Observed response of tropical river streamflow to climate change - evidence from a national database

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November 24, 2022

Abstract

We analyzed streamflow records from more than 300 stations across Thailand, a tropical country in Southeast Asia. Temporal changes in runoff yield were assessed over the 1960-2015 period, highlighting a prominent downward trend over the last two decades. To identify potential drivers of these changes, gridded data products representing precipitation, temperature, evapotranspiration, and land cover were also assessed. We found that runoff yield is primarily driven by annual precipitation, which has experienced an unprecedented decline since 2010. Two sub-regions with particularly robust data coverage reflected a spatial contrast in hydrologic response: a more consistent response of runoff yield to precipitation is observed in the sub-region characterized by a high density of forest cover relative to the region characterized by high cropland cover. This feature underscores the need to take land use and irrigation practices into account when forecasting, and determining management strategies for, tropical river streamflow in a warming climate.

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Key Points:

- Observed river flows across Thailand were analyzed from 1960 to 2015, highlighting a prominent decreasing trend during the most recent years.
- Decreasing river flows across Thailand appear to be linked primarily to an unprecedented decline in precipitation.
- Two regions in Thailand with contrasting land cover profiles showed notable differences in hydrologic response to changes in precipitation.

Abstract

We analyzed streamflow records from more than 300 stations across Thailand, a tropical country in Southeast Asia. Temporal changes in runoff yield were assessed over the 1960-2015 period, highlighting a prominent downward trend over the last two decades. To identify potential drivers of these changes, gridded data products representing precipitation, temperature, evapotranspiration, and land cover were also assessed. We found that runoff yield is primarily driven by annual precipitation, which has experienced an unprecedented decline since 2010. Two sub-regions with particularly robust data coverage reflected a spatial contrast in hydrologic response: a more consistent response of runoff yield to precipitation is observed in the sub-region characterized by a high density of forest cover relative to the region characterized by high cropland cover. This feature underscores the need to take land use and irrigation practices into account when forecasting, and determining management strategies for, tropical river streamflow in a warming climate.

1 Introduction

Over the past decade there has been a surge in the number of observational investigations focused on understanding river flow regimes and changes in hydrological extremes at the global and regional scales [*Berghuijs et al.*, 2017; *Blöschl et al.*, 2019; *Blöschl et al.*, 2017; *Do et al.*, 2017; *H X Do et al.*, 2020a; *Hall and Blöschl*, 2018; *Hodgkins et al.*, 2019; *Hodgkins et al.*, 2017; *Wasko and Nathan*, 2019; *Yin et al.*, 2018]. However, many regions across the tropics – such as Northern Africa, Middle East and Southeast Asia – are still inadequately assessed in (or even excluded from) global investigations that detect and differentiate drivers of change in river flows [*Dai*, 2016; *H X Do et al.*, 2020b; *Gudmundsson et al.*, 2019; *Wasko et al.*, 2020]. This research gap is partially due to the absence, even in the most comprehensive global databases, of in-situ measurements for many countries [*Addor et al.*, 2019; *Dai*, 2016; *Do et al.*, 2018; *Gudmundsson et al.*, 2018]. The collective under-representation of tropical rivers across these efforts has hindered a reliable projection of global water resources availability in a warming climate [*Dai*, 2016; *Hoegh-Guldberg et al.*, 2018; *Jahandideh-Tehrani et al.*, 2019], as the tropics occupy nearly one-fifth of the global land mass [*Peel et al.*, 2007] and tropical river basins usually have the highest runoff yield [*Syvitski et al.*, 2014] relative to basins in other latitudes.

Southeast Asia is one example of a tropical region that has been underrepresented in global assessments of hydrological change, despite the high susceptibility of the region's flow regimes to changes in regional and global climate [*Adamson and Bird*, 2010; *Syvitski et al.*, 2014; *Xu et al.*, 2019]. Regional and national climate research across Southeast Asia has highlighted substantial changes in temperature and precipitation extremes [*Q V Do et al.*, 2020; *Le et al.*, 2019; *Singh and Qin*, 2019; *Supari et al.*, 2020; *Tangang et al.*, 2019], which are likely the key drivers of severe floods [*Delgado et al.*, 2010; *Eccles et al.*, 2019] and droughts [*Adamson and Bird*, 2010; *Räsänen et al.*, 2016] that have imposed considerable damage and disrupted the livelihood of millions of Southeast Asia citizens. Over the past decade, widespread droughts [*Pal and Bhatt*, 2020; *Prabnakorn et al.*, 2019] – resulting from declining annual precipitation due to the influence of El Nino–Southern Oscillation [*Dutta*, 2018; *Marjuki et al.*, 2016; *Vu et al.*, 2018], and exacerbated by hydropower and irrigation dams [*Hecht et al.*, 2019; *Israngkura*, 2000] – have elevated societal concern of an uncertain future facing regional water resources [*UNESCAP*, 2020]. Nevertheless, the extent of the impact of these climate conditions to water resources over Southeast Asia remains unclear, as most investigations into streamflow in Southeast Asia only assessed records of a handful of stream gauges [*Delgado et al.*, 2010; *Hecht et al.*, 2019; *Li et al.*, 2017; *Ligaray et al.*, 2015; *Loi et al.*, 2018; *Vo et al.*, 2016; *Xu et al.*, 2019].

