Shifts in streamflow and flood timings over the Upper Ping River Basin, Thailand

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Abstract. This study investigated spatiotemporal changes in streamflow and flood timing within the Upper Ping River Basin of Thailand, a major area providing a source of inflow to the largest reservoir, the Bhumibol Dam. To investigate this, a robust circular statistics framework was applied to examine three timing metrics: mean streamflow, streamflow center and peak flood timing. Daily streamflow data from 17 gauging stations spanning the period 1995–2024 were used for the analysis. The results reveal that the spatial gradient of these timings similarly occurs earlier in the upstream mountainous area and progressively later in the downstream floodplain areas. To confirm the seasonality strength of streamflow and flood timing, the resultant length and Rayleigh uniformity tests were used. The results indicated that flood and streamflow timings were significantly concentrated around their respective mean dates. Furthermore, their temporal distribution was found to be unimodal, indicating strong seasonality. Analysis of temporal trends revealed a significant delay in all metrics with 0.71, 0.84 and 0.86 days per decade for mean streamflow, streamflow center and peak flood timings respectively. Moreover, the pronounced delay in peak flood timing, coupled with its positive correlation to streamflow center timing, suggests that delaying flood timing may be a significant driver of the change in basin hydrological timing.

1 Introduction

Shifts in the hydrological cycle at both global and regional scales have led to changes in the seasonality and patterns of river streamflow [1]. Therefore, the analysis of flood and streamflow timing has become important as it serves as a tool for understanding flood generation mechanisms and observed hydrological changes. Even minor shifts in the seasonality of floods and streamflow consequently lead to environmental impacts, increasing the risk of floods [2] and droughts [3], and affecting the security of water resources for agriculture. Furthermore, studies on the timing of streamflow and flood are the basis for water resource planning and management, especially in basins with large hydraulic structures.

The analysis of the timing of these floods and streamflow typically considers three main indices as flood timing (the day of peak flow), mean streamflow (the flow-weighted

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average date) and streamflow center timing (half of the total annual streamflow has passed a given gauge). Challenge in analyzing these flood and streamflow metrics is that the characteristics of annual data are cyclical. While traditional linear statistics are inappropriate to analyze due to misleading trend interpretation, circular statistics can effectively handle the cyclical continuity of data between the end of one year and the beginning of the next. This method converts an ordinal day of the year into an angular value to calculate the mean direction [4].

However, a significant challenge in trend analysis is the definition of the water year. Wasko, Nathan and Peel [5] demonstrated that using calendar year can lead to an incorrect interpretation of the trend of direction. A local water year, which begins at the 1st of the lowest average monthly stream flow months for each station was suggested. Similarly, Berghuijs, Hale and Beria [6] found that directional statistics are more reliable than traditional one such as the streamflow center timing or a non-cyclical mean streamflow timing as they are not dependent on an arbitrarily chosen start date for the water year.

Several studies have shown trends in the changing timing of flooding and streamflow in many regions worldwide [5, 7-9]. For a specific basin in which streamflow is dominated by snow, the identified trend presents earlier due to snowmelt contributed by warming temperatures. In snow-free regions, such as Southeast Asia, southern Australia [8] and Southern Brazil, later floods have been observed. This is consistent with changes in rainfall and soil moisture accumulation [10]. Moreover, the trends depend on a key driver corresponding to floods such as earlier cyclone landfalls [11].

The Upper Ping River Basin which is the primary source of water for the largest reservoir in Thailand, the Bhumibol Dam. Changes in streamflow and flood timing are of paramount importance for risk management and national water security. However, the application of robust methodologies, i.e., circular statistics combined with a local water year definition, remains limited in the context of Thailand. While previous study has demonstrated general hydrological trends, quantitative analysis that investigates and differentiates the spatio-temporal shifted across three timing metrices using robust circular statistics has not been yet conducted for the Upper Ping River Basin. Therefore, this research aims to analyze the spatial and temporal changes in three streamflow timing indices: 1) mean streamflow timing, 2) streamflow center timing and 3) peak flood timing using selected 17 streamflow gauging stations in the Upper Ping River Basin. This study aims to investigate the temporal shifts of key streamflow and flood timings by quantifying the annual timing of mean streamflow, streamflow center and peak flood across the basin.

