A decrease in river discharge and rainfall amount, from a 100-year data set, in response to El Niño events on the interannual temporal scale for the Philippines

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Abstract

The El Niño Southern Oscillation (ENSO) modulates rainfall amount variability and, by extension, river discharge in the Philippines on seasonal to interannual temporal scales. The El Niño phase (ENP) of ENSO considerably decreases rainfall amounts on a seasonal scale in the western Pacific with varying degrees of heterogeneity expressed across the Philippines. Our understanding of the response in the hydroclimate to ENPs on interannual timescales is still relatively immature. As such, to investigate the hydroclimate response, a composite time series of 29 rainfall and 61 river discharge stations spanning 1901-2020 and 1908-2017 C.E., respectively, and covering the four major climate types in the Philippines were assessed. Our results suggest, regardless of climate type, that river discharge and rainfall data decrease following ENPs. The median response suggests that the decreasing trend can last up to seven years. Further, the hydroclimate response follows either a decreasing trend, if at conception of an ENP, or an increasing trend, if at the termination of an ENP. As water-scarcity becomes an area of immediate concern in an increasingly warming climate, our results have implications for interannual water resource management in this drought-prone tropical archipelago.

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Key Points:

- A river discharge and rainfall data set spanning 100 years in the Philippines used to analyze the hydroclimate response to El Niño periods.
- Composite river discharge and rainfall means, with seasonality and long-term trends removed, show decrease following El Niño event where an event is sea surface temperature >1°C in Nino 3.4 region.
- The decreasing trend in the hydroclimate variables can up to last several years using a Superposed Epoch Analysis.

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Abstract

The El Niño Southern Oscillation (ENSO) modulates rainfall amount variability and, by extension, river discharge in the Philippines on seasonal to interannual temporal scales. The El Niño period (ENP) of ENSO considerably decreases rainfall amounts on a seasonal scale in the western Pacific with varying degrees of heterogeneity expressed across the Philippines. Our understanding of the response in the hydroclimate to ENPs on interannual timescales is still relatively immature. As such, to investigate the hydroclimate response, a composite time series of 29 rainfall and 61 river discharge stations spanning 1901-2020 and 1908-2017 C.E., respectively, and covering the four major climate types in the Philippines were assessed. Our results suggest, regardless of climate type, that river discharge and rainfall data decrease following ENPs. The median response suggests that the decreasing trend can last up to seven years. Further, the hydroclimate response follows either a decreasing trend, if at conception of an ENP, or an increasing trend, if at the termination of an ENP. As water-scarcity becomes an area of immediate concern in an increasingly warming climate, our results have implications for interannual water resource management in this drought-prone tropical archipelago.

1 Introduction

Coupled air-sea interactions of the El Niño Southern Oscillation (ENSO) in the Pacific Ocean lead to tropical drought conditions in the Philippines during El Niño (warm) phases on a seasonal temporal scale (Lyon, 2004; Lyon et al., 2006). The drought conditions during an El Niño phase of ENSO is induced by the late onset of the rainy season, early termination of the rainy season, or a weak monsoon system characterized by isolated heavy rainfall events of short-durations (Lansigan et al., 2000). Geographically, the Philippines is located in the western Pacific between 4°40'N to 21°10'N, 116°40'E to 126°34'E with over 7,000 islands in the archipelago (Figure 1a). The large agronomic sector of the Philippines relies on seasonal rainfall for crop production and multiple previous studies have highlighted the loss in crop production during El Niño events (Lansigan et al., 2000; Cinco et al., 2014; Stuecker et al., 2018). The seasonal response in rainfall as a result of El Niño events is spatially heterogeneous across the Philippines and continues to be an active area of research (Lyon, 2004; Lyon et al., 2006; Villafuerte II et al., 2014; Villafuerte et al., 2015). However, the legacy effects of El Niño events on the hydroclimate in the Philippines are still poorly understood and understudied in the literature. Further, the legacy effect of El Niño with respect to drought conditions (Kolusu et al., 2019), terrestrial ecosystems (Jorge-Romero et al., 2021), and coral reefs (Claar et al., 2018) highlight the need to investigate the response of hydroclimate to El Niño periods on an interannual temporal scale.

Understanding the relationship between the hydroclimate and El Niño periods on an interannual temporal scale is important for water resource management, especially since extreme El Niño events are predicted to increase in intensity and frequency due to anthropogenic-induced greenhouse warming (Cai et al., 2014). In this study we leverage 100-year long river discharge (1908-2017 C.E.) and rainfall amount (1901-2020 C.E.) data spatially spread across the Philippine archipelago to discern the relationship between hydroclimate variables and El Niño events for the 20^{th} and 21^{st} century. In this study, rainfall discharge data and rainfall amount data constitute the two hydroclimate variables of interest. Paired rainfall amount and river discharge response to ENSO phases provide a nuanced response to hydroclimate variability, which might be missed if only one of the two hydroclimate variables is used (Schmidt et al., 2001; Poveda et al., 2001; Poveda et al., 2011). River discharge acts an integration of rainfall over a given river basin and provides insight into the lagged response of the land-atmosphere water cycle. Rainfall data on the other hand is a closer reflection of the ocean-atmosphere water cycle and larger-scale dynamical moisture delivery (or lack thereof) due to ENSO teleconnections (Lyon et al., 2006). Next, to assess the range of hydroclimate responses to the El Niño

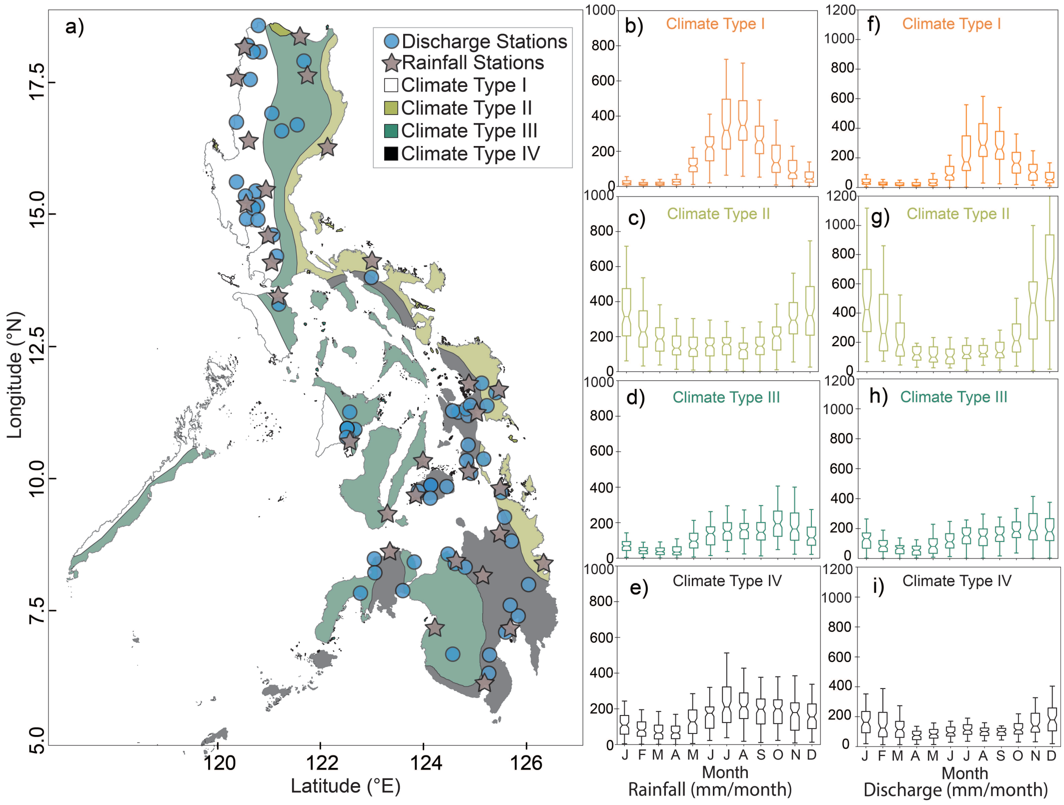

Figure 1. (a) Map of the Philippines with river discharge stations and rainfall amount stations used in this study. The prevalent climate types following Ibarra et al. (2021) (see also Makanas (1990); Jose and Cruz (1999); Tolentino et al. (2016)) are overlain with different colors. Rainfall and river discharge distribution for (b,f) Climate Type I, (c,g) Climate Type II, (d,h) Climate Type III, (e,i) Climate Type IV as monthly box plots highlight differences in the seasonality of the hydroclimate.

phase of ENSO, we conducted multiple sensitivity analyses using different criterion. First, we investigated the response to different intensities of El Niño events. Next, we investigated the response at the beginning and termination of El Niño periods. An event typifies a single time unit and a period typifies a duration of time. Lastly, to isolate the interannual temporal variability of the hydroclimate variables, we removed the seasonal and long-term trends from the composite time series. The composite time series were the mean river discharge and rainfall station data for the four different Climate Types.

In this work, Superposed Epoch Analysis suggests that rainfall and river discharge decrease at statistically significant values in response to the El Niño phase of ENSO. The duration of the decreasing trend can last up to seven years following the event of interest. Our sensitivity analyses highlight the nuanced hydroclimate response to the El Niño period. At the conception of an El Niño period, the hydroclimate variables decrease. Conversely, at the termination of an El Niño period, hydroclimate variables increase towards wetter conditions. Further, rainfall has a quicker, albeit a smaller amplitude, response to the El Niño phase compared to river discharge. Our results have implications for water resource management avenues that traditionally investigate the seasonal response to the El Niño or La Niña phases of ENSO. As irrigation-dependent ecosystems address the growing scarcity of water (Perez-Blanco & Sapino, 2022), we highlight the legacy effects of El Niño and its implications for water resource management on an interannual temporal scale. Addressing tropical droughts modulated through El Niño and subsequent health concerns on an interannual temporal scale provides a framework to investigating long-term impacts of El Niño in the Philippines and global tropics(Kovats, 2000).

2 Methods and Data set Description

Four major climate types prevail in the Philippines based on the modified Coronas Classification, following Tolentino et al. (2016) and Ibarra et al. (2021) (Figure 1a; (Makanas, 1990; Jose & Cruz, 1999). River discharge (interchangeably termed here as streamflow) and rainfall data were subdivided following the four major climate types. Composite rainfall (averaged over 1901-2020 CE) and river discharge (averaged over 1908-2017 CE) climatologies reveal a distinct boreal summer wet season (June-October) for Climate Type I (Figure 1b and 1f) and a distinct boreal winter wet season (November-March) for Climate Type II (Figure 1c and 1g). Climate Type III (Figure 1d and 1h) and Climate Type IV (Figure 1e and 1i) have a less distinctive wet season.

River discharge and rainfall data, termed here as hydroclimate variables, were largely collated from multiple observation stations and one gridded spatial data set. The different data sets are briefly described below. Data handling steps to construct composite river discharge and rainfall time-series covering the 20^{th} and 21^{st} century for each climate type are also described. All steps described herein were conducted using Python3.2 (Van Rossum & Drake, 2009) and available as part of this publication (See Section 6).

2.1 River Discharge Data set

Monthly streamflow observations from 61 river discharge stations spanning 1908-2017 C.E. were analyzed in this study (Supplemental Table 1). Streamflow observation data for 55 stations from 1946 C.E. onwards come from Ibarra et al. (2021) and comprise three Philippine data sets: Bureau of Research Standards data set, Global Runoff Data Centre data set, and Global Streamflow Indices and Metadata archive reference data set. The acquisition and processing of streamflow data for the 55 stations are discussed in detail in Tolentino et al. (2016) and Ibarra et al. (2021). Briefly, the Philippines' Department of Public Works and Highways maintains records of river discharge data initially through the Bureau of Research and Standards and now through the Bureau of Design. The Global Runoff Data Center is a global data set that records river discharge data and was initiated with the World Meteorological Organization. Global

Streamflow Indices and Metadata archive is a collection of daily streamflow observations (Gudmundsson et al., 2018).

We extend the Ibarra et al. (2021) streamflow observation data by incorporating historical river discharge data that spanned 1908-1922 C.E for eight rivers. The historical river discharge data is the result of daily streamflow measurements between 1908-1914 and 1918-1922 C.E. made by the Irrigation Division of the Bureau of Public Works (Williams & Gochoco, 1924). Daily streamflow measurements were not made between December 1914 and June 1918 due to lack of funds. Historical data for 53 rivers are available through the Bureau of Public Works. However, the daily measurements made were sparse and sporadic (Williams & Gochoco, 1924). Therefore, the criteria for selecting historical river discharge measurements in this study were twofold. First, data that extended the river discharge observations collated by Ibarra et al. (2021) were included. Second, historical river discharge data that had measurements for nine or ten years (1908-1913 and 1918-1922 C.E.) were included for further analyses. Eight historical river discharge data met this criteria (BPW in Supplemental Table 1). In total, 61 river discharge station data sets with monthly mean values of river discharge were included in this analysis (Supplemental Figure 1a-d). For this study, daily discharge measurements reported in liters/second were averaged to monthly means and normalized by the drainage area (units of sq. km), resulting in mm/month units, comparable to the data sets collated in Ibarra et al. (2021). In cases where diurnal streamflow measurements were made, we first took the daily average before down sampling to area normalized monthly means.

2.2 Rainfall Amount Data set

Monthly rainfall data from 29 stations spanning 1901-2020 C.E. were analyzed (Supplemental Table 2, Supplemental Figure 2a-d). Data was collated from three different data sets. The Philippine Weather Bureau (PWB) data set, later digitized and archived by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), included daily rainfall amounts spanning 1901-1940 C.E. for 65 stations across the Philippines (Kubota et al., 2017). However, the measured rainfall amount data are sporadic and sparse, hence, only PWB stations that had ten years of continuously measured rainfall data were selected for analyses. 14 stations with daily rainfall data covering 1901-1940 C.E. met the aforementioned criteria. The daily data were summed to give monthly rainfall totals in mm/month. Next, the Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) contains a gridded daily rainfall amount in inches based on a dense network of rain-gauge stations interpolated at 0.25x0.25° (Yatagai et al., 2012). Rainfall data for 26 stations spanning 1951-1990 C.E. that extended either the PWB station data or data from 1991-2020 C.E. (final data set) were incorporated as monthly rainfall totals in mm/month. The final data set (denoted as modern in Supplemental Table 2) is from the United States National Centers for Environmental Information (NCEI), an official repository of climate data from the World Meteorological Organization (Makanas, 1990; Lawrimore et al., 2011). The Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA) regularly deposits its meteorological data in the NCEI. This third data set spans 1991-2020 C.E. Rainfall data measured in inches was converted to monthly totals in mm. In order to include data with extreme rainfall amounts and to make the rainfall data comparable to river discharge data, daily rainfall data was summed to monthly rainfall totals. In this analysis, we are interested in investigating the spatial and temporal hydroclimate response to the El Niño phase of ENSO. In order to compare amplitude and lead and lag variability between rainfall and river discharge, we selected rainfall station data that was spatially and temporally equivalent to a river discharge station and within the same Climate Type (Figure 1a). Hence, we note that there are multiple additional rainfall station data from the PAGASA/NCEI data set that were not utilized in this study. Out of 58 NCEI stations, we only used rainfall data from 28 stations spanning 1991-2020 C.E.