Our study aims to fill in this gap by providing a first-of-its-kind large-sample assessment of long-term changes (from 1960 to 2015) in annual streamflow across Thailand, which represents 24% of the total area of mainland Southeast Asia. We used a national database of more than 300 stations as the observational basic for this assessment. To identify potential drivers of streamflow changes, we also assessed spatiotemporal variations of four variables: temperature, annual evapotranspiration, annual precipitation, and land cover.

2 Data and Methods

In Thailand, the Royal Irrigation Department (RID) coordinates the monitoring infrastructure for river water level and discharge measurements. We downloaded monthly discharge records that are publicly accessible from the RID's website (http://water.rid.go.th/hyd; accessed: July 31, 2020). We identified basic metadata (i.e. geographical coordinates and catchment area) of each gauge using available information on the RID's website, and selected 328 stations associated with these metadata for this assessment. The catchment area of the selected stations ranges from 17 to 118,752 km^2, with a median of 1,235 km^2.

We note that the hydrologic regime of many streams in Thailand, as with other Southeast Asia countries, is heavily modified by hydropower dam construction and irrigation withdrawals [*Jahandideh-Tehrani et al.*, 2019]. The extent of dam construction and irrigation impacts is so extensive, in fact, that our analysis would not be possible if we based it only on "natural" or "near-natural" streams [*Do et al.*, 2017]. Instead, our approach aims to take advantage of a publicly available database that has undergone quality control by data authorities; to use that data set to conduct a large-sample assessment focused on identifying regional patterns of changes in river flow; and to relate these changes to climate and landscape attributes. Figure 1 includes a graphical summary of data availability (we flagged years with less than 11 data points of monthly streamflow as "no data available"). The number of stations with available data has increased over time, reflecting recent investments of the Thai government on water monitoring infrastructure to support Integrated Water Resources Management [*World Bank*, 2011]. We note that data in many stations is not up-to-date, leading to a rapid decrease in data availability over the most recent years. Stations with a relatively long record (more than 50 years of data) are generally located in the northern part of the country.