1. To analyze the spatial patterns and seasonality strength of these timing metrics from upstream to downstream areas.
2. To determine the magnitude of change and direction of temporal trends in these metrics over the past three decades (1995-2024).

To achieve these objectives, this study applied a robust analysis based on circular statistics, a method well suited for cyclical data. By examining these changes, this study provides crucial insights into the changes in hydrological timing offering valuable information for adapting to water management planning.

2 Study location and data used

The Upper Ping River Basin is located in the northern region of Thailand. This basin encompasses an area of approximately 15,000 square kilometers, approximately one-half of the total basin area. The elevation of this catchment ranges from 200 m to 2,577 m above mean sea level, encompassing mountainous to flood-prone areas. The annual average precipitation ranges between 986.5 and 1712.3 mm, with the peak time typically occurring in October. Consequently, the average yield of runoff in this study area is approximately

6.50 liters per square kilometer per second. During the flood season, usually in September, the average peak rate reaches 852.9 cubic meter per second. Conversely, a low-flow month is usually April, which is defined as the first day of this month as the start date of the local water year. The tributaries of the Upper Ping River flow in a north-to-south direction, discharging into the Bhumibol Dam, which is located in the Middle Ping River Basin. This dam serves as the main inflow source for the Bhumibol Reservoir, a large-scale storage facility critical for irrigation, hydropower generation, tourism, and the mitigation of both drought and flood disasters.

This study utilized daily streamflow records from the Royal Irrigation Department (RID) of Thailand in the Upper Ping River Basin. Site selection was based on strict criteria for data availability, specifically minimum record length and annual data completeness. At least 20 years record length and 95 percent are the minimum requirements for the data length and annual percent completeness respectively. Based on these screening criteria, 17 daily stream flow sites met these conditions. Figure 1 shows the location of the selected sites in the Upper Ping River Basin distributed across the mountainous area to the low-lying plain of the Upper Ping River Basin. These stations are the primary stream flow gauges that observe the water level and streamflow rate of the Ping River and its tributaries. The selected gauging network began recording data between 1995 and 2003 as shown in Figure 1 (b). This figure summarizes the resulting data availability from a filtering process in which daily streamflow data with a missingness threshold exceeding 5% were removed.

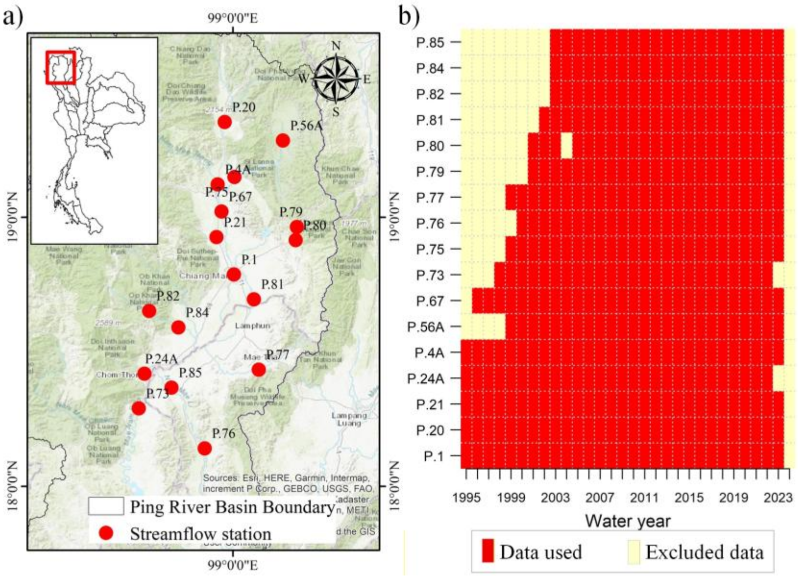

Fig. 1. location of selected 17 streamflow stations (a) and data availability at each station which percent completeness greater than 95% (b)

