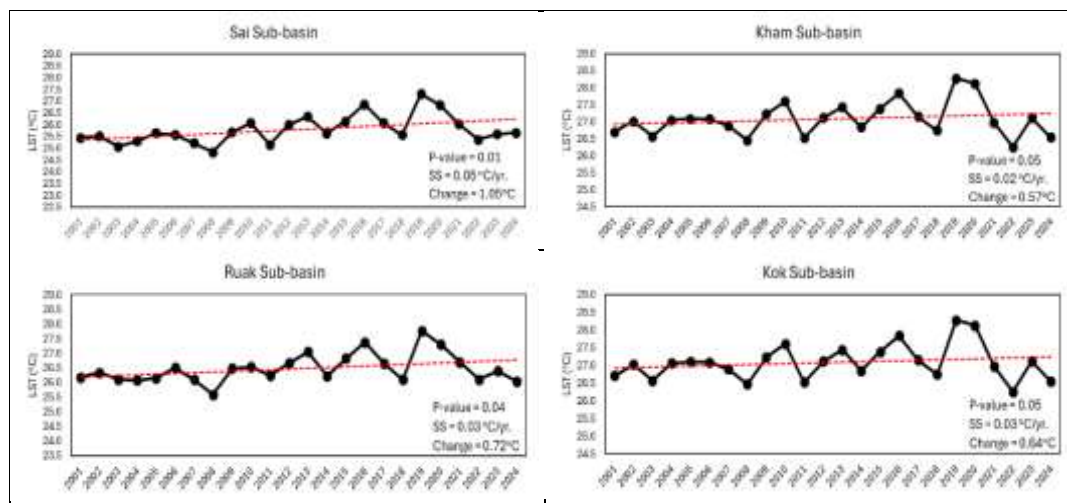


Figure 3. Spatial distribution of land surface temperature (LST) trends in the Ruak, Sai, Kham, and Kok sub-basins during 2001–2024 based on the Mann–Kendall test and Sen's Slope estimator.

Table 3. Frequency of LST exceeding the Hot Threshold during 2001–2024.

Duration	LST Hot-Threshold Exceedance (Time/Year)				
	Sai	Ruak	Kham	Kok	Average
2001-2014	2.1	1.5	1.9	6.9	3.1
2015-2024	3.3 (59%)	2.5 (67%)	2.4 (29%)	8.3 (20%)	4.1 (44%)

These findings indicate that not only has the average land surface temperature increased over time, but the occurrence of unusually high-temperature events has also become more frequent. This pattern suggests an increasing heatwave tendency within the Kok River Basin, particularly in areas experiencing rapid land-use transformation and urban development. The increasing frequency of extreme heat events may have important implications for water demand, agricultural productivity, ecosystem health, and wildfire risk, highlighting the need for adaptive management strategies under future climate change conditions.

4.3 Analysis of Streamflow Changes

The trend analysis of streamflow in the Kok River Basin was conducted using data from three key hydrological stations (G.8, Kh.72, and Kh.89) during 1994–2023. Trends were evaluated using the Mann–Kendall (MK) test and Sen's Slope (SS) estimator, as shown in **Figure 4**. The results indicate that annual runoff exhibited statistically significant decreasing trends ($p < 0.05$) at all stations, with rates of change of -17.2 , -5.5 , and -1.7 mcm/year at stations G.8, Kh.72, and Kh.89, respectively. Over the entire study period, these trends correspond to cumulative reductions of approximately -516.6 , -166.4 , and -49.5 mcm, respectively. For momentary peak discharge, a significant decreasing trend was observed only at station G.8, with a rate of change of -4.7 cms/year, equivalent to a cumulative reduction of approximately -141 cms during the study period. No statistically significant trends were detected at stations Kh.72 and Kh.89. These findings suggest a basin-wide decline in streamflow, particularly in the upper watershed, which is likely associated with changes in rainfall patterns, increasing climate variability, and land-use changes in upstream areas.