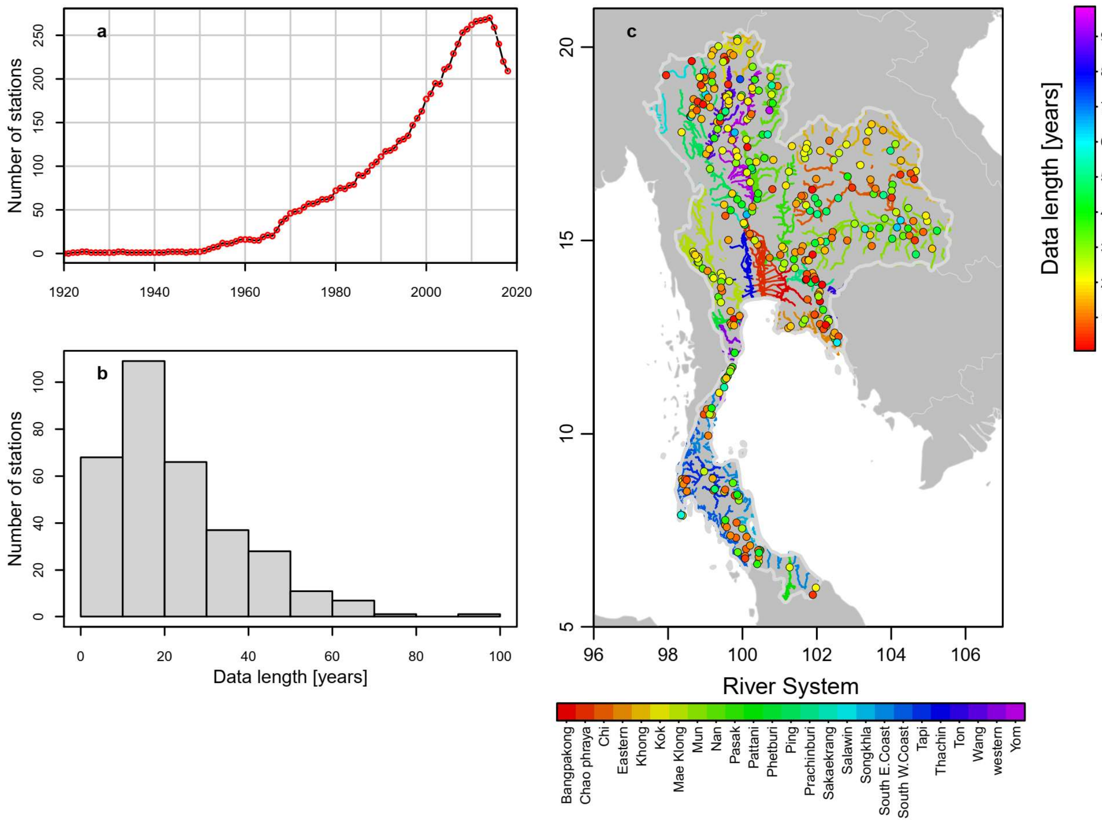

Figure 1. Summary of streamflow records that have been made publicly available by the Royal Irrigation Department. (a) The number of stations with at least 11 months of data per calendar year; (b) histogram of data length (in years) for gaging stations (not necessarily continuous); and (c) the geographical locations and corresponding data length (color dots) of the 328 stations used in our study across Thailand's river networks (color lines represent the 25 major river systems as defined by the Royal Irrigation Department [*Souris*, 2007]).

To explore the potential influence of climate and landscape attributes on changes in streamflow, we also used the following gridded data products:

- The Asian Precipitation Highly-Resolved Observational Data Integration Towards Evaluation of water resources (APHRODITE) dataset [*Yatagai et al.*, 2012]. This dataset provides gridded daily total precipitation and temperature data at a 0.25 arc-degree longitude-latitude resolution across the Monsoon Asia region from 1960 to 2015 (temperature is available from 1961 onward). We aggregated daily data from this database to annual (cumulative precipitation and average temperature using calendar year) time steps.
- The Global Land Evaporation Amsterdam Model (GLEAM v3.3) dataset [*Gonzalez Miralles et al.*, 2011; *Martens et al.*, 2017]. This dataset provides evapotranspiration estimates across the globe at a 0.25 arc-degree longitude-latitude resolution based on satellite observations and numerical models. We obtained yearly data from GLEAM for this assessment.

- The European Space Agency Climate Change Initiative Land Cover (ESA CCI-LC) dataset [*ESA*, 2017]. This dataset provides estimates for land cover from 1992 to 2015 at a 300m resolution. We used the classification scheme of the Intergovernmental Panel on Climate Change for change detection [*Santoro et al.*, 2017] and assigned each pixel into one of six categories: agriculture, forest, grassland, wetland, urban area, and other (including water body). To represent potential changes in land cover, we identified the composition of different land cover types over a specific spatial domain for every year.

We aggregated monthly discharge to annual resolution (using calendar year) and the catchment area was used to convert annual discharge (m^3/s) to runoff yield ($ls^{-1}km^{-2}$), allowing for a comparable result across rivers with different basin sizes. We then calculated temporal trends of runoff yield, annual precipitation, evapotranspiration, and temperature using the conventional Theil–Sen slope estimator (τ_{ts}), defined as the median of the average difference in the values between all possible pairs of years [*Sen*, 1968]:

$$\tau_{ts} = median\left(\frac{x_j - x_i}{j-i}\right) \qquad (1)$$

where indices i and j represent year numbers such that $i \in [1, n_{ts} - 1], j \in [2, \mathrm{n_{ts}}], i < j$, and n_{ts} is the number of years in the data record for each time series.

For runoff yield, precipitation, and evapotranspiration, we calculated normalized trends (T_{ts}), defined as a percentage of change per decade relative to the mean of all data points ($\bar{x}_{ts}$), across all locations to facilitate inter-comparison [*Stahl et al.*, 2012]:

$$T_{ts} = \frac{\tau_{ts} \times 10 years}{\bar{x}_{ts}} \times 100 \qquad (2)$$

We then calculated normalized trends of runoff yield, temperature, precipitation and evapotranspiration over three nested time periods: (i) 1960 to 2015 (1961 to 2015 for temperature data; only time series with at least 45 years of data was used); (ii) 1980 to 2015 (only time series with at least 32 years of data was used); and (iii) 1995 to 2015 (only time series with at least 20 years of data was used). We also calculated the percentage of landmass (over a specific region) covered by forest and agricultural land, the two dominant land use categories, over the 1992-2015 period to explore the potential effect of land cover on the regional hydrology.