2.3 Developing Composite Time Series

Composite time-series based on Climate Types were constructed to maximize the length of measured river discharge and rainfall data for subsequent analysis. Data handling steps to construct river discharge and rainfall data composite time series are described:

1. Individual river discharge and rainfall data in monthly means (mm/month) and monthly sums (mm/month), respectively, were categorized according to the four major Climate Types.
2. The mean of the subset river discharge and rainfall data based on Climate Types were calculated. For example, the composite river discharge time series of Climate Type I is the mean of 17 river discharge stations. Similarly, the composite rainfall data time series of Climate Type I is the mean of seven rainfall amount stations.
3. The mean data were then log transformed to approximately conform to a normal distribution. The units are in log(mm/month).
4. The log transformed data were standardized, thereby data is unitless, by removing the mean and scaling to unit variance. Hence, variation on the y-axis of the composite time series is the departure from the log transformed mean,
5. A polynomial fit (order = 3), which best captured the shape of the long-term trend, was applied to the standardized data from Step 4. The long-term trend was removed to isolate the intrinsic variability in El Niño and to minimize anthropogenic induced variability. The resulting trend was then subtracted from the standardized data.
6. Finally, sub-seasonal and seasonal frequencies were removed from the detrended data to isolate the interannual variability of El Niño Cyclicity. The sub-seasonal and seasonal signal was removed by taking the 6 ($\pm$3)- and 12 ($\pm$6)- month centered moving average of each time series.

The resultant composite river discharge and rainfall time series based on the four different Climate Types were compared against the Nino3.4 Relative Index time series (next section).

2.4 Nino3.4 Relative Index

Multiple indices measuring Sea Surface Temperature (SST) anomalies in the tropical Pacific exist to track oscillations between El Niño, Neutral, and La Niña periods. Nino3.4 Index acts as a bellwether to forecast the onset of ENSO conditions (D. Chen et al., 2004). Nino3.4 is the average SST anomaly (departures from 1971-2000 C.E.) in the region bounded by 5°N to 5°S, from 170°W to 120°W. Local SST changes in this region, which is indicative of changing deep tropical convection and atmospheric circulation, are critical for affecting rainfall variability over the Philippines (Lyon, 2004). Recent studies highlight the importance in removing the SST tropical trends to increase the sensitivity of the indices in relation to climate change (Turkington et al., 2019; Van Oldenborgh et al., 2021). The Nino3.4 Relative Index is the Nino3.4 SST anomaly after removing the tropical (20°S-20°N) ocean SST trend (Van Oldenborgh et al., 2021). The SST values used in this study are from the Extended Reconstructed Sea Surface Temperatures Version 5 and span 1854-2020 C.E. (Huang et al., 2017).

An El Niño period changes in its SST definition depending on the cited study. For example, Trenberth (1997) defines an El Niño period if SST anomalies (SSTA) in the Nino3.4 region exceed 0.4°C for 6 months or more. In constrast, NCEI characterizes an El Niño period by time-periods when SSTA in the Nino3.4 region exceeds 0.5°C for 5 months (Dole et al., 2018). Lastly, the National Climate Center classifies an El Niño period if SSTA in the Nino3.4 region exceeds 0.8°C, which is approximately 1 standard deviation greater than the average SST (Nicholls, 1991). Given the range in definitions of what constitutes an El Niño period, in this analysis we considered an El Niño period when SSTA in the Nino3.4 region exceeded 1°C for 3 months or more. Next, normal El Niño events are classified as deviations of 1°C or greater. Lastly, extreme El Niño events are classified by a deviation of 2.2°C or greater in the Nino3.4 region, following the 1997/97 and 2015/16 events (Santoso et al., 2017). To assess the response of the background (noise) tropical Pacific conditions, a superfluous signal with a minimally positive SSTA is defined when SSTA in the Nino3.4 region range between 0 to 0.2°C.

2.5 Hydroclimate Response to El Niño Events

Multiple Superposed Epoch Analysis (SEA) with different criterions were conducted to evaluate the range in response of the hydroclimate variables (river discharge and rainfall) to El Niño events and periods. SEA is a statistical test that identifies the link, magnitude, and significance between discrete events and continuous time series within a probabilistic framework, which is optimized by averaging across all events (Haurwitz & Brier, 1981). Recently, a modified double-bootstrap SEA framework (Rao et al., 2019) that quantifies uncertainty in the median response and in the natural background variability has been used to investigate ENSO (Dee et al., 2020), drought (Gazol & Tíscar, 2020), and river discharge (Rao et al., 2020). Briefly, the median response in a SEA is a deviation in climatology from a pre-event time frame covering a post-event time frame. A total window length of 11 years, which covers 3 years pre-event to 7 years post-event was used in our study. Year 0, therefore corresponds to an El Niño event in the format of YYYY-MM. Detailed methodology for the double-bootstrap SEA is described in Rao et al. (2019). SEA was not conducted on historical (1901-1940 C.E.) river discharge data due to a lack of sufficient and continuous data but was nevertheless included in our time series for graphical comparison with contemporaneous rainfall data. To capture the whole range in the hydroclimate response, SEA was conducted on the composite river discharge and rainfall data with five different categories/criterion of what defines an event of interest.

1. Category I/Normal El Niños: A discrete time-series list where every month with SSTA in Nino3.4 Relative Index is greater than 1°C and is thus considered an El Niño event of interest.
2. Category II/Extreme El Niños: A discrete time-series list with only extreme El Niños, defined when SSTA in Nino3.4 Relative Index is greater than 2.2°C. If multiple consecutive months have SSTA's greater than 2.2°C, only the month with the largest SSTA was considered an event of interest. Therefore, the discrete time-series is constructed with the peak of extreme El Niños.
3. Category III/Conception of an El Niño period: A discrete time-series that defines an event of interest as the first month during an El Niño period of at least 3 continuous months greater than 1°C.
4. Category IV/Termination of an El Niño period: A discrete time-series that defines an event of interest as the last month during an El Niño period of at least 3 continuous months greater than 1°C.
5. Category V/Superfluous Signal Response: A discrete time-series that defines an event of interest within the neutral phase where SSTA is between 0 and 0.2°C.

The categories therefore capture different flavors during ENSO's El Niño phase. Category I and II capture the intensities of El Niño events. Category III and IV together capture the response of the hydroclimate variables during the life-cycle (i.e., conception to termination) of an El Niño period. Category V (superfluous signal) was added to assess the validity of the SEA between signal and background conditions of the tropical Pacific. The 5^{th} percentile, median, and 95^{th} percentile hydroclimate response is calculated from 1,000 composite matrices using unique subsets of N events at random without replacement from the discrete event time-series. N events randomly selected represent approximately half the total number of events for each category. Events that were beyond the post-year time period were not included. For example, 2015-05, is an El Niño event of interest under Category I, however, the post-event 7-year period dates to 2022-05 C.E. As there is no hydroclimate or SST data (yet) available for that period, 2015-05 is not included in the discrete time-series, which signifies the events of interest. The 1^{st}, 5^{th}, 10^{th}, 90^{th}, 95^{th}, 99^{th} significance thresholds needed to be exceeded for the SEA response to be significant were calculated using random bootstrap generated by drawing pseudo events over the entire time series for the same number of (N) events (Brad Adams et al., 2003). The significance thresholds provide a robust assessment such that when the response crosses the threshold there is high confidence that the response is not a random signal. The superfluous signal category falls within neutral conditions of ENSO atmosphere-ocean dynamics. The category assesses whether it is the El Niño phase of ENSO that contributes to the hydroclimate response or neutral tropical Pacific Ocean conditions. If the hydroclimate response to Category V is the same for Category I-IV as shown by SEA, delineating between El Niño or neutral conditions as the causal mode modulating the hydroclimate response would be difficult.

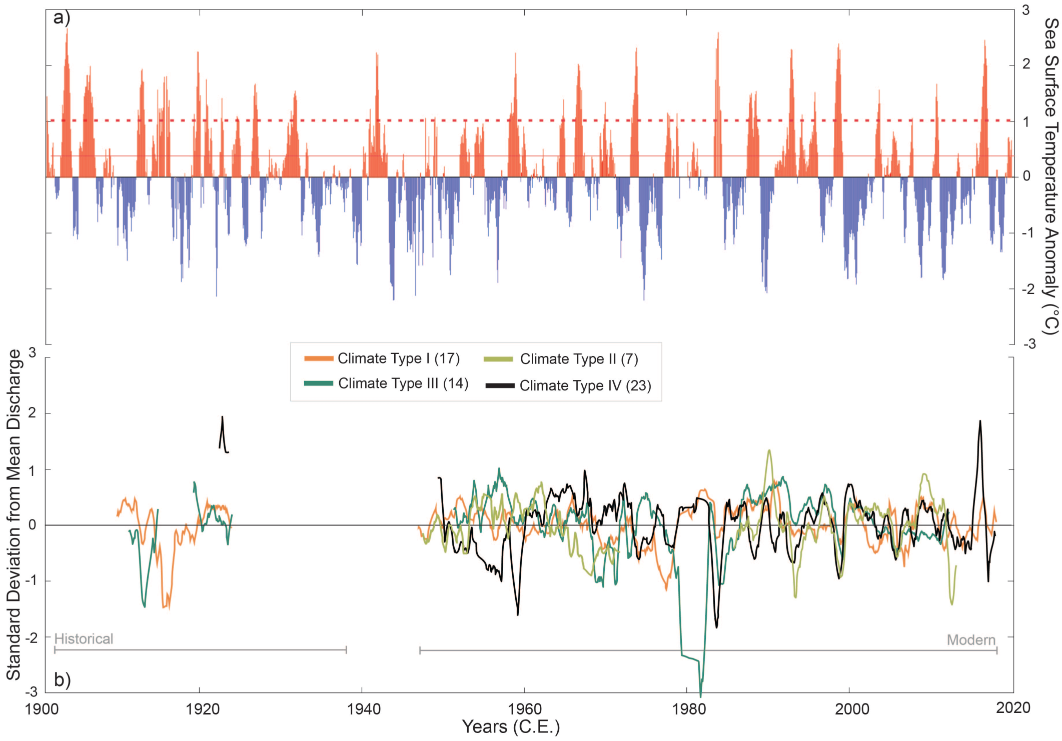

Figure 2. (a) Sea-surface temperature anomalies (SSTA) for the Nino3.4 region with the tropical trend removed (Nino3.4 rel. index). b) Time-series of river discharge data based on different climate types region for the 20^{th} and 21^{st} century. The red dashed line indicates extreme El Niño events. The red solid line indicates criteria for superfluous signal sensitivity test. N is the number of river discharge stations in each Climate Type to calculate a composite record.

3 Results

The composite river discharge and rainfall time series with the long-term trend and seasonal signal removed for the four climate types compared against Nino3.4 Relative Index are shown in Figure 2 and 3, respectively. The composite hydroclimate time series covers historical (1901-1940 C.E.) and modern (1950 - 2020 C.E.) periods. The results from the data handling steps to obtain the composite time series for the four Climate Types for river discharge and rainfall data are in Supplemental Figure 3-6 and Figure 8-11, respectively. The polynomial fit to remove the long-term trend and the subsequent detrended river discharge and rainfall data are in Supplemental Figure 7a-h and Figure 12a-h.

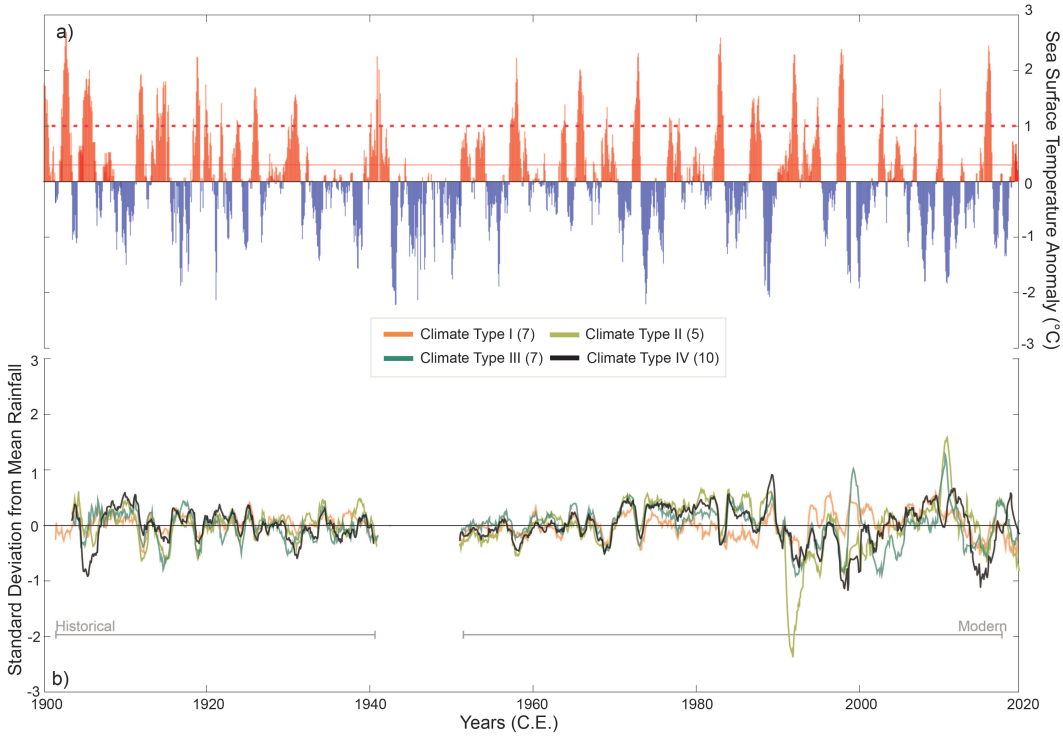

Figure 3. (a) Sea-surface temperature anomalies (SSTA) for the Nino3.4 region with the tropical trend removed (Nino3.4 rel. index). b) Time-series of rainfall data based on different climate types region for the 20^{th} and 21^{st} century. The red dashed line indicates extreme El Niño events. The red solid line indicates criteria for superfluous signal sensitivity test. N is the number of rainfall stations in each Climate Type to calculate a composite record.

3.1 Seasonal Distribution of El Niño events

The highest number of El Niño events in Category I/Normal El Niños (see Section 2.5. for definitions of different Categories) occur during the boreal winter (October-February) months (Figure 4a and 4e). For all four Climate Types, El Niño events of interest in Category I of composite river discharge and rainfall data occur throughout the year. April is the month with the lowest number of El Niño events. The extreme El Niño event (Category II), which is typically the peak (a single month) with SSTA's greater than 2.2°C falls during the boreal winter months (Figure 4b and 4f). This is in agreement with literature suggesting that boreal winter is the maturation period for the Nino3.4 region in the Pacific Ocean (McPhaden, 2003). Here we define the conception of an El Niño period as the first month of at least three continuous months with SSTA's greater than 1°C (Category III) filtered from events in Category I. The seasonal distribution of Category III events is bimodal over Spring (April-June) and Winter (October-January) months (Figure 4c and 4g). The termination of the El Niño period is the last month of at least a three-month period with SSTA's greater than 1°C (Category IV) filtered from events in Category I. A majority of events in Category IV occur during the boreal late winter/early spring (February - March) months (Figure 4d and 4h); hence, suggesting that the conception of El Niño events occur in spring or winter. Conversely, El Niño periods terminate in the winter. Seemingly, El Niño events of interest are absent (for Category II, III, IV) during the boreal summer months of July-September. This highlights the complex nature of investigating El Niño response to hydroclimate variability on the seasonal scale. The variation in the number of counts in river discharge and rainfall data (y-axis in Figure 4) lies in the time-continuous nature of the composite time-series for the four major Climate Type. A strength of Superposed Epoch Analysis is that it provides a response to an aggregated event list. Further, the removal of the seasonal signal and long-term trends from the composite river discharge and rainfall amount data provides an opportunity to investigate responses on intra to interannual scales.