3 Methodology

Streamflow metrics, including streamflow center, mean streamflow and peak flood timing are estimated using ordinal day (i). The streamflow center timing defined by Court [12], is the day of the year when half of the total annual flow has passed a given streamflow gauge. This timing is sensitive to changes in the basin flow regime resulting from watershed management and water allocation [8]. The mean streamflow timing is defined by the mean weight of the timing or center of mass of flow for the daily hydrograph of yearly data. This timing has been shown to respond to teleconnection with oceanic indices [9]. Finally, the peak flood timing represents the day in which the maximum annual flow occurs. All streamflow metrics are computed based on the water year starting on April 1st, which corresponds to the onset of hydrological cycle following the minimum average monthly discharge in the basin. Accordingly, the ordinal day of this analysis begins at this date $(i=1)$.

Here, the annual mean timing of such streamflow metrics was calculated by adapting robust circular statistics. Firstly, the ordinal day i is converted to an angular value θ_i, where m is the number of days in the year. Note that m is equal to 366 for the leap year.

$$\theta_i = \frac{i}{m} \times 2\pi \tag{1}$$

where angular value is equal to 0 radian, it corresponds to April 1st and 2π radian refers to March 31st.The mean timing $\bar{\theta}$ or mean direction (in radians) in calculated by

$$\bar{\theta} = \tan^{-1}\left(\frac{\bar{y}}{\bar{x}}\right) \tag{2}$$

where $\bar{x}$ and $\bar{y}$ are the mean lengths of x and y in Cartesian coordinates calculated from the projection of the direction. These means of projection length are determined using:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n}\cos(\theta_i) \tag{3}$$

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n}\sin(\theta_i) \tag{4}$$

The mean timing $\bar{\theta}$ of the streamflow center, mean streamflow and peak flood timing were calculated station-by-station. Here, seasonality strength of the streamflow metrics is identified by using the related statistics R, which is the square root of sum square product of $\bar{x}$ and $\bar{y}$, as well known as resultant length. This statistic value ranges between 0 and 1. If they are close to 1, it means that all data points are clustered in a single direction, while a value approach to 0 suggests that the data are uniformly distributed around the whole year [13].

In reference to three types of timing distribution as per Dhakal, Jain [14] --pseudo uniform, pseudo unimodal and pseudo trimodal--, this study accounted for those of distribution characteristics of the timing metrics. It is important to note that the historical records of rainfall storms which influence streamflow characteristics are not limited to the flood season, they frequently occur beyond the flood period. Consequently, the statistical uniformity Rayleigh test was employed to identify the types of distributions. The Rayleigh statistics range between 0 and 1, where a higher statistic value represents a strong tendency towards a pseudo unimodal mode. The significance level of these results was indicated by a p-value with a threshold of 0.05 applied to this study.

This study evaluated the temporal changes in streamflow metrics using a circular approach. To measure this tendency, linear statistics were applied on a station-by-station basis. The spatial average of the linear slope representing the annual rate of change for the streamflow metrics was adopted. Moreover, the rate of change at every site was calculated to plot the relationship between peak flood timing and streamflow center timing and mean streamflow timing. These relationships were investigated to determine whether the shifting of peak flood timing by the impact of climate change has contributed to center or mean streamflow timings.