3 Results and discussion

The results of our trend analysis (Fig. 2) indicate that the rate of change across Thailand, and surrounding regions, has not been consistent across key climate variables. Local trends of each variable also differ substantially across the nested reference periods, further highlighting the complex temporal variation of Southeast Asia climate.

Among the three variables, average temperature has the most stable increasing trend (Fig. 2a-c), although the rate of changes over the last two decades (1995-2015) is much higher than the rate of changes over the long-term (1961-2015). Trends of evapotranspiration from 1980 to 2015 (Fig. 2h) generally follow the increasing trends of average temperature. A similar temperature–evapotranspiration relationship is also observed from 1995 to 2015, excepting the eastern region (Fig. 2i), which shows a mild decrease in annual evapotranspiration despite a high increasing rate of mean temperature (more than 0.5°C per decade; Fig. 2c). This inconsistency is not unexpected, as there is a wide range of factors that could modulate evapotranspiration such as solar radiation, wind speed, water availability, the physical attributes of the vegetation, and soil characteristics [*Bosch and Hewlett*, 1982; *Brutsaert and Parlange*, 1998; *Zhang et al.*, 2001]. For instance, the increase in temperature coinciding with intensifying rainfall may lead to an increase in total volume of water vapor in the atmosphere, and thus result in decreasing evapotranspiration. We also note that cropland covers more than 70% of Thailand landmass (the spatial distribution of land cover observed in 2015 is showed in Fig. 2g), indicating a potential influence of vegetation attributes to evapotranspiration. This influence is likely captured by GLEAM algorithms, which also take into account land-cover type in estimating potential evaporation rate [*Martens et al.*, 2017].