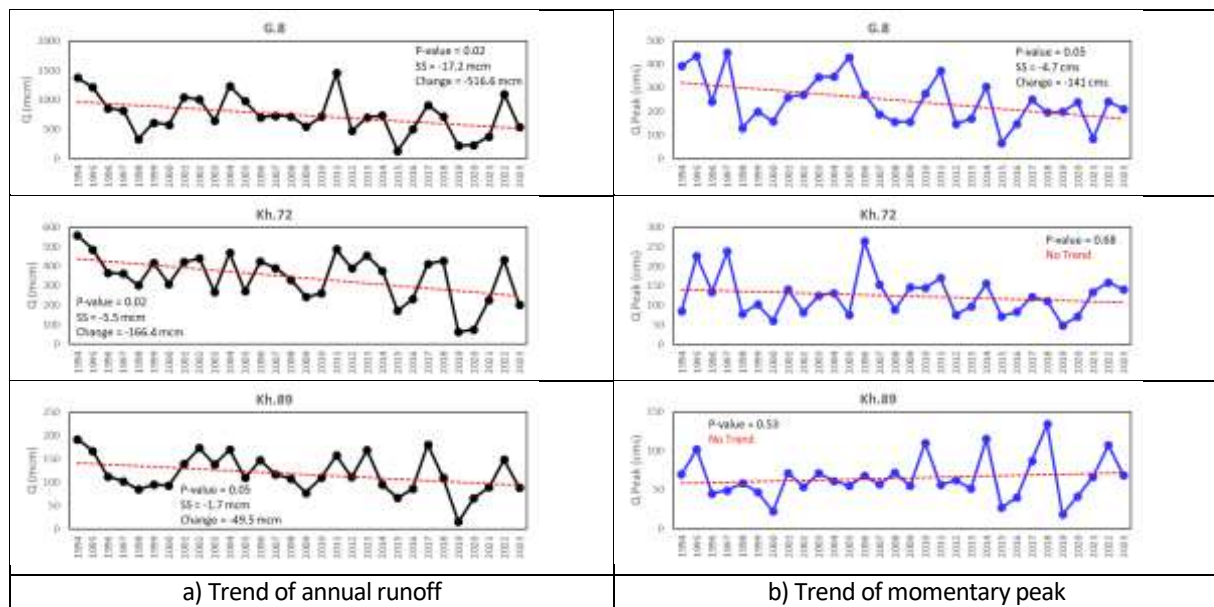


Figure 4. Trends in annual runoff and momentary peak discharge at stations G.8, Kh.72, and Kh.89 during 1994–2023, based on the Mann–Kendall and Sen's Slope tests.

4.4 Analysis of Water Quality Changes

Water quality conditions in the Kok River Basin were assessed using monitoring data collected by the Pollution Control Department (PCD) in 2024, covering the Kok, Sai, and Ruak sub-basins. The results revealed heavy metal contamination, particularly lead (Pb) and arsenic (As), at several monitoring stations. Arsenic concentrations exceeded the national water quality standard (0.01 mg/L) at multiple locations, with the highest values observed in the Sai sub-basin, ranging from approximately 0.027–0.031 mg/L, or 2.7–3.1 times above the standard limit. In addition, lead concentrations exceeded the standard threshold (0.05 mg/L) at some stations during the monitoring period, indicating increasing concerns regarding water quality in the basin. When combined with historical satellite imagery analysis (**Figure 5**), noticeable land-use changes were identified in the upstream areas along the Thailand–Myanmar border, particularly the expansion of exposed land surfaces and mining-related activities. These spatial changes are consistent with reported environmental concerns and the observed occurrence of heavy metal contamination in the study area. The findings suggest that upstream land-use changes, especially mining activities, may be associated with the elevated levels of lead and arsenic detected in the Kok River Basin. Although a direct causal relationship cannot be confirmed from this study alone, the integration of field observations and remote sensing data provides an effective

approach for monitoring water quality risks in transboundary river basins and supports future environmental management and pollution control efforts.

4.5 Analysis of Land Use Change

Land use change in the Kok River Basin was analyzed using the MCD12Q1 (IGBP) land cover product (Friedl et al., 2010) for the period 2001–2024. The original 17 land cover classes were reclassified into five major categories: forest (F), agriculture (A), water bodies (W), urban areas (U), and mixed/other land (M) to facilitate watershed-scale analysis. The reliability of the MCD12Q1 dataset was evaluated by comparison with land use data from the Land Development Department (LDD) of Thailand, and the results indicated a moderate to good level of agreement, demonstrating its suitability for spatial analysis at the basin scale.