3.2 River Discharge Response to Different El Niño Criterion

River discharge for all Climate Types shows strong and statistically significant decreases in the years following El Niño events of interest and lasting up to three to five years where an event is defined as any time (YYYY-MM) with SSTA greater than 1°C (Table 1a and Figure 5a). The decreasing trend and the magnitude varies based on the Climate Type. The strongest decrease in discharge (median response), relative to the three-year pre-event mean, occurs three years post-event (i.e. year 0 + 3 on the x-axis) before increasing (at a statistical significance) to pre-event mean for Climate Type I (orange crosses in Figure 5a). The 5^{th} and 95^{th} percentile response (orange shading in Figure 5a) represents the degree of uncertainty based on 1000 unique sets of 50 El Niño events from a total of 103 potential events. Similarly, for Climate Type II (where the SSTA threshold is 2.2°C, extreme El Niños), the strongest decrease in discharge (median response) occurs five years post-event (Table 1a) before increasing (olive green crosses in Figure 5a). The magnitude (amplitude) of river discharge decrease is the most severe and the trend lasts the longest for Climate Type II compared to the remaining three Climate Types. The magnitude and length of decrease in river discharge for Climate Type III is similar to Climate I's response: strongest decrease in discharge (median response) occurs four years post-event (dark green crosses in Figure 5a). However, the increase in discharge is more staggered in Climate Type III compared to Climate Type I. The decrease and increase in river discharge (median response) for Climate Type IV (black crosses in Figure 5a) follows a similar pattern to Climate Type III. However, the amplitude of decrease is approximately two times more severe in Climate Type IV than Climate Type I for Category I.

In Category II (Table 1b), river discharge for all Climate Types shows a strong decrease in the years following extreme El Niño events and lasting up to four (Climate Type I) or seven (Climate Type II and IV) years. The decrease in river discharge, relative to the pre-event mean, is statistically not significant for Climate Type III. The magnitude of the strongest decrease is for rivers in Climate Type II (-0.7 on the y-axis). The decrease in river discharge for Climate Types I is followed by an increase to pre-event mean climatology.

Our SEA results for Category III that take a subset at the conception of a El Niño periods (Table 1c) suggest a decrease in river discharge (median response) for all Climate

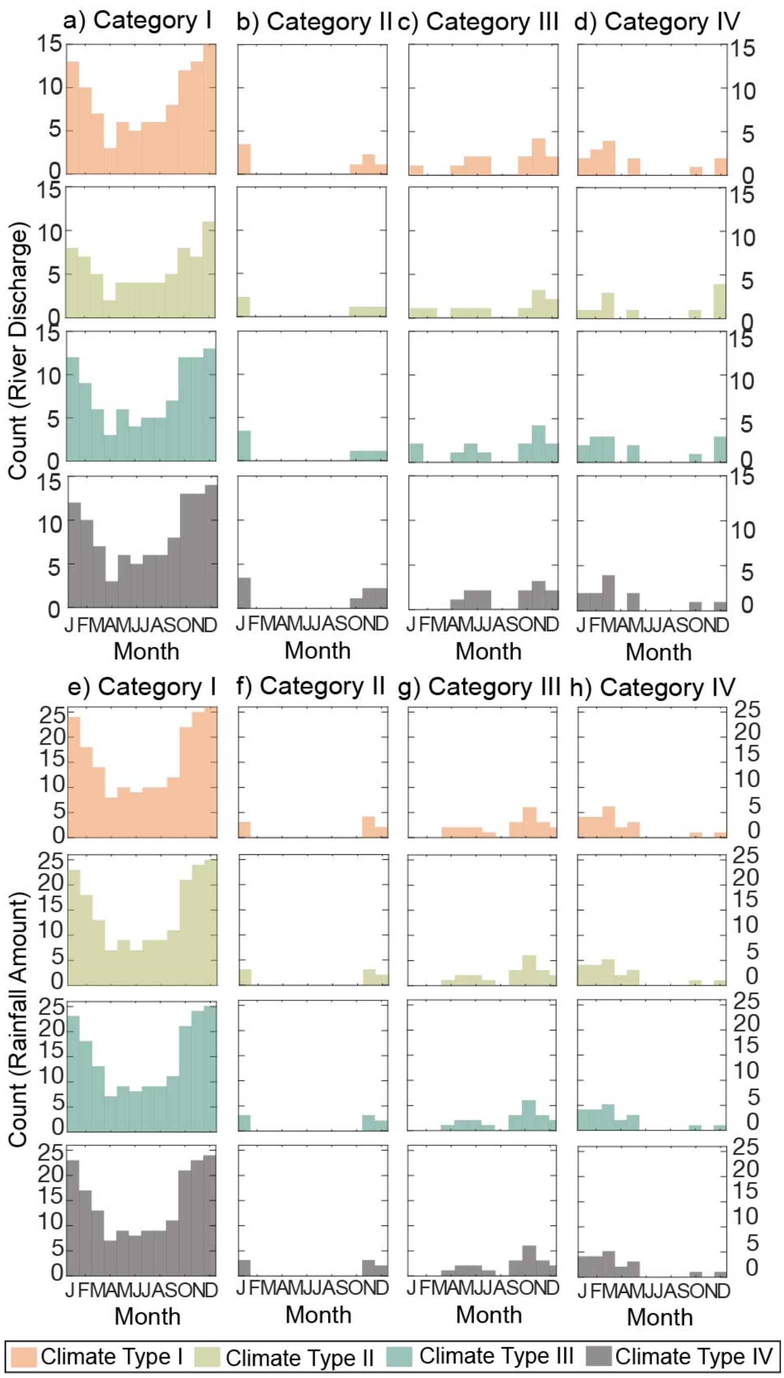

Figure 4. Histogram demonstrating the monthly timing of El Niño events for Superposed Epoch Analysis sensitivity tests that fall under Category I (a,e), Category II (b,f), Category III (c,g), Category IV (d,h) for the four different Climate Types. Columns a) to d) show the monthly distribution of El Niño events for river discharge (modern) composite time series. Columns e) to h) depict the distribution of El Niño events for rainfall (historical + modern) time series.

Table 1. Sensitivity tests investigating the response of discharge to different categories of El Niño events using Superposed Epoch Analysis

Sensitivity Criteria	Number of Events	Post-Event Response	Max. Response Year (Amplitude)	Statistical Significance	
a) Category I/ Normal El Niños: SSTA > 1°C					El Niño Intensity Category
Climate Type I	103	↓ 1-3 yr ; ↑ 4-7yr	+ 3 (-0.10)	1%	
Climate Type II	67	↓ 1-5 yr ; ↑ 6-7yr	+ 5 (-0.20)	1%	
Climate Type III	94	↓ 1-4 yr ; ↑ 5-7yr	+ 4 (-0.10)	5%	
Climate Type IV	103	↓ 1-4 yr ; ↑ 5-7yr	+ 4 (-0.20)	1%	
b) Category II/ Extreme El Niños: SSTA > 2.2 °C					
Climate Type I	6	↓ 1-4 yr ; ↑ 5-7yr	+ 4 (-0.15)	5%	
Climate Type II	5	↓ 1-7 yr	+ 7 (-0.70)	1%	
Climate Type III	*6*	↓ *1- 2yr ;* ↑ *2-7yr*	*+ 1 (-0.10)*	*Not Significant*	
Climate Type IV	8	↓ 1-7 yr	+ 3 (-0.40)	1%	
c) Category III/ Conception of an El Niño Period: First month in an El Niño Period where SSTA > 1°C					Timing within El Niño Period Category
Climate Type I	12	↓ 1-7 yr	+ 7 (-0.30)	1%	
Climate Type II	*11*	↓ *1-7 yr*	*+ 7 (-0.20)*	*Not Significant*	
Climate Type III	11	↓ 1-5 yr ; ↑ 6-7yr	+ 5 (-0.20)	10%	
Climate Type IV	12	↓ 1-7 yr	+ 7 (-0.50)	1%	
d) Category IV/ Termination of an El Niño Period: Last month in an El Niño Period where SSTA > 1°C					
Climate Type I	12	↑ 1-7yr	+ 7 (0.30)	95%	
Climate Type II	*11*	↓ *1-5 yr ;* ↑ *6-7yr*	*+ 5 (-0.50)*	*Not Significant*	
Climate Type III	11	↑ 1-7yr	+ 7 (0.25)	90%	
Climate Type IV	12	↑ 1-7yr	+ 7 (0.40)	90%	
e) Category V/Superflous Signal Check: 0.2°C < SSTA > 0°C					Noise Category
Climate Type I	70	↑ 1-7yr	+ 7 (0.05)	95%	
Climate Type II	41	↓ 1-3 yr ; ↑ 4-7yr	+ 3 (0.05)	95%	
Climate Type III	*56*	↓ *1-7 yr*	*+ 7 (0.05)*	*Not Significant*	
Climate Type IV	*68*	↑ *1-7yr*	*+ 7 (0.05)*	*Not Significant*	

Types. The decreasing trend lasts between five (Climate Type III) and seven (Climate Type I and IV) years. The magnitude of the strongest decrease is for rivers in Climate Type IV (-0.5 on the y-axis). The median response is statistically not significant for Climate Type II. Conversely, our SEA results for Category IV that takes a subset at the termination of an El Niño period (Table 1d) suggests an increase in river discharge (median response) for Climate Types I, III, and IV. The increasing river discharge trend lasts for seven years for the three Climate Types. The magnitude of the strongest increase, similar to Category III, is for rivers in Climate Type IV (0.4 on the y-axis). River discharge decreases at a statistically insignificant level for Climate Type II.

To ascertain the response of neutral conditions or the background variability (Category V), our SEA result suggests an increase for Climate Type I and II. The response in Climate Type III and IV is statistically insignificant. The superfluous signal response is the opposite from Category I and II, which are the normal and extreme El Niño events. Further the amplitude of the response is much smaller (0.05) compared to the response when using different El Niño criterion. Therefore, this analysis adds confidence that the response in river discharge to El Niño events in the Nino3.4 region is a robust deviation from the neutral climate conditions.

Table 2. Sensitivity tests investigating the response of historical rainfall data to different categories of El Niño events using Superposed Epoch Analysis

Sensitivity Criteria	Number of Events	Post-Event Response	Max. Response Year (Amplitude)	Statistical Significance	
a) Category I/ Normal El Niños: SSTA > 1°C					El Niño Intensity Category
Climate Type I	83	↓ 1-4 yr ; ↑ 5-7yr	+ 4 (-0.02)	1%	
Climate Type II	71	↓ 1-2 yr ; ↑ 3-7yr	+ 2 (-0.10)	1%	
Climate Type III	72	↓ 1-2 yr ; ↑ 3-7yr	+ 2 (-0.10)	1%	
Climate Type IV	69	↓ 1-2 yr ; ↑ 3-7yr	+ 2 (-0.10)	1%	
b) Category II/ Extreme El Niños: SSTA > 2.2 °C					
Climate Type I	3	Not Enough Events For SEA			
Climate Type II	2				
Climate Type III	2				
Climate Type IV	2				
c) Category III/ Conception of an El Niño Period: First month in an El Niño Period where SSTA > 1°C					Timing within El Niño Period Category
Climate Type I	9	↓ 1-7 yr	+ 7 (-0.20)	1%	
Climate Type II	8	↓ 1-7 yr	+ 7 (-0.20)	1%	
Climate Type III	8	↓ 1-7 yr	+ 7 (-0.30)	10%	
Climate Type IV	8	↓ 1-7 yr	+ 7 (-0.30)	5%	
d) Category IV/ Termination of an El Niño Period: Last month in an El Niño Period where SSTA > 1°C					
Climate Type I	9	↑ 1-7yr	+ 7 (0.20)	95%	
Climate Type II	8	↑ 1-7yr	+ 7 (0.30)	95%	
Climate Type III	8	↑ 1-7yr	+ 7 (0.30)	95%	
Climate Type IV	8	↑ 1-7yr	+ 7 (0.30)	99%	
e) Category V/Superflous Signal Check: 0.2°C < SSTA > 0°C					Noise Category
Climate Type I	56	↑ 1-7yr	+ 7 (0.05)	95%	
Climate Type II	55	↑ 1-5 yr ; ↓ 6-7yr	+ 5 (0.10)	95%	
Climate Type III	55	↑ 1-2 yr ; ↓ 3-7yr	+ 2 (0.05)	95%	
Climate Type IV	68	↑ 1-2 yr ; ↓ 3-7yr	+ 2 (0.05)	95%	

3.3 Rainfall Amount Response to Different El Niño Criterion

Historical (Table 2a) and modern (Table 3a) rainfall response for all Climate Types shows strong and significant decrease in the years following El Niño events and lasting up to two to four years where an event is defined as any time period with SSTA greater than 1°C (Figure 5b and 5c). That said, the magnitude of decrease is not as strong as the response observed in river discharge. Second, the recovery to pre-event mean climatology is faster by two to three years in both historical and modern rainfall response compared to the river discharge response for Category I, likely demonstrating importance of aquifer storage and transient storage even in tropical settings with (relatively) small catchments such as in the Philippines.

The low number of events in Category II for the historical rainfall data (Table 2b) precludes a formal SEA assessment. However, SEA shows a decreasing trend in the modern rainfall at a statistical significance level for Climate III and IV in response to extreme El Niño events (Category II). This is similar to the river discharge response to years following extreme El Niño events. The median response in rainfall suggests an increase to pre-event mean conditions after three years following the strongest decrease in rainfall amount. Rainfall response is not significant for Climate Type I and is not included in the subsequent discussion. The increase in Climate Type II is statistically significant at the $90^t h$ confidence level (Table 3b) for modern rainfall data. This response in the hydroclimate stands out as an outlier compared to the modern rainfall response in Climate Types III and IV.