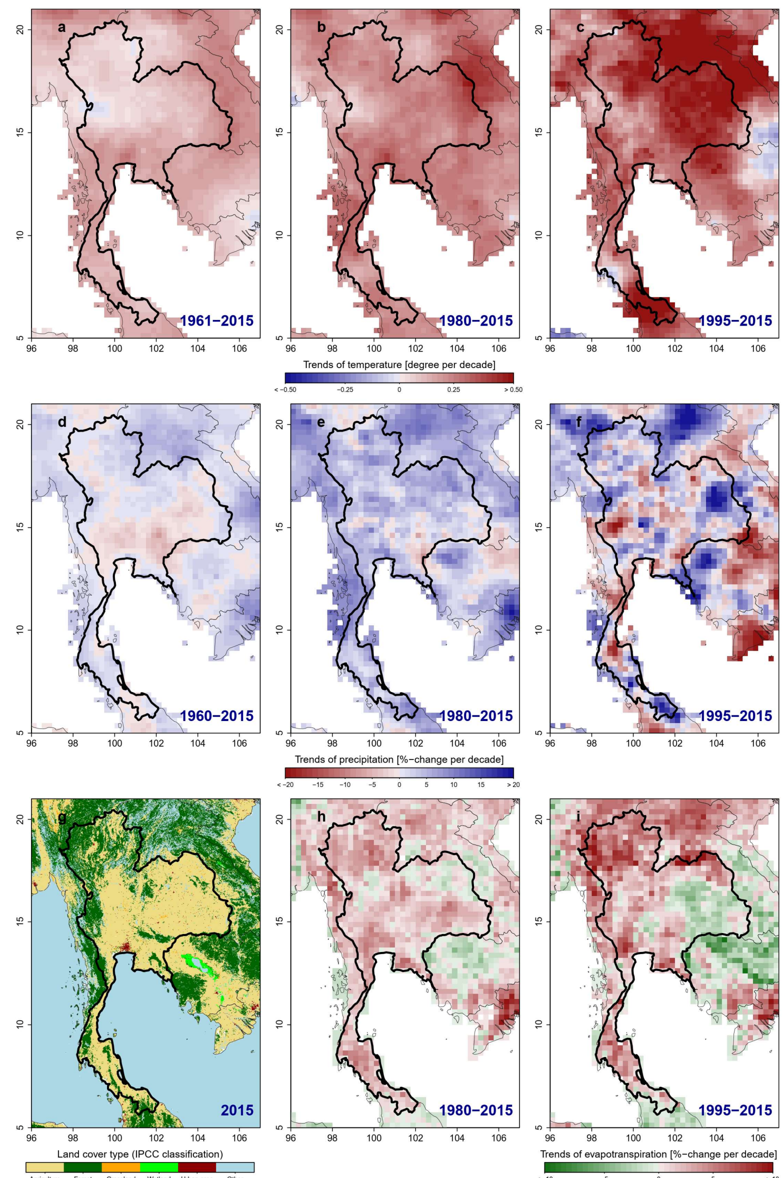

Figure 2. Trends of annual temperature (panels a-c), total precipitation (panels d-f), and evapotranspiration (panels h-i) across Thailand (bounded by the thick lines) and the surrounding areas. Changes were assessed over three nested periods (1960-2015, 1980-2015, and 1995-2015; note that data is only available since 1961 and 1980 for temperature and evapotranspiration respectively). Land cover in 2015 is also shown (panel g) for reference; the six-category classification scheme of the Intergovernmental Panel on Climate Change was used.

Changes detected from annual precipitation (Fig. 2d-f) indicates a highly spatiotemporal variation of precipitation across Thailand relative to that observed in annual temperature and evapotranspiration, and is generally consistent to gauge-based evidence [*Limsakul and Singhruck*, 2016]: a mixture between increasing and decreasing trends from 1960 to 2015, a dominant increasing trend from 1980 to 2015, and a high spatial variation of changes from 1995 to 2015. This high variation of precipitation, particularly the out-of-phase precipitation over the past decade, is attributable to meridional shifts in the Intertropical Convergence Zone [*Byrne et al.*, 2018; *Tan et al.*, 2019] which are susceptible to large-scale climate variability in El Nino–Southern Oscillation events [*Barlow et al.*, 2002; *Limsakul and Singhruck*, 2016].

Figure 3 shows the magnitude of changes in runoff yield across stations with sufficient data over the three reference periods, complementing the findings of previous investigations into changes of river flows over a small subset of catchments [*Ligaray et al.*, 2015; *Prabnakorn et al.*, 2019; *Xu et al.*, 2019]. The results indicate a generally consistent sign of changes to regional trends observed in precipitation, which is somewhat expected as runoff yields over tropical river basins are highly susceptible to the amount of annual rainfall [*Dettinger and Diaz*, 2000].

From 1960 to 2015, streamflow observations exhibit a mixture of changes, ranging from -16.6 to 14.7% per decade (Fig. 3a) with more stations showing a decreasing trend (19) than an increasing trend (13 stations). It is informative to note that stations associated with a decreasing trend are generally located in the regions characterized by a deficiency in annual precipitation (presented in Fig. 2d). Over the 1980-2015 reference period, trends in streamflow records show a clear tendency toward an increasing trend (Fig. 3b), ranging from -13.0 to 26.9% per decade. Of all 54 stations with sufficient data, 39 stations (75%) are associated with an increasing trend. We also note that most stations associated with a decreasing trend are located over the Ping River Basin (upper north region) and Prachin Buri Basin (southeastern region), of which annual precipitation also exhibited a mild decrease (Fig. 2e).