The reclassified land use data were subsequently analyzed for temporal trends in the Kok, Kham, Ruak, and Sai sub-basins using the Mann–Kendall (MK) trend test and Sen's Slope (SS) estimator during 2001–2024, as presented in **Table 4**. Significant changes were identified in three major land use categories: forest, agricultural land, and urban areas. Forest cover increased by approximately 3.8–16.9% in the Kok, Ruak, and the Kham sub-basins, while agricultural land showed a significant decline of approximately 17.9–28.3% across all sub-basins. In contrast, urban areas expanded by approximately 1–25%, with the Sai sub-basin exhibiting the highest rate of urban growth among all sub-basins. These land use trends are consistent with the findings from previous sections, particularly the increase in land surface temperature (LST) and the growing frequency of flood events in certain areas, highlighting the influence of land use change on environmental and hydrological processes within the basin.

A more detailed examination of the original MCD12Q1 (IGBP) classes revealed that the observed increase in forest cover does not necessarily indicate the recovery of natural forests. Instead, part of the increase appears to be associated with changes in land use practices, including the conversion of agricultural land to monoculture plantations, such as maize cultivation, and the abandonment of cultivated land that subsequently developed into degraded forest areas (Class 8). These trends reflect substantial structural changes in land use across the Kok River Basin and may have long-term implications for soil water retention, biodiversity, and ecosystem stability.



Figure 5. Expansion of mining areas in the upstream Kok River Basin based on historical satellite imagery.

4.6 Analysis of Fire Occurrence Changes

The analysis of fire occurrences in the Kok River Basin was conducted using MOD14A2 products, which provide active fire (hotspot) data derived from the MODIS sensor. Only pixels with confidence levels of 7, 8, and 9 were considered, representing moderate to high confidence in fire detection, to ensure the reliability of wildfire identification during the study period from 2001 to 2024 (Giglio et al., 2016). To examine temporal changes, the number of hotspots during the most recent decade (2015–2024) was compared with the earlier period (2001–2014), as summarized in **Table 5**. The results indicate that, overall, the historical period (2001–2014) exhibited a higher frequency of fire occurrences, averaging 4,024.7 hotspots per year, representing a slight decrease of approximately 2% in the recent decade. However, a more detailed spatial analysis reveals contrasting trends across land-use categories. Fire occurrences within forested areas increased by 4.9% during 2015–2024 compared to the earlier period. In contrast, agricultural areas experienced a substantial decline of 34.4% in hotspot occurrences, while urban areas showed an increase of approximately 26.7%.

These fire occurrences are driven by both natural processes and human activities, particularly the use of fire for land preparation in agricultural practices, such as maize cultivation. This finding is consistent with the land use change analysis presented in **Section 4.5**, which identified an expansion of monoculture cropping systems in upstream areas. In addition, fire activity is closely associated with air pollution issues, especially fine particulate matter (PM_{2.5}), which typically reaches elevated levels during the dry season from February to April in northern Thailand, including Chiang Rai Province (Pollution Control Department, 2023; Chiang Rai Provincial Office Report, 2024). In summary, although long-term statistical trends in fire occurrence are not strongly significant, the observed increase in recent fire activity in specific land-use categories indicates rising fire risk in the basin. This trend reflects the combined influence of land use change and regional climatic conditions, highlighting increasing vulnerability to fire-related environmental impacts in the study area.

Table 4. Land use change trends in the Kok, Ruak, Kham, and Sai sub-basins based on Mann-Kendall (MK) and Sen's Slope (SS) analyses during 2001–2024.