4 Discussion

4.1 Hydroclimate Response to the Intensity of El Niño Events

Following normal (Category I) and extreme (Category II) El Niño events, rainfall and river discharge decrease relative to the pre-event three-year hydroclimate means. The duration of the decreasing trend lasts between three to seven years from the event year (0 on the x-axis) depending on the Climate Type and intensity of the El Niño event (Table 1a-b, 2a-b, 3a-c). Next, the decreasing trend in river discharge lags by one or two years compared to the rainfall. Alternatively, rainfall recovers to the pre-event hydroclimate mean faster by one or two years compared to river discharge. Lastly, we found that the amplitude of response is greater for river discharge compared to rainfall (Figure 6). The difference in the amplitude and the duration of the decreasing trend is likely attributed to multiple factors that govern river discharge and streamflow conditions. Variability in streamflow conditions are sensitive to effective rainfall amount, vegetation type, size and slope of catchment area, bedrock lithology, baseflow conditions, and floodplain/aquifer storage (Stoelzle et al., 2014; Yang et al., 2017). Comparatively, rainfall amount is intimately linked to ocean-atmosphere dynamics in the western Pacific Ocean (Lyon, 2004). Further, the composite time series used in the SEA to assess the response is following the removal of seasonal and long-term trends. Therefore, the varied response in amplitude/magnitude and duration within the different Climate Types for Category I (normal El Niño events) suggests that land-surface features such as vegetation and soil type, as well as dependency on agricultural intake, antecedent soil moisture conditions, and balance between precipitation and evapotranspiration might be important factors modulating the amplitude and the duration of the response. Finally, consistent trends in the duration and amplitude of rainfall response for historical (Table 2a) and modern (Table 3a) time between Climate Types suggest that the El Niño phase of the ENSO dynamics over the 20^{th} and 21^{st} century modulate rainfall consistently through the observed time.

The large magnitude and consistent decrease in the hydroclimate using the peak of extreme El Niño (Category II) events suggests the legacy of El Niño events could lead

Table 3. Sensitivity tests investigating the response of modern rainfall data to different categories of El Niño events using Superposed Epoch Analysis

Sensitivity Criteria	Number of Events	Post-Event Response	Max. Response Year (Amplitude)	Statistical Significance	
a) Category I/ Normal El Niños: SSTA > 1°C					El Niño Intensity Category
Climate Type I	105	↓ 1-4 yr ; ↑ 5-7yr	+ 4 (-0.02)	1%	
Climate Type II	105	↓ 1-2 yr ; ↑ 3-7yr	+ 2 (-0.02)	1%	
Climate Type III	105	↓ 1-3 yr ; ↑ 4-7yr	+ 3 (-0.10)	1%	
Climate Type IV	103	↓ 1-4 yr ; ↑ 5-7yr	+ 4 (-0.10)	1%	
b) Category II/ Extreme El Niños: SSTA > 2.2 °C					
Climate Type I	*6*	↓ *1-7 yr*	*+ 7 (-0.02)*	*Not Significant*	
Climate Type II	6	↑ 1-7yr	+ 7 (0.30)	90%	
Climate Type III	6	↓ 1-3 yr ; ↑ 4-7yr	+ 3 (-0.10)	5%	
Climate Type IV	6	↓ 1-3 yr ; ↑ 4-7yr	+ 3 (-0.10)	5%	
c) Category III/ Conception of an El Niño Period: First month in an El Niño Period where SSTA > 1°C					Timing within El Niño Period Category
Climate Type I	12	↓ 1-7 yr	+ 7 (-0.15)	1%	
Climate Type II	12	↓ 1-4 yr; ↑ 5-7yr	+ 4 (-0.20)	1%	
Climate Type III	12	↓ 1-5 yr ; ↑ 6-7yr	+ 5 (-0.15)	10%	
Climate Type IV	12	↓ 1-7 yr	+ 7 (-0.40)	1%	
d) Category IV/ Termination of an El Niño Period: Last month in an El Niño Period where SSTA > 1°C					
Climate Type I	*12*	↑ *1-7yr*	*+ 7 (0.05)*	*Not Significant*	
Climate Type II	12	↑ 1-7yr	+ 7 (0.40)	95%	
Climate Type III	12	↑ 1-7yr	+ 7 (0.30)	99%	
Climate Type IV	12	↑ 1-7yr	+ 7 (0.30)	95%	
e) Category V/Superflous Signal Check: 0.2°C < SSTA > 0°C					Noise Category
Climate Type I	*77*	↓ *1-7 yr*	*+ 7 (-0.01)*	*Not Significant*	
Climate Type II	*77*	↓ *1-7 yr*	*+ 7 (-0.01)*	*Not Significant*	
Climate Type III	*77*	↓ *1-7 yr*	*+ 7 (-0.01)*	*Not Significant*	
Climate Type IV	*77*	↓ *1-7 yr*	*+ 7 (-0.01)*	*Not Significant*	

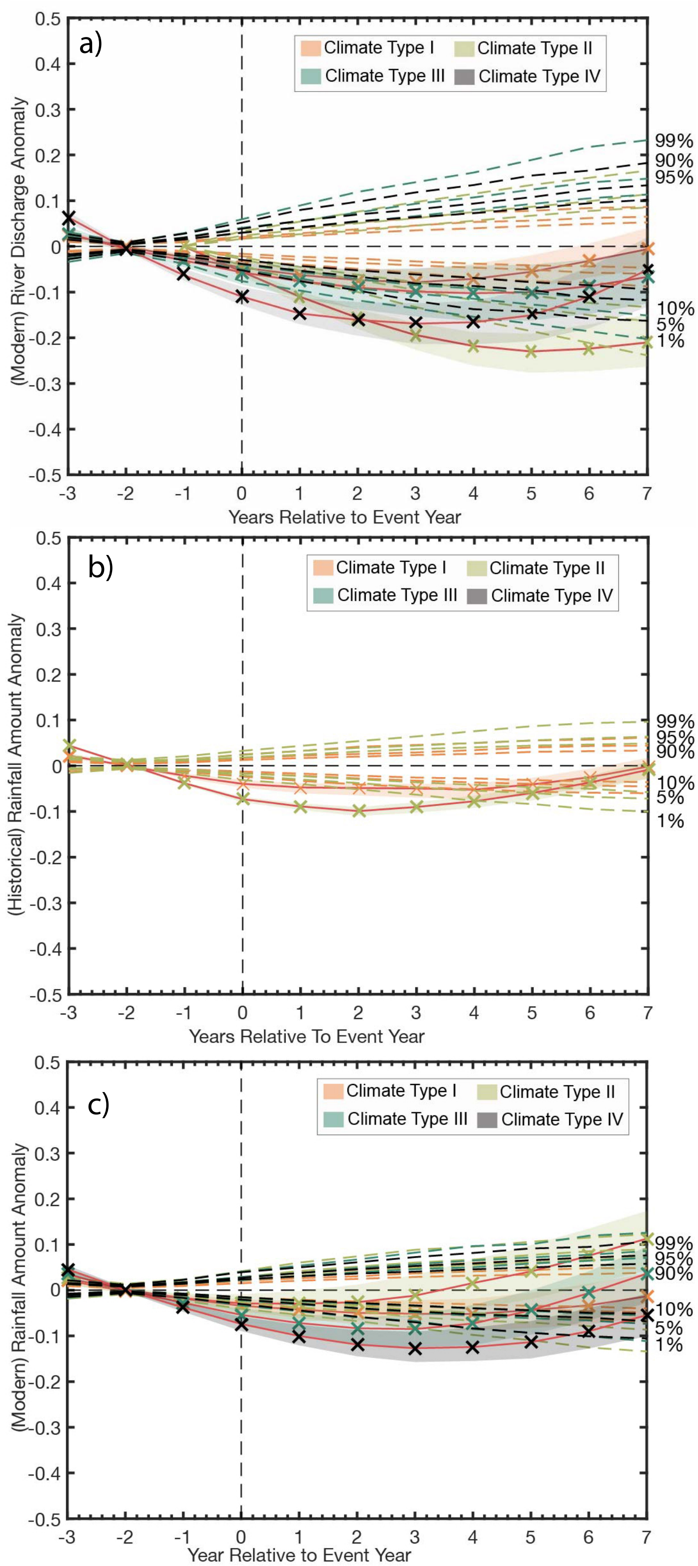

Figure 5. Superposed Epoch Analysis (SEA) showing (a) river discharge, (b) historical rainfall, and (c) modern rainfall response to El Niño events where an event is from a discrete time-series with months corresponding to SSTA's greater than 1°C. Uncertainty intervals for the different Climate Types are 5^{th} and 95^{th} percentiles of the hydroclimate response, while the sub-horizontal lines indicate the threshold required for the epochal median anomalies (red lines) to be statistically significant using random bootstrapping at three different confidence intervals. Climate Type III and IV response for the historical rainfall amount (b) is the same as Climate Type III and hence not clearly visible.

to potential long-term (multi-year) droughts. The peak of the extreme El Niño is considered an event of interest in Category II. The subsequent ensuing event list comprises events in the 1950s (Event: 1957-12), 1960s (Event: 1966-01), 1970s, (Event: 1972-12) 1980s (Event: 1982), and 1990s (1992-01). Each decade in our event list is attributed to prevalent drought conditions in Southeast Asia (Sheffield & Wood, 2007; Venkatappa et al., 2021). Further, long-term drought conditions in Southeast Asia are attributed to the El Niño phase of ENSO (Harger, 1995). However, not all severe El Niño events guarantee the nascence of droughts (Harger, 1995). Our SEA results for the extreme El Niño events suggests that the decreasing trend in response to extreme El Niño (Table 1b and 3b) potentially reflects El Niño induced long-term droughts. The decreasing hydroclimate trend continues for up to seven years relative to the pre-event hydroclimate mean for both river discharge and rainfall composite time series. Our results are in-line with investigations into river and rainfall response to ENSO on an interannual to interdecadal temporal scale in Australia (Simpson et al., 1993; Arblaster et al., 2002; Rimbu et al., 2004). The studies investigate the long-term or legacy effects of ENSO on rainfall (Arblaster et al., 2002) and streamflow (Rimbu et al., 2004) variability. Rimbu et al. (2004) found that streamflow variability is strongly correlated to the Niño3 index during the 1900s to 1930s. Our study places the framework of hydroclimate variables responding to the intensity of El Niño events on a response temporal scale lasting on an interannual scale. The latter is an advancement as most studies investigate the seasonal response of ENSO (Schmidt et al., 2001). SEA further allows us to observe an aggregate response, which is useful when investigating El Niño events as characteristics of individual El Niño events are known to be slightly different (Harger, 1995; Wang et al., 2019).

4.2 Temporal Placement in the El Niño Period Dictates the Trend in the Hydroclimate Response

ENSO is not the only source of forcing for tropical droughts but is known to modulate droughts in the global tropics on the interannual and interdecadal temporal scale (Krishnamurthy & Goswami, 2000; Lyon, 2004, 2004; Mendoza et al., n.d.; L. Chen et al., 2021). Here, we discuss how the temporal placement in an El Niño period (Category III and IV) impacts the response in the hydroclimate variables in the Philippines. At the onset of an El Niño period, our results suggest that hydroclimate variables decrease up to seven years (Table 1c, 2c, 3c). Conversely, at the termination of an El Niño period (Category IV), hydroclimate variables increase as quickly as three years (Table 1d, 2d, 3d). The difference in the response based on the temporal placement (i.e., seasonally or inter annually) in an El Niño period highlights the importance of variability between conception and termination of El Niño periods. For example, 1957-04 is an event at the onset of a continuous El Niño period that lasted until 1958-04. Seven years post 1957-04 is 1964-04 and during this interval ENSO oscillates between neutral, La Niña, and El Niño phases (Figure 2a and 3a). Conversely, the termination of the El Niño period (1958-04) is bracketed on the pre-event side with El Niño conditions (1955-04) and with a majority of La Niña and neutral phases of ENSO on the post-event side. Similarly, the 1997-05 event is the onset of a continuous El Niño period that lasted until 1998-03. The pre-event conditions largely fall in the El Niño phase of ENSO and the post-event conditions cover neutral, La Niña, and El Niño phases of ENSO. The difference in the hydroclimate variable response to the placement in an El Niño period implies sensitivity to antecedent surface conditions (Zhu et al., 2007). The conception of an El Niño period (Category III) is followed by El Niño, neutral and La Niña phases of ENSO. The reduction in the convective rainfall circulation system over southeast Asia during the conception of an El Niño period leads to a decrease in rainfall data, which lasts up to seven years and is clearly visible in the historical rainfall data (Table 2c). Further, the pre-event mean is likely during a La Niña or neutral phase, and the antecedent conditions are less likely to be drought prone. Hence, the deviation from the pre-event mean is large. Conversely, the inverse is the case for the hydroclimate response at the termination of an El

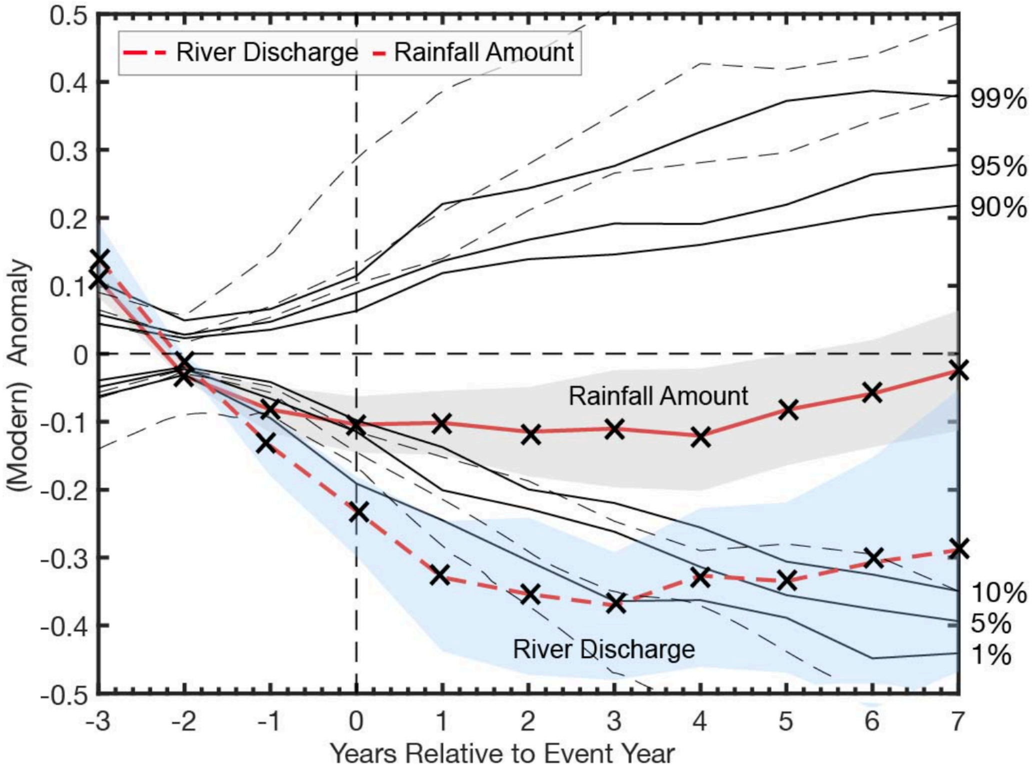

Figure 6. Superposed Epoch Analysis showing modern river discharge (dashed) and rainfall (solid) rainfall response to extreme El Niño events (Category IV) for Climate Type IV. Uncertainty intervals are 5^{th} and 95^{th} percentiles of the hydroclimate response, while the sub-horizontal lines indicate the threshold required for the epochal median anomalies (red lines) to be statistically significant using random bootstrapping at three different confidence intervals. River discharge has a larger amplitude in response to events. Conversely, rainfall has a smaller response and recovers faster to the pre-event mean.