4 Results

4.1 Progression of streamflow timings

As mentioned above, the streamflow timing metrics referred to the Julien date of year beginning on 1st April, the start date of the water year in Thailand, were calculated using circular statistics. The results are displayed in Figure 2 and show that all streamflow metrics have similar spatial patterns in timing. It is clear that the spatial gradient of these timings decreases from earlier occurrences in mountainous upstream areas to later occurrences at lower elevations, from upstream to downstream. For example, stations upstream, P.20 indicate earlier timings in mean streamflow, streamflow center, and peak of flooding (around earlier September). Meanwhile, station located in the downstream of the basin, e.g. P.85, displays delayed timing (around late September to early October). However, the peak flood timing seems to be a higher fluctuation characteristic when compared with the others.

To measure seasonality strength and its variability of such three timings, R-statistics was calculated. The R-statistics for the three timings are displayed in Figure 1 (sub-figure d, e and f). This indicates that the streamflow center timing presents a higher R-statistic value than those of the mean streamflow and peak flood timings. Meanwhile, peak flood timing displays the lowest R-statistic value at most sites due to temporal variability of timing.

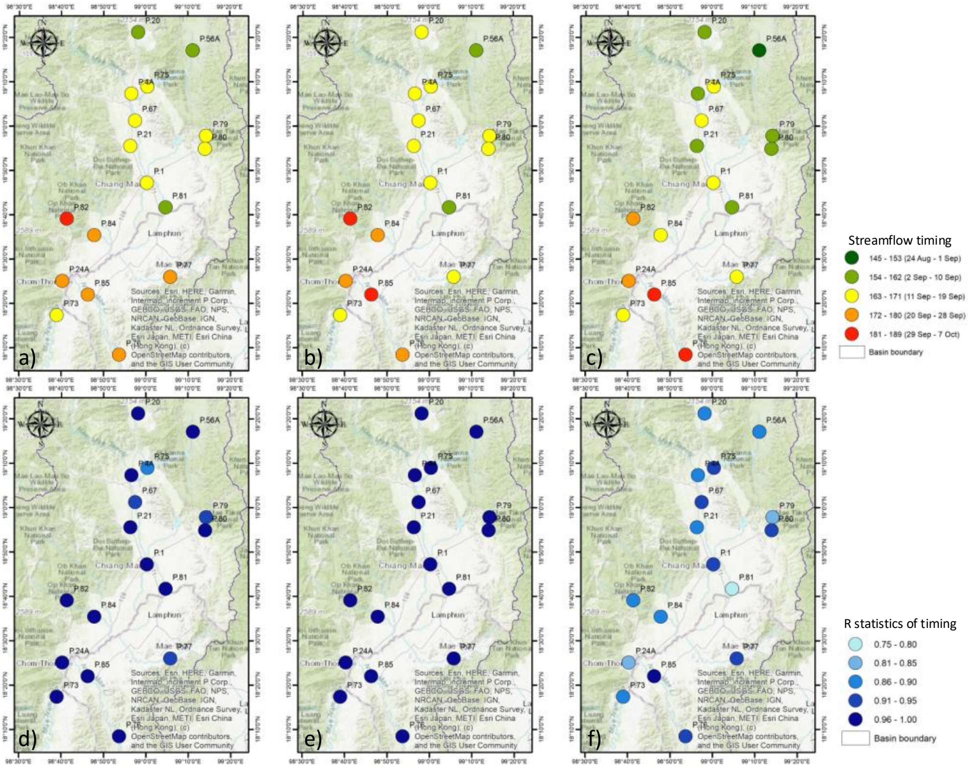

Fig. 2. Spatial plot of streamflow timing metrics and R-statistics for the timing (below the timing). The mean streamflow, streamflow center, and peak flood timings are shown in subfigures a), b), and c) respectively and R statistics are shown below.

4.2 Distribution of streamflow timings

In this study, the statistical distribution of three timings was identified to confirm the distribution of streamflow metrics. Here, the Rayleigh test of uniformity was adopted with their null hypothesis of this test is the timing of streamflow metrics are distributed around a circular direction—i.e., one round of circle for the timing for 1st Apr to next 31st Mar of the next year. Otherwise, the types of distribution are identified by the Rayleigh uniformity test, pseudo uniform, pseudo unimodal or pseudo trimodal. The statistical test of null hypothesis is rejected, and the types of distribution are indicated to be pseudo unimodal modes with the Rayleigh statistics of each site shown in Table 1. For every site, P-values smaller than 0.05, are indicated. This means that the pseudo unimodal distribution is appropriate for describing streamflow timing metrics.