Units: km²

Sub- basin	Forest (F)	Agriculture (A)	Water (W)	Urban (U)	Other (M)
Kok	Pv. = 0.01, SS = 10.1, OA = 242.9, (3.8%) ▲	Pv. = 0.01, SS = -10.6, OA = -254.7, (-17.9%) ▼	No Trend	Pv. = 0.01, SS = 0.3, OA = 6.2, (11.6%) ▲	No Trend
Ruak	Pv. = 0.01, SS = 4.5, OA = 107.3, (9.2%) ▲	Pv. = 0.01, SS = -4.5, OA = -108.1, (-21.9%) ▼	No Trend	Pv. = 0.01, SS = 0.04, OA = 0.9, (8.0%) ▲	No Trend
Kham	Pv. = 0.01, SS = 5.0, OA = 121.8, (16.9%) ▲	Pv. = 0.01, SS = -5.1, OA = -122.2, (-28.3%) ▼	No Trend	Pv. = 0.02, SS = 0.01, OA = 0.02, (0.1%) ▲	No Trend
Sai	No Trend	No Trend	No Trend	Pv. = 0.01, SS = 0.20, OA = 4.8, (24.9%) ▲	No Trend

Note: Example of forest area (F) change in the Kok River Basin. The P-value (Pv.) is 0.01, Sen's Slope (SS) is 10.1 km²/year, and the total change over 24 years (OA) is 242.9 km² (3.8%), which represents the percentage change relative to the mean area. "No Trend" indicates that there is no statistically significant trend. ▼ indicates a significant decreasing trend and ▲ indicates a significant increasing trend.

Table 5 Spatial distribution of hotspot frequency across land-use types in the four sub-basins for the period 2001–2024.

Duration	Hotspot count (number/year)					
	Forest (F)	Agriculture (A)	Water (W)	Urban (U)	Other (M)	Total
2001-2014	3,304.2	713.4	0	6.8	0	4,024.7
Area (km ²)	8,927.8	3,521.3	5.3	103.8	0	12,558.0
2015-2024	3,467.9	468.3	0	8.6	0	3,944
Change (%)	(4.9%)	(-34.4%)	(-)	(26.7%)	(-)	(-2.0%)
Area (km ²)	9,254.0	3,192.8	3.3	108.0	12,558.0	9,254.0

5. Conclusions

This study analyzed spatial and temporal changes in the Kok River Basin by integrating remote sensing products with field-based observations, covering key hydrological, climatological, and environmental variables, including rainfall, land surface temperature (LST), streamflow, land use change, flood occurrence, forest fires, and water quality. Long-term trends and rates of change were assessed using the Mann–Kendall test and Sen's slope estimator to evaluate both the direction and magnitude of environmental changes. The results indicate that the Kok River Basin is experiencing increasing climate variability, characterized by greater fluctuations in rainfall and a higher frequency of extreme hydrometeorological events, including both intense wet conditions and prolonged dry periods. Land surface temperature shows a statistically significant increasing trend, accompanied by a rise in extreme high-temperature events, reflecting intensifying warming conditions and an increased risk of heat-related hazards within the basin.

From a hydrological perspective, streamflow shows significant decreasing trends at multiple gauging stations, suggesting a declining water availability pattern that is consistent with changes in rainfall variability and land use dynamics in the upper catchment. Water quality assessment further reveals concerns regarding heavy metal contamination, particularly arsenic and lead, which are likely associated with upstream land use activities, including mining and land cover disturbance. Land use analysis indicates a reduction in agricultural areas and expansion of urban land, along with structural changes in forest cover. These changes are partly associated with land conversion to monoculture plantations and land abandonment rather than purely natural forest regeneration. Such transformations have direct implications for hydrological processes, including runoff generation and water retention capacity. Fire occurrence analysis shows a slight overall decline in hotspot frequency; however, increasing trends are observed in specific land use categories, particularly forest and urban areas, indicating a rising fire risk driven by human activities and land use change. Fire events are also closely linked to seasonal air pollution issues, particularly PM-2.5 concentrations during the dry season.

Importantly, this study demonstrates the effectiveness of integrating multi-source remote sensing datasets with statistical trend analysis for monitoring long-term environmental changes at the basin scale. The use of satellite-based observations enables continuous spatial and temporal coverage, particularly in complex terrain and transboundary regions where ground-based monitoring is limited or inaccessible.