Niño period. The antecedent conditions are more acutely reflective of drought conditions. Next, the post-event years are followed by neutral to La Niña conditions. Therefore, the general response in hydroclimate is to increase following the termination of El Niño periods. The duration of the response is consistently up to seven years (Table 1d, 2d, 3d) regardless of river discharge or rainfall data. This highlights the relatively quick response to wet conditions (La Niña) compared to dry conditions (El Niño).

5 Conclusions

Philippines is a nation of over 7,000 islands and it heavily relies on rainfall to maintain groundwater and streamflow resources. Understanding the interannual hydrological dynamics of island nations such as the Philippines is imperative to better plan for water resource management (Higley & Conroy, 2019). In our analysis, we utilized a 100-year paired river discharge and rainfall data to ascertain the hydroclimate response to varying intensities and duration of El Niño periods. The mean, log-normalized, scaled, detrended with the seasonal signal removed composite time series for the four major Climate Types was compared against the Nino3.4 Relative Index to discern the interannual response using SEA analysis. Our analysis suggests that the hydroclimate variables decrease in response to normal and extreme El Niño events. The duration of the decreasing trend lasts up to three (normal El Niño events) or seven (extreme El Niño events) years following the event. Further, the hydroclimate metrics respond differently based on the temporal placement (conception to termination) of the event during an El Niño period. Composite river discharge and rainfall data decrease up to seven years following the conception of an El Niño period. Conversely, the hydroclimate response is to increase up to seven years following the termination of an El Niño period. The magnitude of response is lagged in discharge compared to rainfall amount data sets. Further, rainfall amount recovers faster to pre-event means following decreasing trends than river discharge data. The former is more intimately linked to direct ocean-atmosphere dynamics than river discharge data, which depends on multiple hydrological parameters. This is the first study to the best of our knowledge that attempts to quantify the sign, magnitude, and severity of the hydroclimate response to El Niño events for the Philippines on an interannual temporal scale using over 100 years of available data sets. Our results have implication for regions that are prone to tropical droughts and are agrarian societies (Kovats, 2000; Wang et al., 2019; Perez-Blanco & Sapino, 2022). With further development of transfer functions between hydroclimate variables and El Niño indices the fidelity of end of 21^{st} century simulations can be tested (Li et al., 2006; Perry et al., 2020).

6 Open Research

Code written in Python was used for all data reduction and statistical analyses. The code is stored in a GitHub repository: https://doi.org/10.5281/zenodo.6079558 Data required for running the code can be found at in the repository: (will be made available via Zenodo during publication). Superposed Epoch Analysis was implemented following the Matlab code by (Rao et al., 2019).

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Supporting Information for "A decrease in river discharge and rainfall amount, from a 100-year data-set, in response to El Niño events on the interannual temporal scale for the Philippines"

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Introduction The following figures highlight the data processing steps for river discharge and rainfall amount data. The supplemental table includes the list of river discharge and rainfall amount sites, the time covered by the measurements, and the original source of the data used.

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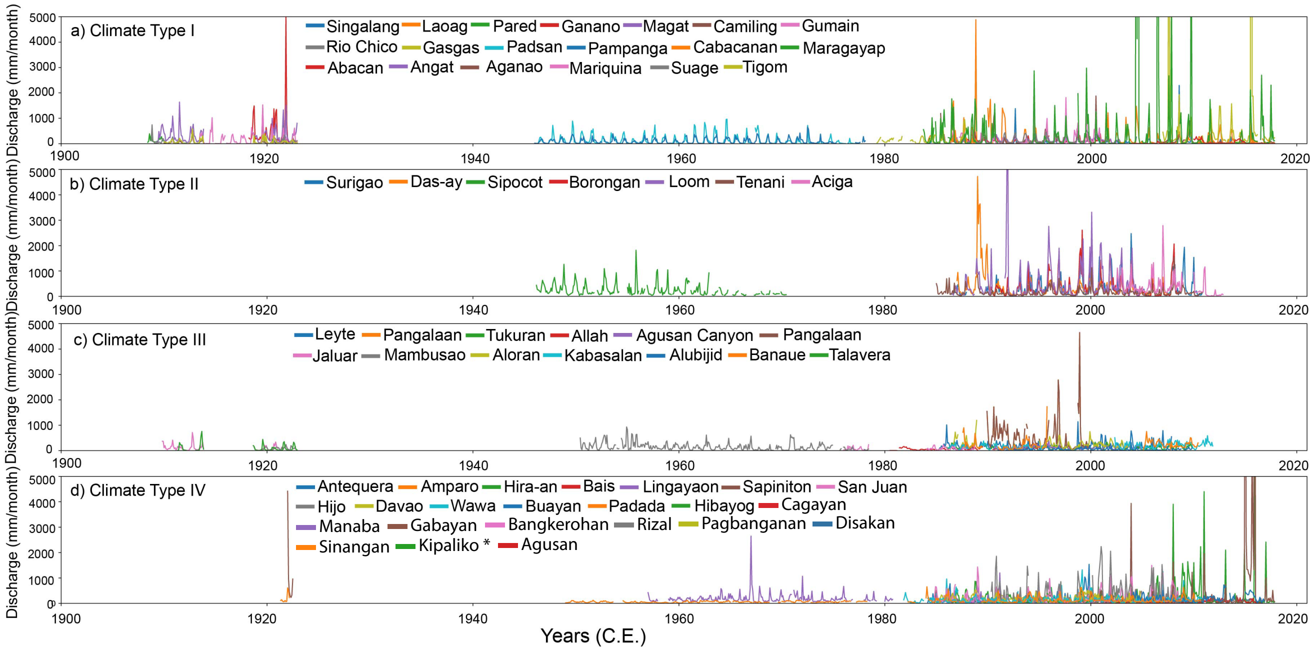

Figure S1. Time series of 61 discharge station data used in this study. River discharge station data that fall under Climate Type I (a), II (b), III (c), IV (d). *Kipaliko has been updated since Ibarra et al. (2021).

Figure S2. Time series of 29 rainfall data used in this study. Rainfall station and gridded data that fall under Climate Type I (a), II (b), III (c), IV (d).

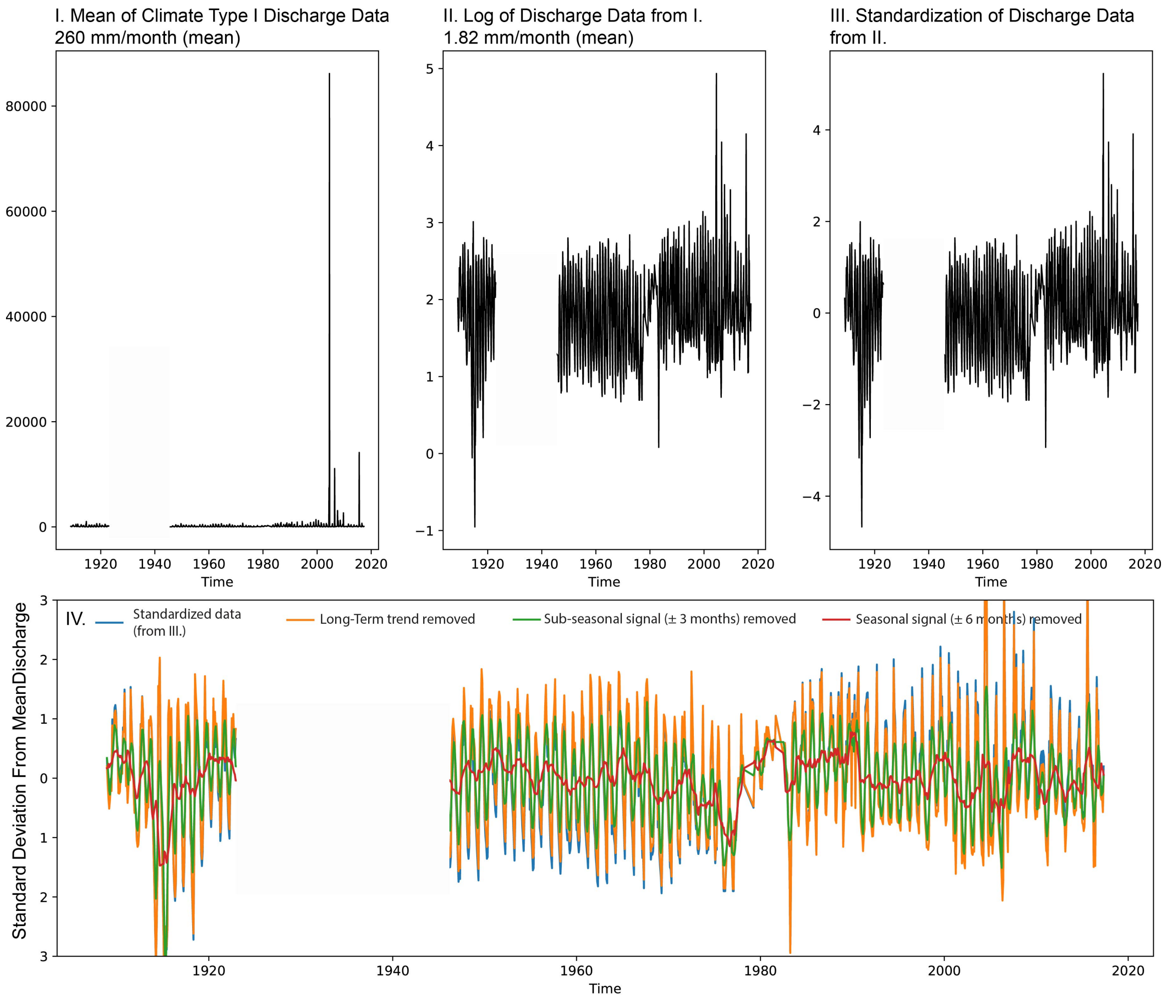

Figure S3. Data reduction steps for river discharge data that fall under Climate Type I I. Mean of area normalized discharge data in mm/month. II. Log of the mean area normalized discharge data. III. Standardized (interchangeable with scaled) discharge data around the log mean. This data is used to remove the long term trends (Supp. Figure. 4). IV. Standardized data plotted with data where long-term trends were removed using a polynomial fit. The sub-seasonal (±3) and seasonal (±6) signal removed data is also plotted.

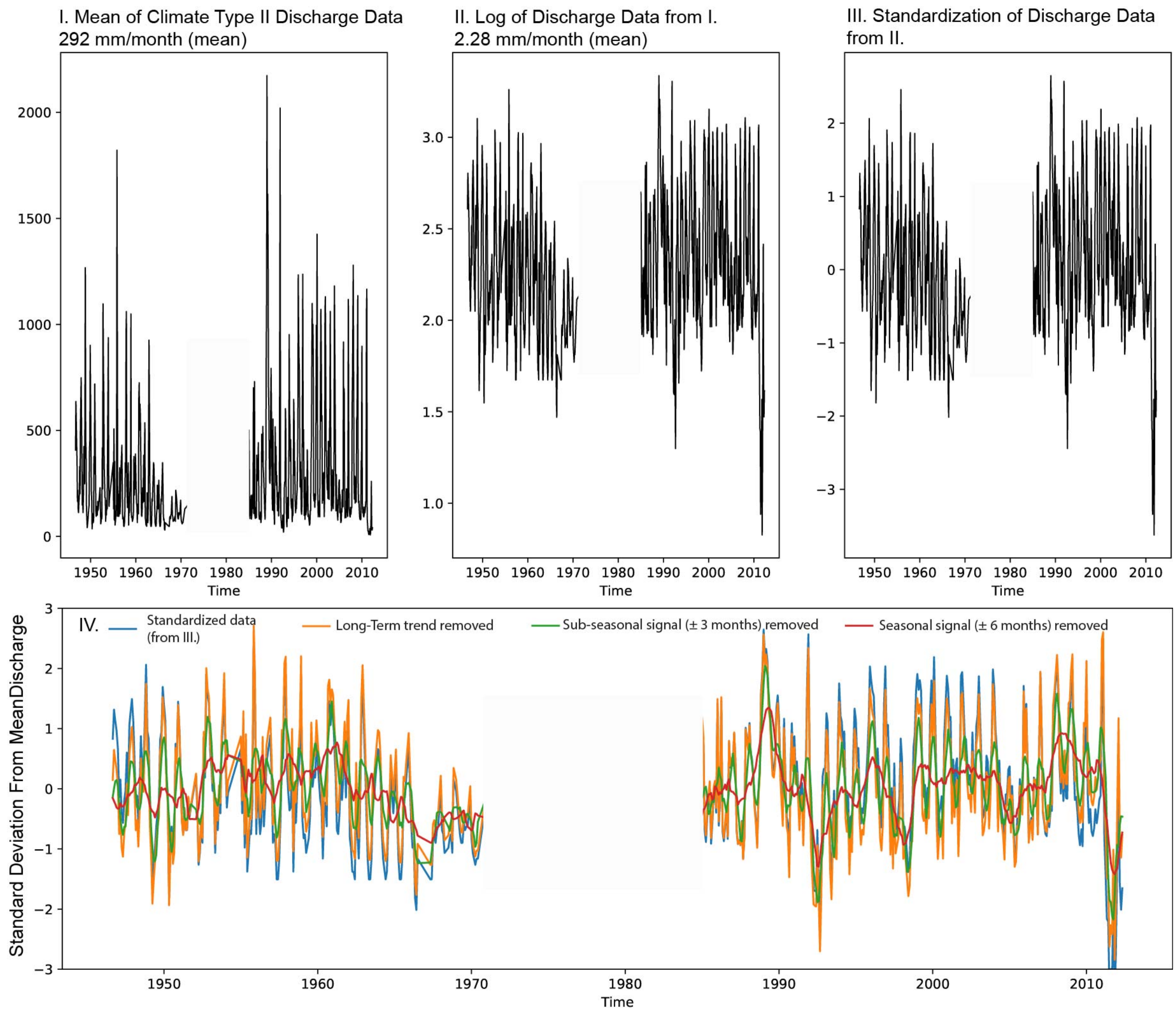

Figure S4. Data reduction steps for river discharge data that fall under Climate Type II I. Mean of area normalized discharge data in mm/month. II. Log of the mean area normalized discharge data. III. Standardized (interchangeable with scaled) discharge data around the log mean. This data is used to remove the long term trends (Supp. Figure. 4). IV. Standardized data plotted with data where long-term trends were removed using a polynomial fit. The sub-seasonal (±3) and seasonal (±6) signal removed data is also plotted.