Figure 3 presents the timing distribution of streamflow metrics representative of upstream, middle stream and downstream. The time distribution of the streamflow metrics seemed to be clear as unimodal distribute around the time cycle. Although the central timing of events clearly shifts from earlier upstream to later downstream, the distributions consistently exhibit a unimodal pattern along the entire Ping River. However, the distribution range for peak flood timing is likely to be wider than the mean and center streamflow timings.

Table 1. Statistical results of Rayleigh uniformity test at each site.

Summary Rayleigh statistics	Max	Mean	Min	Standard deviation
Mean streamflow timing	0.981	0.958	0.872	0.026
Center streamflow timing	0.971	0.887	0.737	0.055
Peak flood timing	0.987	0.975	0.960	0.008

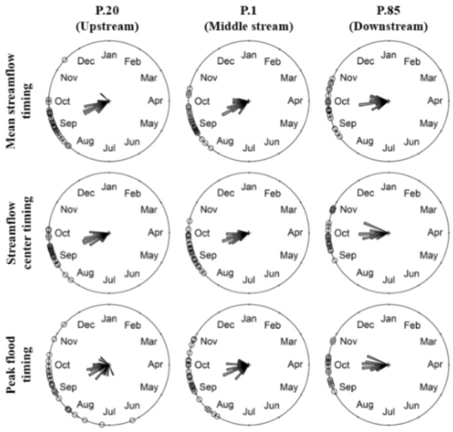

Fig. 3. Time distribution of streamflow metrics throughout representative station P.20 (upstream), P.1 (middle stream) and P.85 (downstream).

4.3 Trend in streamflow metrics

The spatial trend of streamflow metrics was calculated using the linear slope of the 50th percentile level of annual streamflow timings. Figure 4 presents the trend of the streamflow timings between 1995 and 2024. Grey lines indicate site timing and bold black line stands for average timing at all sites. This figure indicates that trend in streamflow timings are slightly increases with average rates of 0.71, 0.84 and 0.86 days/decade for mean streamflow, streamflow center and peak flood timings respectively. This figure also shows that inter-site variability for peak floods appears less smooth and highly sensitive to localized variation, while streamflow center timing appears to be more stable. After that, trend of peak flood that tend to be increase with impact of climate change is evaluated with streamflow center and mean timings as shown in Figure 5. Correlation of peak flood timing versus center and mean streamflow timing are 0.39 and 0.05 respectively. Least-square line fitting was applied to indicate how much the center and mean streamflow timing changed with peak flood timing. This study found that the streamflow timing changed by increased flood timing with a rate of 0.17, while the mean streamflow timing was lower with a rate of 0.03 (see red line in Figure 5). The results found in this study support the results of Gudmundsson and Leonard [15] that flood timing contributes to streamflow center timing in a similar direction. Moreover, this weaker correlation suggests an inconsistency between the timing of extreme peak events and the central tendency of seasonal flow. Such inconsistency may stem from the complex interaction between rainfall patterns and seasonal soil moisture dynamics.