This approach significantly enhances the capability to detect, quantify, and interpret environmental dynamics in a comprehensive and consistent manner over large spatial domains. In summary, the Kok River Basin is undergoing significant environmental transformation driven by the combined effects of climate variability and land use change, which collectively influence hydrological processes, ecosystem conditions, and disaster risks. The findings provide valuable scientific evidence to support sustainable water resources management, disaster risk reduction, and climate adaptation planning in the basin and other transboundary river systems.

REFERENCES

- Broner, I., and Law, R.R.P. (1992). Water balance for irrigation using ET input. *ICID Bulletin*, 41(2), 173–182.
- Didan, K. (2015). MOD13Q1 MODIS/Terra vegetation indices 16-day L3 global 250m SIN grid. NASA LP DAAC.
- Friedl, M.A., Sulla-Menashe, D., Tan, B., et al. (2010). MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets. *Remote Sensing of Environment*, 114(1), 168–182.
- Funk, C., Peterson, P., Landsfeld, M., et al. (2015). The climate hazards infrared precipitation with stations (CHIRPS). *Scientific Data*, 2, 150066.
- Giglio, L., Schroeder, W., and Justice, C.O. (2016). The Collection 6 MODIS active fire detection algorithm and fire products. *Remote Sensing of Environment*, 178, 31–41.
- Guttman, N.B. (1999). Accepting the standardized precipitation index: A calculation algorithm. *Journal of the American Water Resources Association*, 35(2), 311–322.

- Hayes, M.J., Svoboda, M.D., Wilhite, D.A., and Vanyarkho, O.V. (1999). Monitoring the 1996 drought using the SPI. *Bulletin of the American Meteorological Society*, 80(3), 429–438.
- Hirabayashi, Y., Mahendran, R., Koirala, S., et al. (2013). Global flood risk under climate change. *Nature Climate Change*, 3, 816–821.
- Hirsch, R.M., Slack, J.R., and Smith, R.A. (1982). Techniques of trend analysis for monthly water quality data. *Water Resources Research*, 18(1), 107–117.
- IPCC. (2021). *Climate Change 2021: The Physical Science Basis*. Cambridge University Press.
- Kaprom, C. and Sriwongsitanon, N. (2014). Standardized precipitation index mapping for drought monitoring: A case study of the Upper Ping River Basin. Proceedings of the 19th National Civil Engineering Conference, Khon Kaen, Thailand.
- Kaprom, C., Suiadee, W., Prechawit, C., Maneephai, S., Kowsuvon, N., Williams, J., and Sriwongsitanon, N. (2025). Assessing the impact of climate change on rainfall patterns in Thailand. Proceedings of the 4th World Irrigation Forum and 76th ICID IEC Meeting, Kuala Lumpur, Malaysia, p. 91.
- Kendall, M.G. (1975). *Rank Correlation Methods* (4th ed.). Charles Griffin.
- Landis, J.R., and Koch, G.G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, 33(1), 159–174.
- Mann, H.B. (1945). Nonparametric tests against trend. *Econometrica*, 13(3), 245–259.
- McKee, T.B., Doesken, N.J., and Kleist, J. (1993). The relationship of drought frequency and duration to time scales. Proceedings of the 8th Conference on Applied Climatology, 179–184.
- Pekel, J.F., Cottam, A., Gorelick, N., and Belward, A.S. (2016). High-resolution mapping of global surface water and its long-term changes. *Nature*, 540, 418–423.
- Pollution Control Department (PCD). (2023). Thailand air quality situation report. Bangkok, Thailand.
- Sen, P.K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, 63(324), 1379–1389.
- Wan, Z. (2014). New refinements and validation of the MODIS land-surface temperature/emissivity products. *Remote Sensing of Environment*, 140, 36–46.
- World Meteorological Organization (WMO). (2012). *Standardized Precipitation Index User Guide* (WMO-No. 1090). Geneva.
- Wulder, M.A., et al. (2018). Current status of Landsat program. *Remote Sensing of Environment*, 225, 127–147.
- Yue, S., Pilon, P., and Cavadias, G. (2002). Power of the Mann–Kendall test and its modification. *Hydrological Processes*, 16(9), 1807–1822.
- Zeitoun, M., and Warner, J. (2006). Hydro-hegemony. *Water Policy*, 8(5), 435–460.