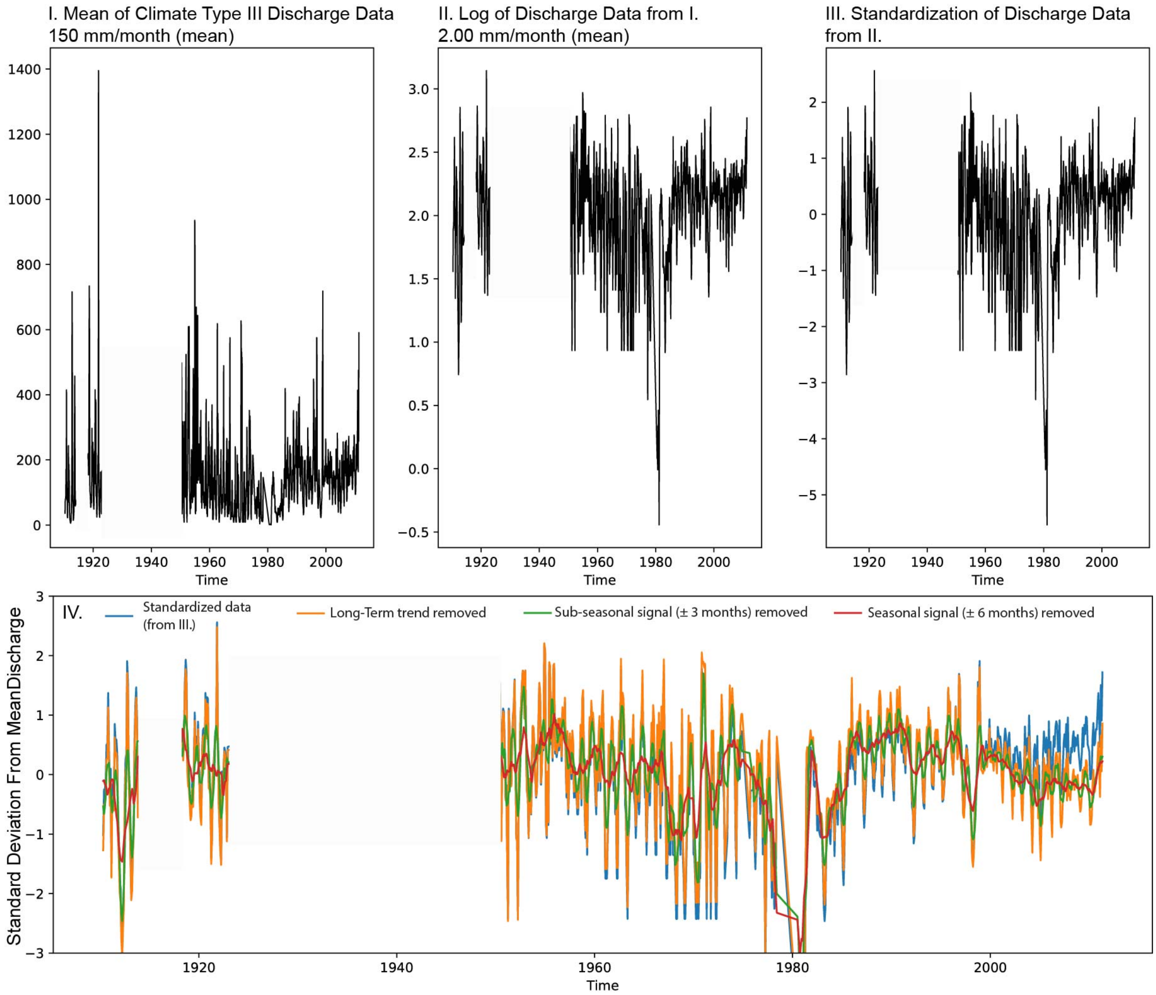

Figure S5. Data reduction steps for river discharge data that fall under Climate Type III I. Mean of area normalized discharge data in mm/month. II. Log of the mean area normalized discharge data. III. Standardized discharge data around the log mean. This data is used to remove the long term trends (Supp. Figure. 4). IV. Standardized data plotted with data where long-term trends were removed using a polynomial fit. The sub-seasonal (±3) and seasonal (±6) signal removed data is also plotted.

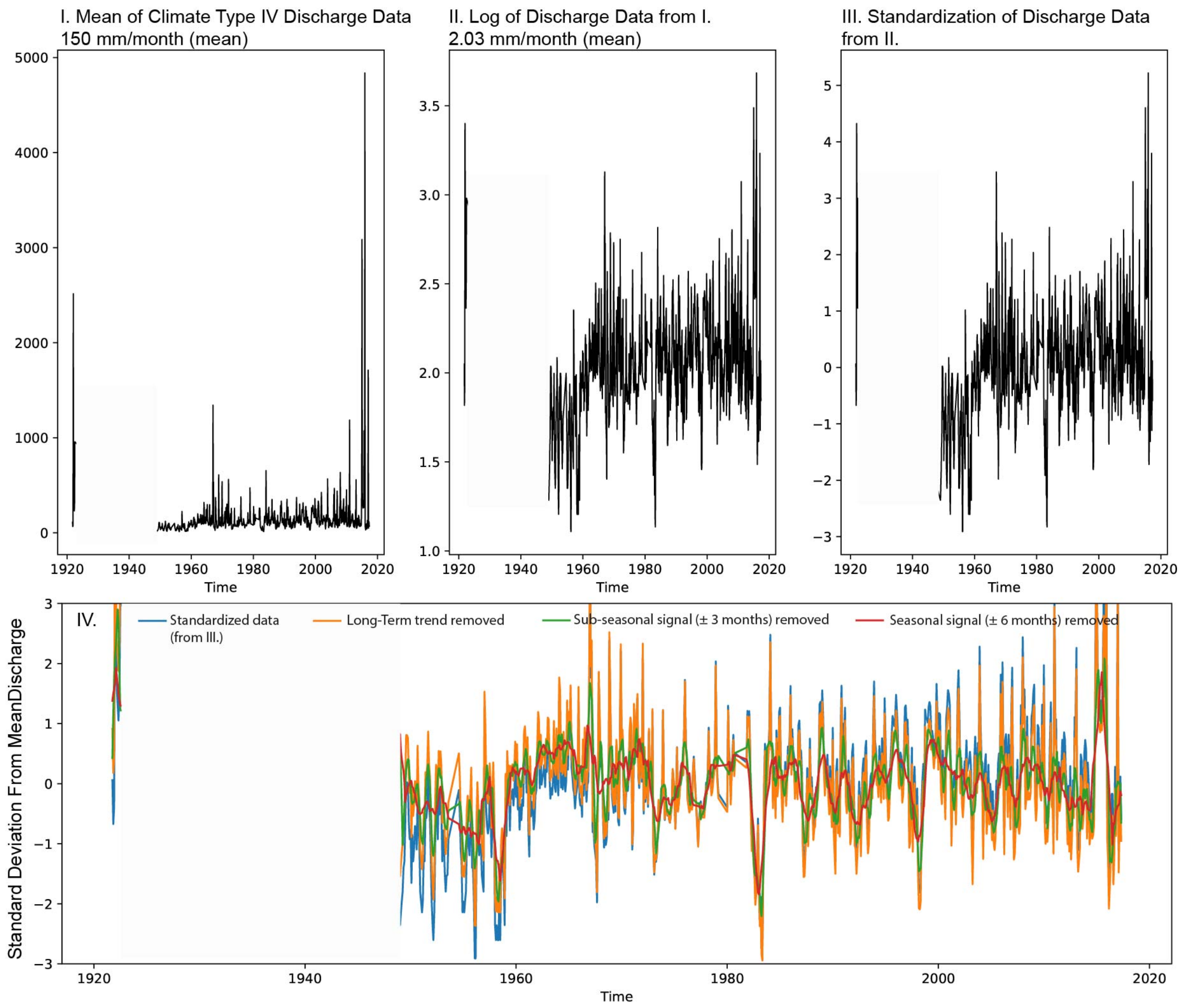

Figure S6. Data reduction steps for river discharge data that fall under Climate Type IV I. Mean of area normalized discharge data in mm/month. II. Log of the mean area normalized discharge data. III. Standardized discharge data around the log mean. This data is used to remove the long term trends (Supp. Figure. 4). IV. Standardized data plotted with data where long-term trends were removed using a polynomial fit. The sub-seasonal (±3) and seasonal (±6) signal removed data is also plotted.

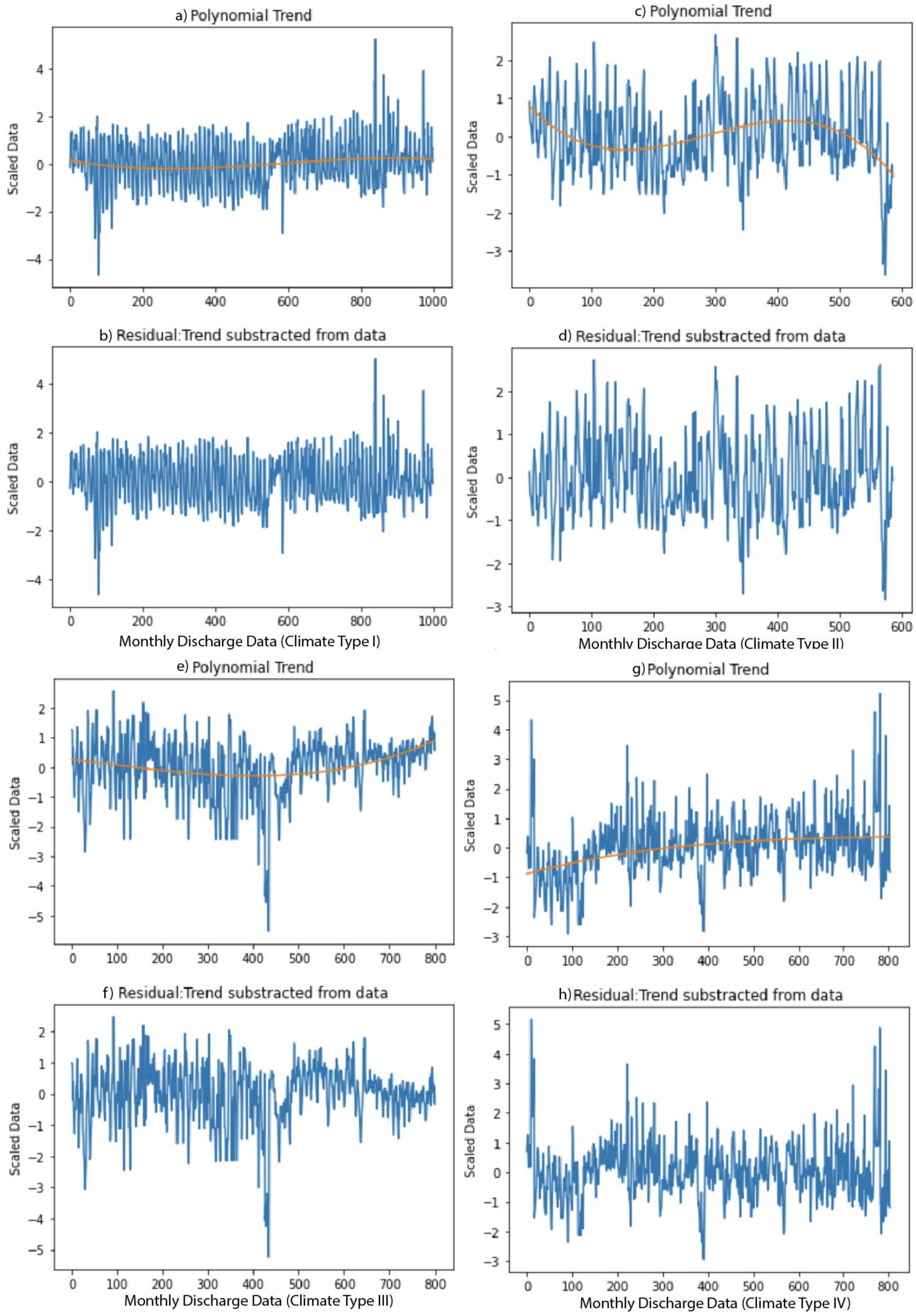

Figure S7. Subtracting long-term trends from standardized monthly discharge data for Climate Type I (a-b), II (c-d), III (e-f), IV (g-h). The orange line (in a,c,e,g) indicates the long-term trend using a polynomial fit (order =3). The residual discharge data (in b,d,f,h) is used for the remaining analyses.

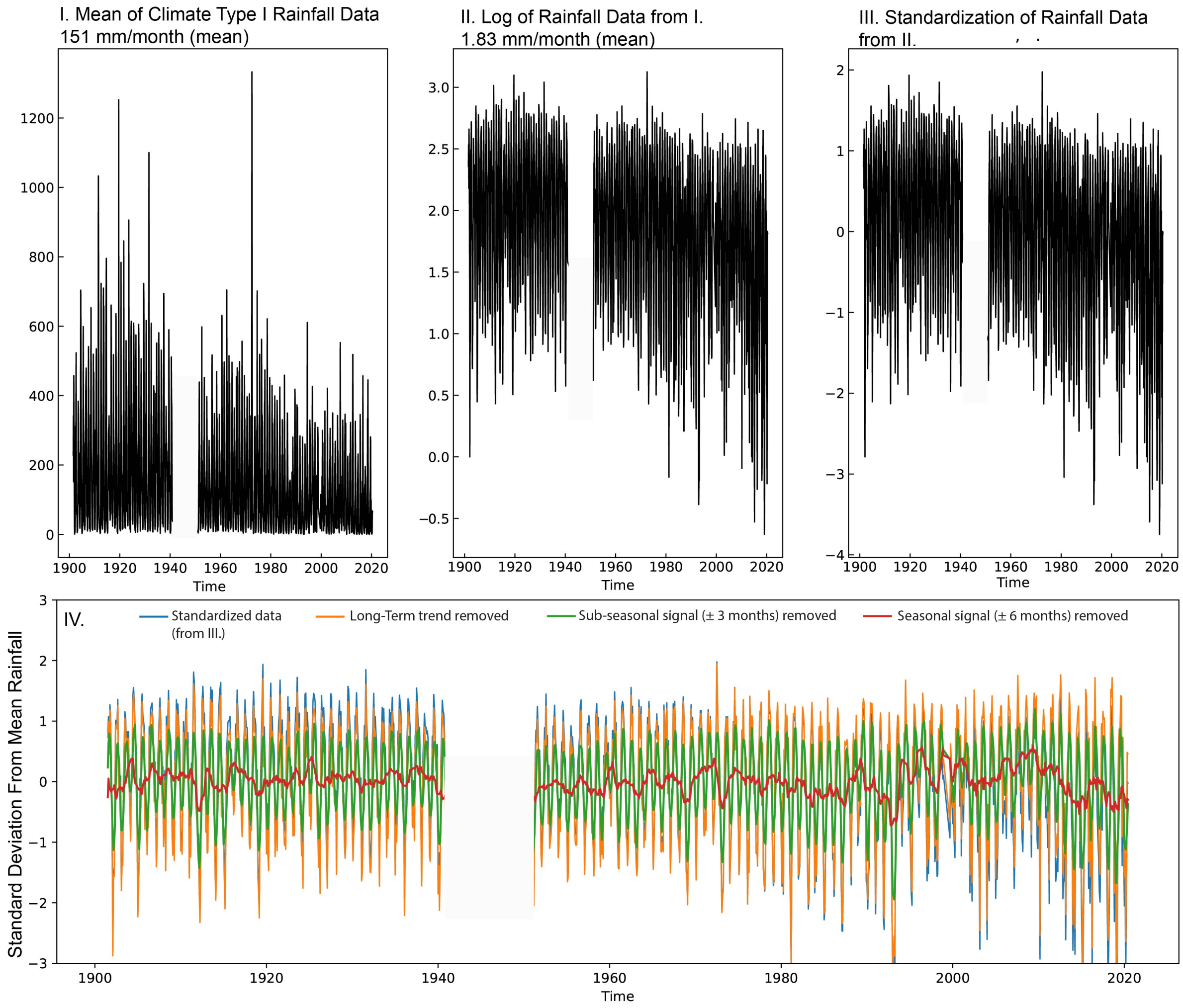

Figure S8. Data reduction steps for rainfall amount data that fall under Climate Type I I. Mean of rainfall amount data in mm/month. II. Log of the mean rainfall data. III. Standardized rainfall data around the log mean. This data is used to remove the long term trends (Supp. Figure. 6). IV. Standardized data plotted with data where long-term trends were removed using a polynomial fit. The sub-seasonal (± 3) and seasonal (± 6) signal removed data is also plotted.