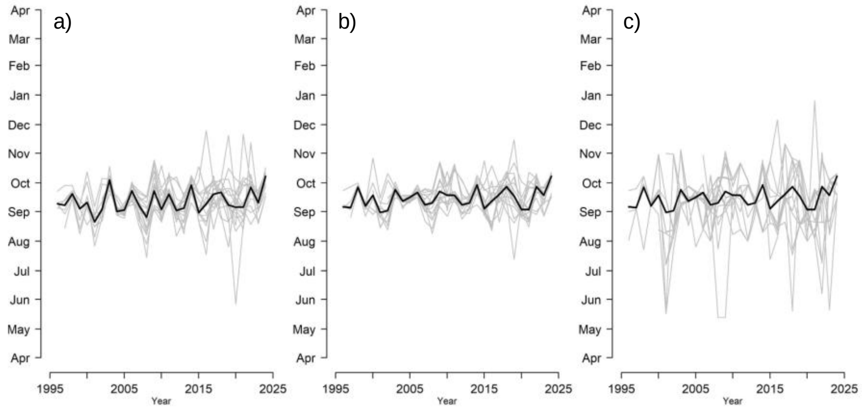

Fig. 4. Average linear trend of streamflow timing metrics between 1995 and 2024: a) mean streamflow, b) streamflow center and c) peak flood timings.

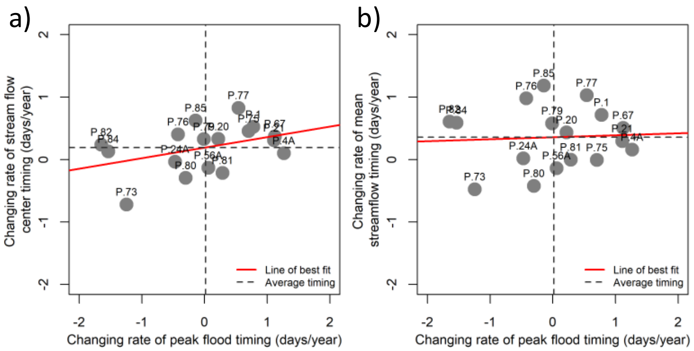

Fig. 5. Relationship between changing rate of peak flood timing and changing rate of streamflow timing: a) streamflow center timing and b) mean streamflow timing.

5 Conclusion

This study aimed to analyze the spatial and temporal shifts of three streamflow timing metrics--mean streamflow timing, streamflow center timing, and peak flood timing-- within the Upper Ping River Basin, Thailand. The daily streamflow series from 17 gauging stations were utilized in this analysis, each with at least 20 years of records and at least 95% daily data completeness. The investigation of this study is based on a robust method for analyzing cyclical data and circular statistics. The analysis revealed a spatial pattern for all three streamflow timing variables and found that stations located in the upstream mountainous areas exhibited earlier timings for streamflow and floods compared to those in the downstream.

Based on the assessment of seasonality strength using R-statistics, streamflow center timing was identified as the most consistent and stable metric, whereas peak flood timing showed the highest inter-annual variability. Moreover, this study applied the Rayleigh uniformity test to these three streamflow metrics. The Rayleigh uniformity test confirmed that the three variables used exhibit a statistically significant unimodal distribution (p-value < 0.05) across all stations. This implies that the occurrence of streamflow events tends to be concentrated within a specific period of the year rather than being randomly distributed.

The most significant finding was the temporal trend. Analysis of the time series revealed a discernible trend towards later occurrences for all three streamflow timings, with average rates of change of 0.71, 0.84 and 0.86 days/decade for mean streamflow, streamflow center, and peak flood timings respectively. The fact that peak flood timing shows the most pronounced delay and has a positive correlation with streamflow center timing suggests that climate-induced changes affecting heavy rainfall and flood events may be a key factor shifting the overall timing of the basin's hydrology. The specific identification of peak flood timing as the most sensitive driver of hydrological shifts in the basin provides critical, actionable information for water resource managers and the operators of the Bhumibol Dam. For instance, flood risk assessments and reservoir operation rules may need to be revised to account for this quantified delay in peak inflows, rather than relying solely on changes in mean streamflow.

Despite these findings, this study has limitations that suggest areas for future investigation. This study prioritized streamflow and flood timings without addressing broader flood impact, not did it isolate the primary drivers of the observed trends. Future research should integrate links with climatic variables, such as changing rainfall extremes, temperature, or large-scale teleconnection indices (e.g., ENSO), to better understand the mechanisms driving these changes.

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