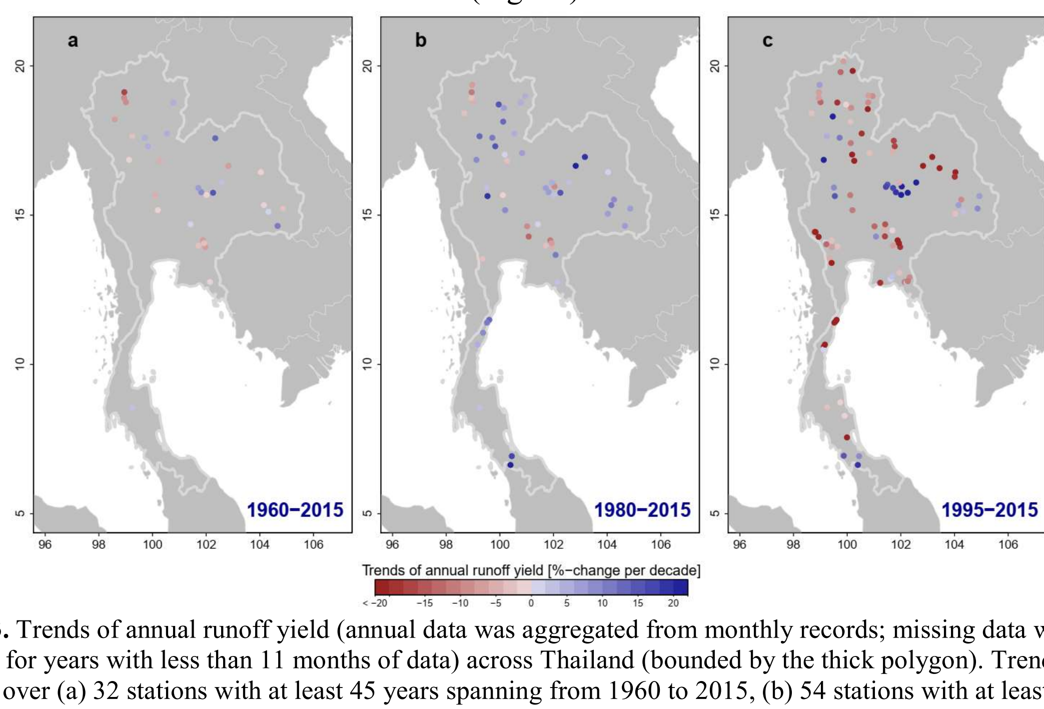

Figure 3. Trends of annual runoff yield (annual data was aggregated from monthly records; missing data was assigned for years with less than 11 months of data) across Thailand (bounded by the thick polygon). Trends were detected over (a) 32 stations with at least 45 years spanning from 1960 to 2015, (b) 54 stations with at least 32 years spanning from 1980 to 2015, and (c) 98 stations with at least 20 years spanning from 1995 to 2015.

A prominent decreasing trend is observed in river annual runoff yield across Thailand from 1995 to 2015 (Fig. 3c). Over this reference period, the rate of changes varies from -58.3 to 42.9% per decade, and a decreasing trend is exhibited over 70 out of 98 stations, confirming the impact of the drying climate condition across Southeast Asia [*Pal and Bhatt*, 2020; *UNESCAP*, 2020] on streamflow regimes. However, we also observed an inconsistency over the northeastern region – annual precipitation has exhibited a notable increase while a dominant decreasing trend was observed in runoff yield – indicating that this rainfall-runoff relationship is not universal, and other landscape attributes such as slope, land cover, water withdrawals and imperviousness of the individual catchment potentially play an important role in modulating changes in river flows.

To differentiate the effect of reference period to that of station density on the results of trend analysis, we compared trends observed over three reference periods across 27 stations that met data-quality criteria of all reference periods (Figure 4). Although there is some consistency between changes detected across different reference periods (correlation ranges from 0.4 to 0.6), the rate of changes from 1995 to 2015 is much higher than that observed over the 1980-2015 and 1960-2015 periods. The composition between increasing and decreasing trends in this subset is generally consistent to the overall trends observed across all stations; that is 9, 18, and 10 of all 27 stations characterized with an increasing trend over the 1960-2015, 1980-2015, and 1995-2015 reference period respectively.

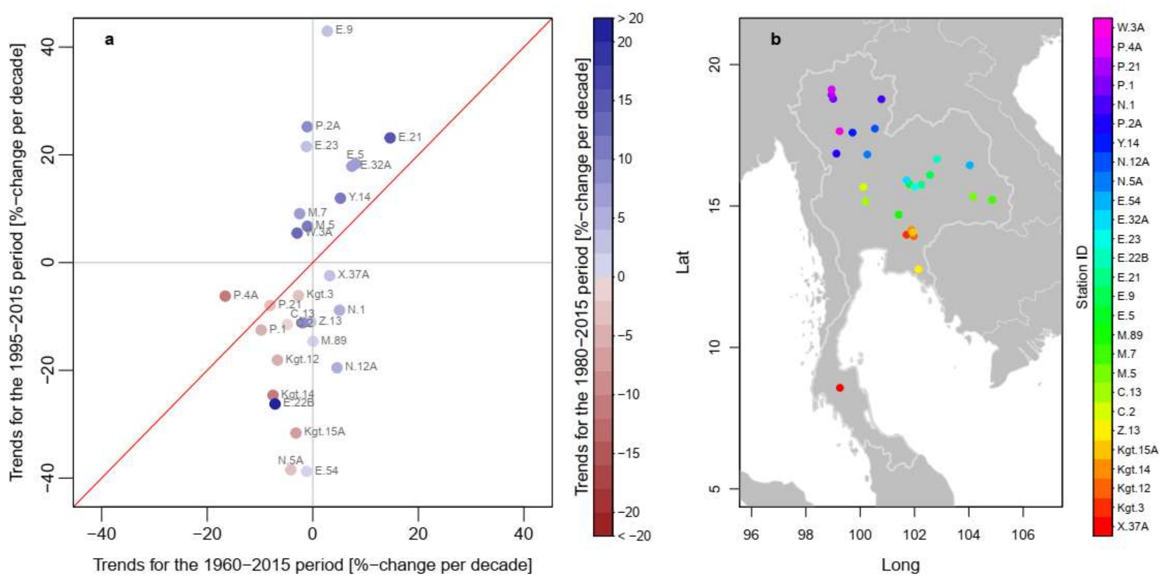

Figure 4. Changes of runoff yield observed over 27 stations with sufficient data across all reference periods (a). The 1:1 line and the geographical locations of these stations (b) were also showed for reference.