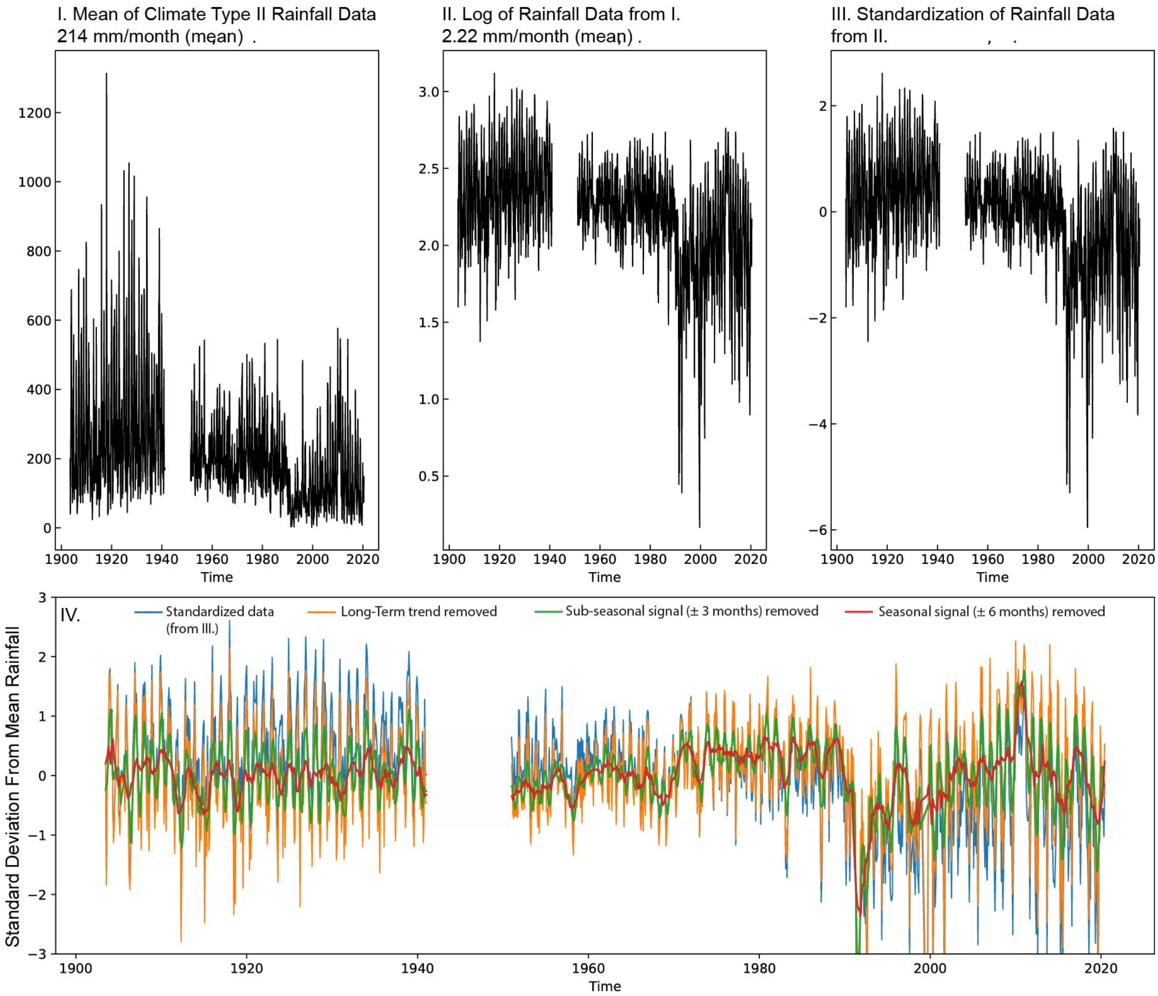

Figure S9. Data reduction steps for rainfall amount data that fall under Climate Type II I. Mean of rainfall amount data in mm/month. II. Log of the mean rainfall data. III. Standardized rainfall data around the log mean. This data is used to remove the long term trends (Supp. Figure. 6). IV. Standardized data plotted with data where long-term trends were removed using a polynomial fit. The sub-seasonal (±3) and seasonal (±6) signal removed data is also plotted.

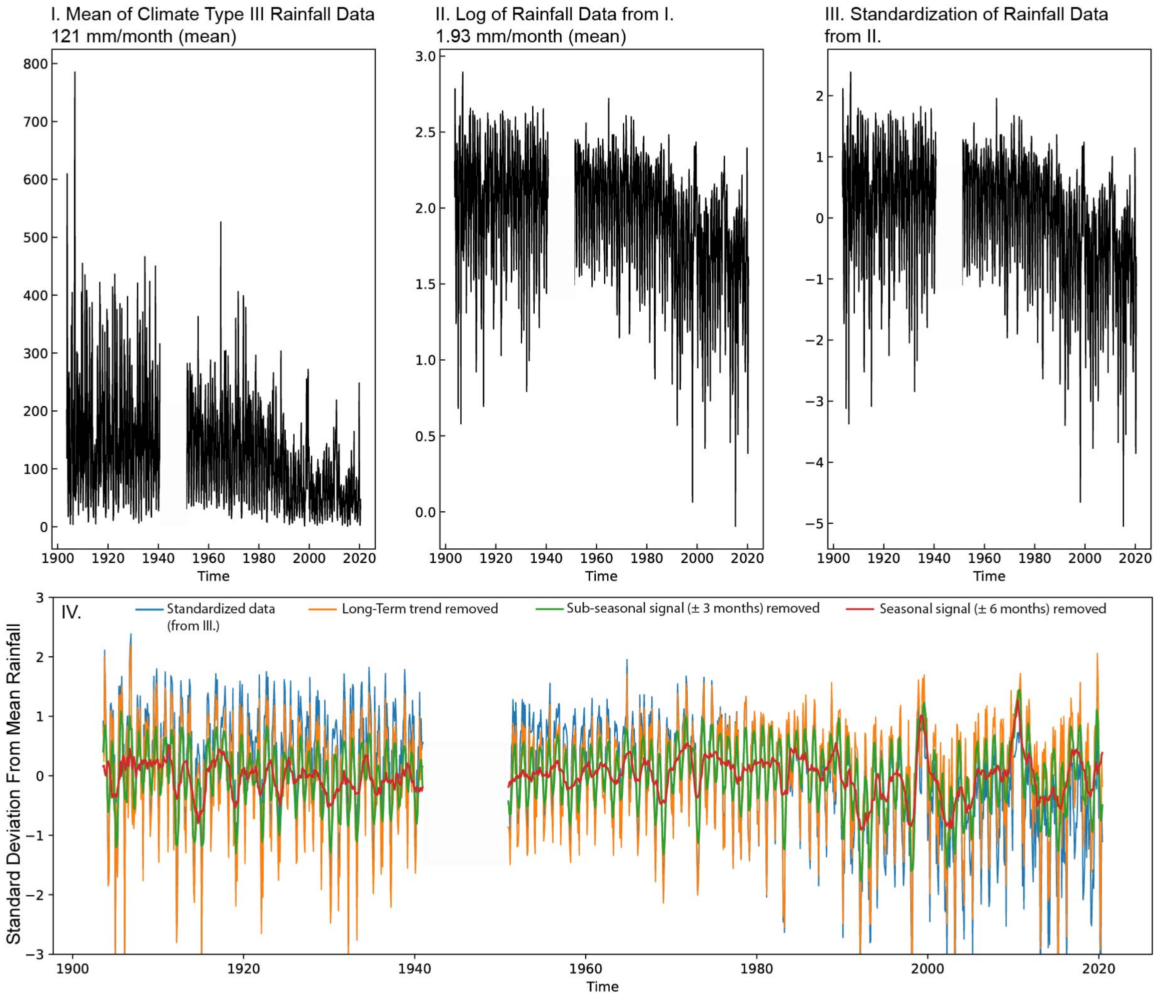

Figure S10. Data reduction steps for rainfall amount data that fall under Climate Type III I. Mean of rainfall amount data in mm/month. II. Log of the mean rainfall data. III. Standardized rainfall data around the log mean. This data is used to remove the long term trends (Supp. Figure. 6). IV. Standardized data plotted with data where long-term trends were removed using a polynomial fit. The sub-seasonal (±3) and seasonal (±6) signal removed data is also plotted.

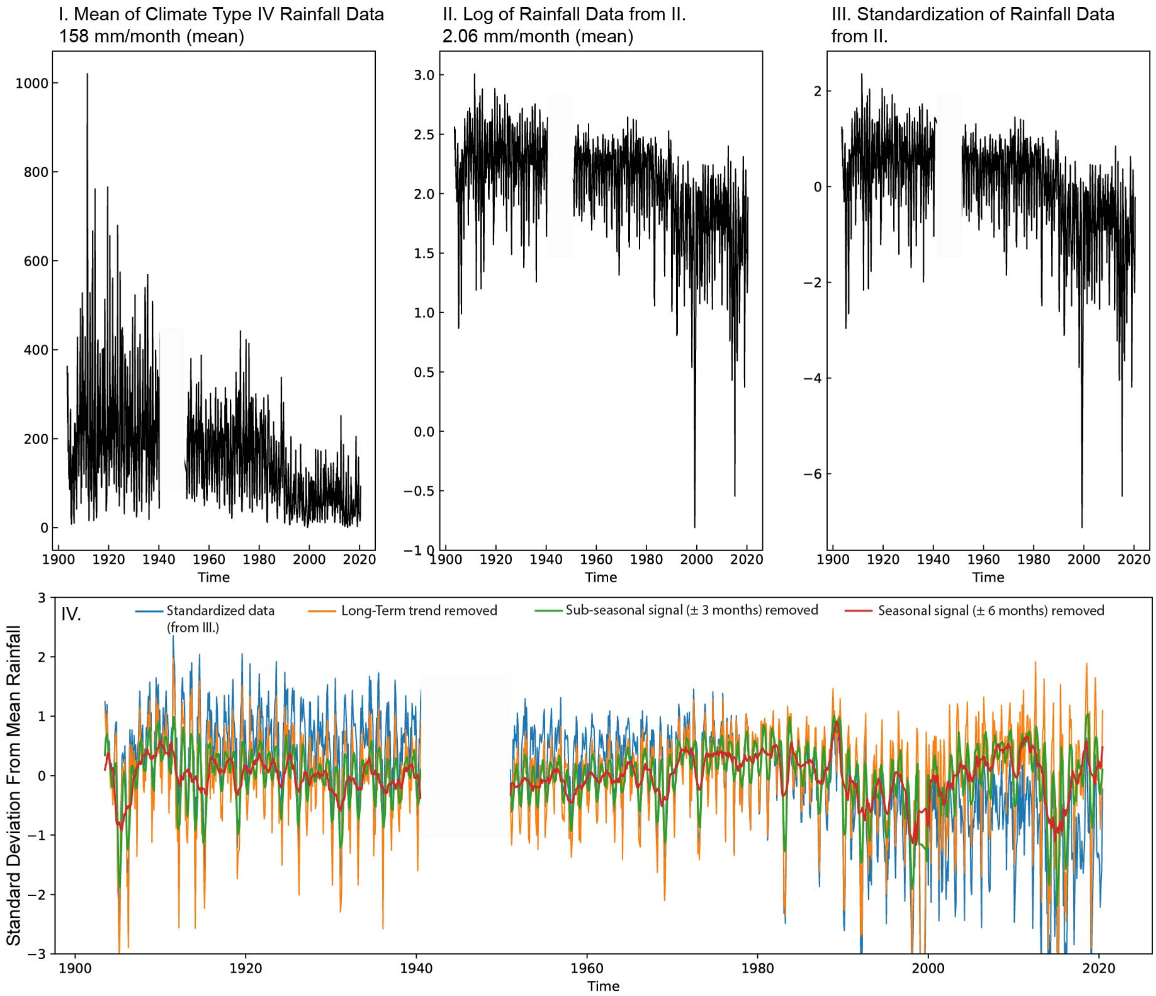

Figure S11. Data reduction steps for rainfall amount data that fall under Climate Type IV I. Mean of rainfall amount data in mm/month. II. Log of the mean rainfall data. III. Standardized rainfall data around the log mean. This data is used to remove the long term trends (Supp. Figure. 6). IV. Standardized data plotted with data where long-term trends were removed using a polynomial fit. The sub-seasonal (± 3) and seasonal (± 6) signal removed data is also plotted.

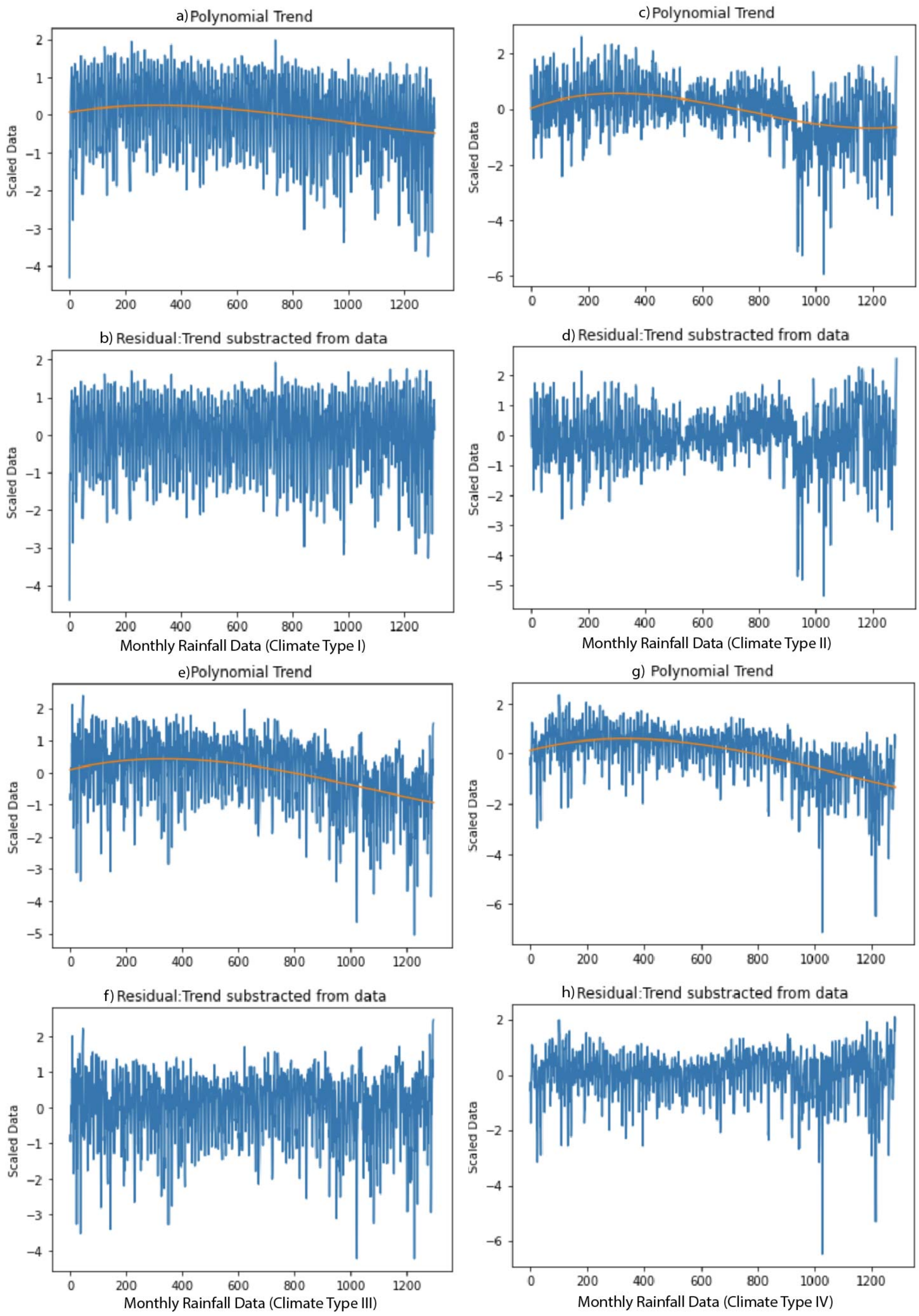

Figure S12. Subtracting long-term trends from scaled monthly rainfall data for Climate Type I (a-b), II (c-d), III (e-f), IV (g-h). The orange line (in a,c,e,g) indicates the long-term trend using a polynomial fit (order =3). The residual rainfall data (in b,d,f,h) is used for the remaining analyses.

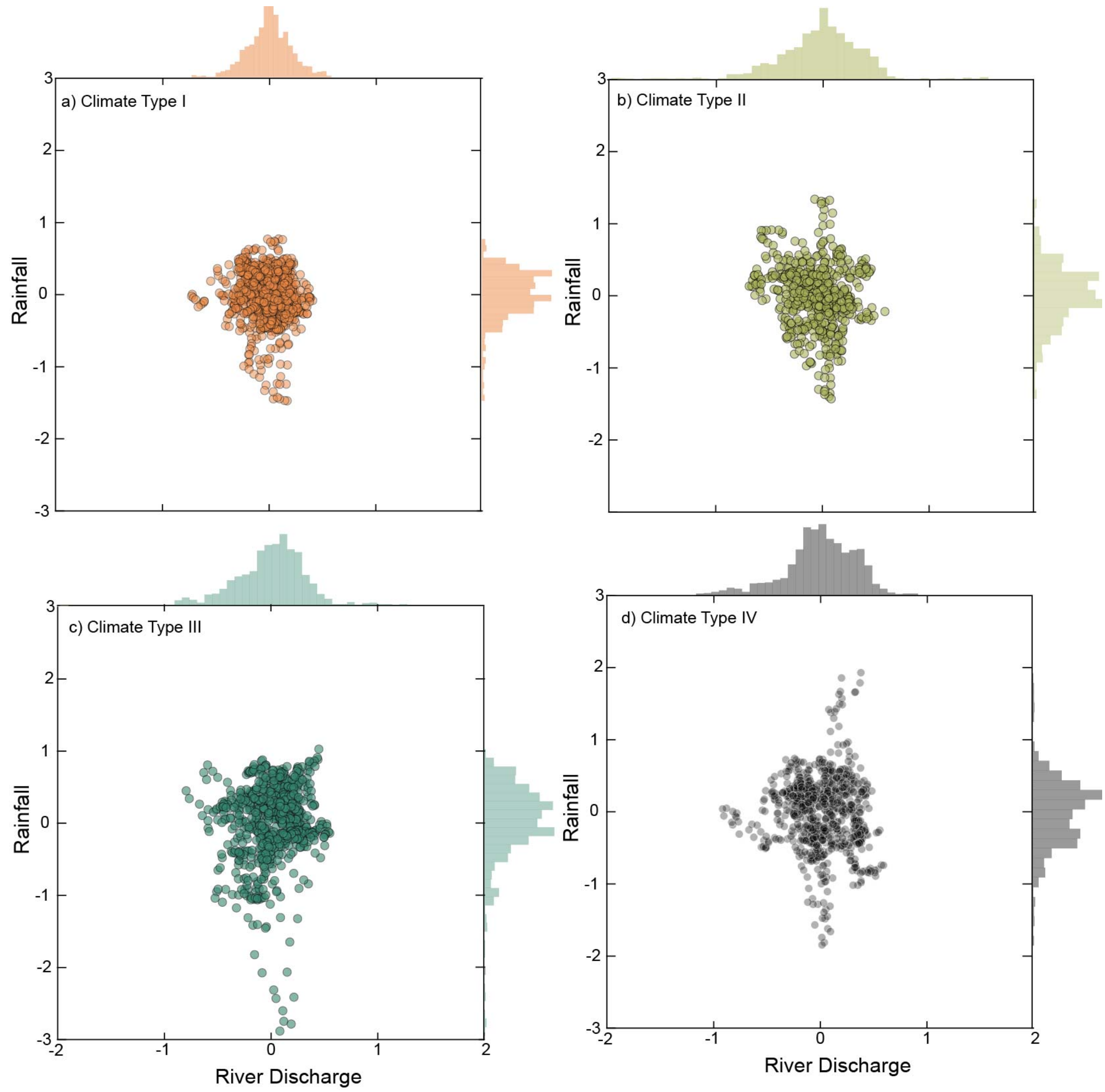

Figure S13. Bivariate plot of rainfall amount and river discharge data based on Climate Types.

Table S1. River discharge station name with Latitude and Longitude, Time Period Covered, Climate Type, and data source. Data from Ibarra et al. (2021); Williams and Gochoco (1924)

River Name	Latitude	Longitude	Years Covered	Climate Type	Dataset
Singalang River	17.56	120.64	1984-2015	1	used in Ibarra et al. (2021)
Antequera River	9.76	123.9	1984-2016	4	used in Ibarra et al. (2021)
Amparo River	10.10	124.91	1985-2007	4	used in Ibarra et al. (2021)
Hira-an River	11.26	124.67	1986-2010	4	used in Ibarra et al. (2021)
Leyte River	11.28	124.56	1985-2007	3	used in Ibarra et al. (2021)
Surigao River	9.73	125.50	1986-2010	2	used in Ibarra et al. (2021)
Bais River	9.88	124.14	1989-2015	4	used in Ibarra et al. (2021)
Lingayaon River	11.19	124.86	1957-1991	4	used in Ibarra et al. (2021)
Sapiniton River	11.32	124.82	1984-2010	4	used in Ibarra et al. (2021)
Laoag River	18.20	120.58	1921-1922;1984-2016	1	used in Ibarra et al. (2021) + BPW
Pared River	17.90	121.68	1983-1996	1	used in Ibarra et al. (2021)
Ganano River	16.69	121.55	1918-1921;1986-2001	1	used in Ibarra et al. (2021) + BPW
Magat River	16.58	121.25	1920-1922;1986-2002	1	used in Ibarra et al. (2021) + BPW
Camiling River	15.61	120.37	1985-2017	1	used in Ibarra et al. (2021)
Gumain River	14.91	120.56	1985-2001	1	used in Ibarra et al. (2021)
Rio Chico River	15.44	120.75	1985-2006	1	used in Ibarra et al. (2021)
San Juan River	14.21	121.15	1986-1999	4	used in Ibarra et al. (2021)
Pangalaan River	13.30	121.19	1989-1999	3	used in Ibarra et al. (2021)
Das-ay River	10.37	125.16	1987-2007	2	used in Ibarra et al. (2021)
Tukuran River	7.87	123.59	1986-2009	3	used in Ibarra et al. (2021)
Hijo River	7.39	125.83	1986-2016	4	used in Ibarra et al. (2021)
Cagayan River	8.39	124.61	1991-2004	4	used in Ibarra et al. (2021)
Davao River	7.09	125.59	1984-1999	4	used in Ibarra et al. (2021)
Allah River	6.67	124.56	1980-1994	3	used in Ibarra et al. (2021)
Agusan Canyon River	8.32	124.80	1986-2004	3	used in Ibarra et al. (2021)
Wawa River	8.81	125.70	1981-2010	4	used in Ibarra et al. (2021)
Buayan River	6.31	125.26	1986-2004	4	used in Ibarra et al. (2021)
Gasgas River	18.08	120.83	1978-1988	1	used in Ibarra et al. (2021)
Jalaur River	10.93	122.67	1909-13;1918-22;1976-88	3	used in Ibarra et al. (2021) + BPW
Padsan River	18.08	120.7	1946-1979	1	used in Ibarra et al. (2021)
Pampanga River	15.17	120.78	1946-1977	1	used in Ibarra et al. (2021)
Sipocot River	13.81	122.99	1946-1970	2	used in Ibarra et al. (2021)
Mambusao River	11.26	122.57	1919-1922;1950-1978	3	used in Ibarra et al. (2021) + BPW
Padada River	6.66	125.28	1949-1978	4	used in Ibarra et al. (2021)
Aloran River	8.42	123.82	1978-2003	3	used in Ibarra et al. (2021)
Cabacanan River	18.58	120.8	1979-2017	1	used in Ibarra et al. (2021)
Maragayap River	16.75	120.37	1908-09;1912;1919-22; 2004-17	1	used in Ibarra et al. (2021) + BPW
Abacan River	15.11	120.70	2004-2017	1	used in Ibarra et al. (2021)
Hibayog River	9.87	124.14	2004-2017	4	used in Ibarra et al. (2021)
Manaba River	9.63	124.13	2001-2016	4	used in Ibarra et al. (2021)
Gabayan River	9.84	124.45	1922; 2001-2017	4	used in Ibarra et al. (2021) + BPW
Bangkerohan River	10.34	124.83	1984-1990;2000-2009	4	used in Ibarra et al. (2021)
Borongan River	11.62	125.40	1990-2008	2	used in Ibarra et al. (2021)
Loom River	11.38	125.23	1986-2004	2	used in Ibarra et al. (2021)
Pagbanganan River	10.63	124.86	1984-2008	4	used in Ibarra et al. (2021)
Rizal River	11.38	124.90	1990-2008	4	used in Ibarra et al. (2021)
Tenani River	11.80	125.12	1985-2001	2	used in Ibarra et al. (2021)
Disakan River	8.48	123.04	1985-1991;1997-2000	4	used in Ibarra et al. (2021)
Kabasalan River	7.83	122.77	2002-2011	3	used in Ibarra et al. (2021)
Sindangan River	8.21	123.05	1990-2003	4	used in Ibarra et al. (2021)
Alubijid River	8.57	124.47	1991-2009	3	used in Ibarra et al. (2021)
Kipaliko River	7.60	125.68	2004-2016	4	used in Ibarra et al. (2021)
Banaue River	16.91	121.06	1987-1995;2005-2010	3	used in Ibarra et al. (2021)
Aciga River	9.26	125.57	2002-2015	2	used in Ibarra et al. (2021)
Agusan River	7.99	126.03	1921-22;1982;1984-87; 1989-2010	4	used in Ibarra et al. (2021) + BPW
Angat River	14.90	120.79	1909-1913;1918-1922	1	BPW
Suague River	10.94	122.51	1908-1913;1918-1922	1	BPW
Tigom River	10.76	122.54	1909-1913;1918-1922	1	BPW
Mariquina River	14.61	121.07	1912-1922	1	BPW
Aganao River	10.78	122.51	1910-1913;1918-1922	1	BPW
Talavera River	15.35	120.55	1911-1913;1918-1922	3	BPW

Table S2. Rainfall station name with with Latitude and Longitude, Time Period Covered, Climate Type, and data source. Data from Yatagai et al. (2012); Kubota et al. (2017); Lawrimore et al. (2011)

Rainfall Station	Latitude	Longitude	Years Covered	Climate Type	Dataset
Vigan	17.55	120.35	1903-40;1951-90; 1991-2020	1	PWB; APHRODITE; Modern
Tagbilaran	9.66	123.85	1903-40;1951-90;1991-2020	4	PWB; APHRODITE; Modern
Maasin City	10.13	124.86	1903-40;1951-90;1991-2020	4	PWB; APHRODITE; Modern
Surigao	9.78	125.48	1903-40;1951-90;1991-2020	2	PWB; APHRODITE; Modern
Laoag City	18.18	120.53	1951-90; 1991-2020	1	APHRODITE; Modern
Tuguegarao	17.63	121.75	1903-40;1951-90; 1991-2020	3	PWB; APHRODITE;Modern
Clark Intl	15.18	120.55	1951-90;1991-2020	1	APHRODITE; Modern
Cabanatuan	15.46	120.95	1951-90;1991-2018	1	APHRODITE; Modern
Ambulong	14.08	121.05	1903-40;1951-90;1991-2020	1	PWB; APHRODITE; Modern
Calapan	13.41	121.18	1951-90;1991-2020	3	APHRODITE; Modern
Cotobato	7.16	124.21	1951-90;1992-2020	3	APHRODITE; Modern
Dipolog	8.6	123.35	1951-90;1991-2020	4	APHRODITE; Modern
Gen Santos	6.11	125.18	1951-90;1991-2020	4	APHRODITE; Modern
Mactan	10.31	123.98	1951-90;1991-2020	3	APHRODITE; Modern
Daet	14.13	122.98	1951-90;1991-2020	4	APHRODITE; Modern
Lumbia	8.41	124.61	1991-2018	3	Modern
Davao	7.13	125.65	1903-40;1991-2020	4	PWB; Modern
Aparri	18.36	121.63	1903-40;1951-90;1991-2020	3	PWB; APHRODITE;Modern
Baguio City	16.4	120.6	1903-40;1951-90;1991-2020	4	PWB; APHRODITE; Modern
Borongan	11.66	125.45	1903-40;1951-90;2001-2020	2	PWB; APHRODITE; Modern
Daniel Romualdez	11.22	125.02	1951-90;1991-2020	4	APHRODITE; Modern
Iloilo	10.7	122.56	1903-40;1991-2011	1	PWB; Modern
Catbalogan	11.78	124.88	1903-40;1951-90;1991-2020	4	PWB; APHRODITE; Modern
Malaybalay	8.15	125.13	1951-90	4	APHRODITE
Casiguran	16.26	122.13	1951-90;1991-2020	2	APHRODITE; Modern
Hinatuan	8.36	126.33	1927-40:1951-90;1991-2020	2	PWB;APHRODITE; Modern
Manila	14.58	120.98	1903-40;1951-90;1991-2020	1	PWB; APHRODITE; Modern
Dumaguete	9.33	123.3	1903-40;1951-90;1991-2020	3	PWB; APHRODITE; Modern
Butuan	8.95	125.48	1901-40;1951-90;1991-2020	2	PWB; APHRODITE; Modern

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