The results of trend analysis of key climate variables and runoff yield across the nested periods suggest that a single metric such as the normalized trend may not fully reflect the complexity of temporal hydro-climatic changes across Thailand. To further explore the relationship between changes in Thailand's river flows and changes in climate and landscape attributes, we then focused on two regions (of all nine climate regions defined in *Tangang et al.* [2019] based on the magnitude and seasonal cycle of rainfall) that have relatively good streamflow coverages. Figure 5 shows that temperature exhibited an overall increasing trend over both regions (bounded by red boxes in Fig. 5d), consistent to that showed in Figure 2.

Evapotranspiration showed a decreasing trend over the most recent years in northeastern Thailand (Fig. 5b); while a steady increasing trend of evapotranspiration is observed over the northern region. This assessment also highlights a high inter-annual variation and an unprecedented declining rate since 2010 of regional precipitation.

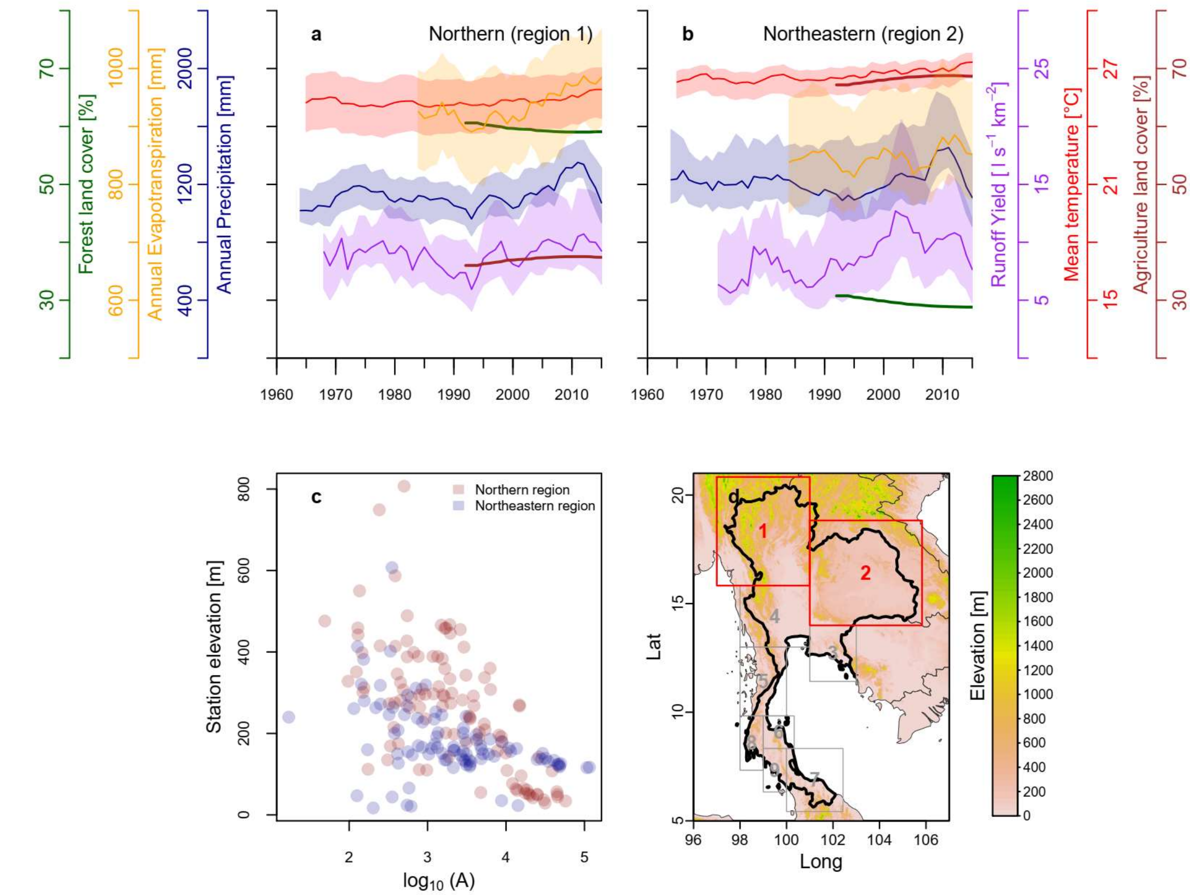

Figure 5. Temporal variation of annual runoff yield (purple), precipitation (blue), evapotranspiration (orange), surface temperature (red), the percentage of agricultural (brown) and forest (dark green) land cover over the northern (panel a) and the northeastern (panel b) Thailand. Years with less than ten data points were assigned a missing value. Runoff yield, precipitation, temperature and evapotranspiration were smoothed by a 5-year moving-window filter (right-aligned); the solid lines represent the median while the shaded bands represent the range between the 25th and 75th percentiles (extracted from the normal distribution that estimated using all available data points) within each region. The log-transformed catchment area and elevation associated with all stations within the two regions were also showed (panel c; the boundaries of the two focused regions are highlighted by red boxes in panel d). Elevation is obtained from the HydroSHEDS dataset at the 3 arc-second (about 90 meter) resolution [*Lehner et al.*, 2006].

Over these two regions, regional runoff yield exhibits a strong response to changes in precipitation, although the relationship is less consistent over the northeastern region (Fig. 5b) relative to the northern region (Fig. 5a). For instance, regional runoff yield over the northeastern region shows an overall increasing trend during the 1985-2002 period while regional precipitation exhibited a mild decline from 1985 to 1995, followed by a gradual increase. Data availability is a potential reason for this discrepancy, as missing data is more common over the northeastern stations relative to the northern counterpart.

Another factor that could lead to this discrepancy is the contrasting landscape attributes of these two regions. Specifically, northern Thailand is characterized by mountainous topography (Fig. 5c) and forest land cover (about 60%) while the northeastern region has a low-elevation cropland profile (nearly 70%). Catchments over northeastern Thailand, therefore, are more likely (relative to northern Thailand) to be influenced by irrigation, leading to a slightly less consistent response to precipitation. It is informative to note that the contrasting landscape attributes appear to also modulate changes in evapotranspiration, which has exhibited opposing patterns over the last decade despite similar trends observed in temperature and precipitation. We also note that the composition of land cover types also changes over time, indicating a gradual transition from forest land cover to cropland in both regions since 1992. These observed patterns have reinforced a common concern of the growing number, and significant influence of hydropower dams as well as irrigation expansion on regional hydrology across Southeast Asia [*Biemans et al.*, 2011; *Hecht et al.*, 2019], making it difficult to reliably forecast and manage water resources in a warming climate [*Jahandideh-Tehrani et al.*, 2019].

4 Conclusion

This study provides the first long-term, observation-based, large-sample assessment of changes in river flows over the mainland Southeast Asia. The results show a strong response of tropical rivers across Thailand to a highly varying precipitation regime, which has exhibited an unprecedented decrease since 2010, leading to widespread and persistent drought. These findings reflect a pressing demand for robust regional projection of precipitation [*Tangang et al.*, 2020], which is crucial to developing and implementing water policy to support sustainable development in tropical regions. This study also shows a relatively less consistent response of river flows to precipitation over regions associated with a high percentage of cropland relative to that dominated by forest land cover. The transition of forest to cropland observed during the 1992-2015 period in Thailand also indicates the needs for more efforts to quantify the impact of land cover changes and human activities on regional hydrology of Southeast Asia [*Hecht et al.*, 2019; *Jaramillo and Destouni*, 2015]. More importantly, the study highlights the commendable efforts (in operating, maintaining observational networks; and in making up-to-date streamflow records publicly available) of national water agencies to support advances in tropical river hydrology.

Acknowledgments and Data

The authors thank the Royal Irrigation Department of Thailand for making streamflow observations publicly available. Observational streamflow are accessible at http://water.rid.go.th/hyd. APHRODITE temperature and precipitation are accessible at https://www.chikyu.ac.jp/precip. EASCCI-LC dataset is available at https://www.esa-landcover-cci.org. GLEAM dataset is available at https://www.gleam.eu. HydroSHEDS elevation data is available at https://hydrosheds.org. GIS layers of Thailand's river networks were downloaded from http://www.savgis.org/thailand.htm.

HXD is currently funded by the School for Environment and Sustainability, University of Michigan, through grant number U064474. PNDV and HTP were supported by The University of Danang, University of Science and Technology, through Project number T2020-02-22.

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