Research paper

# A Study of Rainfall Changes and Thresholds of Extreme Rainfall Events in the Lienhuachih Area of Central Taiwan

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【Summary】

Hydrological fluctuations tend to greatly vary, and rainfall characteristics have recently been significantly affected by influences of global warming worldwide. Rainfall changes and the occurrence of extreme events have received more attention because of their great impacts on ecosystem operations, agricultural activities, and design of hydraulic structures. Rainfall types, regimes, and long-term changes, and thresholds of extreme events were analyzed for the Lienhuachih area in this study using rainfall records from April 1928 to December 2016. Rainfall is unevenly distributed in the annual cycle with about 85.8% of amount and 68.8% of rainy days concentrated from April to September. Therefore, the wet season in the study area was defined as being from April to September rather than from May to October as in most other parts of Taiwan, owing to heavier spring rains. The Lienhuachih area has a mean annual rainfall of about 2409.0 mm and rainfall-days of about 144.6 d. An analysis of long-term rainfall changes showed a decreasing trend of about 28.0, 29.2, and 17.6 mm decade$^{-1}$, for the annual total, and wet and dry seasons, respectively. Rainfall-days also showed a steadily decreasing trend of about 4.6, 2.3, and 2.4 d decade$^{-1}$ for the annual total, and wet and dry seasons, respectively. Thresholds for extreme rainfall and drought were roughly 600 mm d$^{-1}$ and 65 consecutive days of no rainfall, respectively, as estimated by quantities from the Extreme Value Type I frequency analysis of 50-yr return period. The decreasing trend for both rainfall amounts and rainfall-days and the more-frequent occurrence of extremely torrential rainfall indicate that rainfall will increasingly become temporally concentrated in the study area. This phenomenon may bring about greater difficulties for water resources management.

**Key words:** rainfall type, long-term change, threshold of extreme rainfall events, Lienhuachih.

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研究報告

# 蓮華池地區降雨變遷及極端降雨事件門檻值之研究

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## 摘　要

近年來受到暖化的影響，世界各地水文事件的變動範圍日益擴大且降雨特性亦明顯的改變。由於降雨量雨分布的變化與極端降雨事件對生態系運作、農業活動和水利工程構設計有顯著的影響，因此格外受到關注。本報告藉由分析蓮華池地區1928年4月至2016年12月的降雨記錄，探討該地區的降雨型態、時間分布、長期變化趨勢以及極端降雨事件閾值。蓮華池地區年平均降雨量約2409.0 mm，降雨天數約為144.6天。由於在時間上分布相當不平均且春雨雨量較豐，致85.8%的年降雨量以及68.8%的年降雨日數集中於4至9月；因此該地區的濕季訂為4至9月，而非台灣其他多數地區的5至10月。長期的降雨變化分析顯示，蓮華池地區全年度、濕季及乾季降雨量均呈遞減趨勢，降幅每10年分別約為28.0、29.2與 17.6 mm。降雨天數亦呈減少趨勢，全年度、濕季及乾季的降幅每10年分別約為4.6、2.3與 2.4 天。以極端值一型分佈函數經頻率分析所求得50年回歸週期日降雨量及連續無降雨天數，作為該地區極端降雨與極端乾旱的閾值，獲知該地區日降雨量需大於600 mm及連續65天無降雨方達到極端降雨與乾旱的門檻。降雨量和降雨日數的減少趨勢以及超大豪雨事件越趨頻繁，顯示蓮華池地區降雨在時間上分布日趨集中，此現象將使水資源經營管理日顯棘手。

**關鍵詞：**降雨型態、長期變遷、極端降雨閾值、蓮華池。

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## INTRODUCTION

Due to the impacts of global warming, abnormal weather phenomena around the world are occurring more frequently than they occurred in the past, and therefore the terms “climate change” and “extreme weather” are often mentioned. Climate is a general term for the long-term average of meteorological phenomena in a region. Meteorology refers to the physical phenomena of a region’s atmospheric conditions, and is usually the amount or characteristic of physical factors such as air temperature, pressure, humidity, wind speed and direction, and solar radiation in the stratosphere. These factors constitute regional climate elements. The “average state” of each meteorological factor is the mean of the statistic, and the average temperature and rainfall are often used to describe the climatic pattern of a region. Extreme weather refers to phenomena of severe anomalies or rare occurrences of meteorological events. The magnitudes of these meteorological factors are extremely low or high or have never appeared in the historical records of a region and are inversely related to their occurrence. Extreme weather events are generally based on a region’s long-term weather records and must be consistent with the definition of statistical extremes. Although there is no strict definition of an extreme weather event, it is generally considered to be in the highest and lowest 2.5% range of historical records, or its quantity is greater than the level of the 50-yr return period. To judge or study extreme climate, one must have long-term and stable observation data and then only can put forward convincing persuasion (Alexander et al. 2006, Katz 2010).

Hydrologic systems are sometimes impacted by extreme events, such as severe storms, floods, and droughts. Those impacts can have profound influences on almost all event series in our lives. In addition, characteristics of precipitation, i.e., the amount, type, and distribution in space and time, play important roles in ecosystem operations, agricultural activities, social structures, economic development, meteorological applications, and the design of hydraulic structures. Therefore, studies of regional precipitation and its changes are important for a variety of agricultural, hydrological, and meteorological applications. Many studies have indicated that the regional heterogeneity in the amounts of precipitation and magnitudes of temperature are significantly changing, and extreme events of both temperature and rainfall are occurring more frequently through the years in low-elevation areas of Taiwan, most likely due to the influences of global warming. In addition, consecutive days of no rainfall have also increased throughout the entire island, and this phenomenon combined with the frequently occurring extreme weather events have made water supply and watershed management more severe in Taiwan (Hsu and Chen 2002, Wang 2004, Wang et al. 2008). Hilly lands, which have elevations ranging 100~1000 m and occupy about three-tenths of the total area of Taiwan, are believed to be experiencing the same situations but with little study or direct evidence to prove that. Therefore, historical rainfall records of the Lienhuachih meteorological station, a typical meteorological station of hilly land in central Taiwan, were examined to analyze the tendency of the magnitude of rainfall changes and thresholds of extreme rainfall and drought. Hopefully, the results will be useful for the effective management of water resources and ecosystems in the future.

## MATERIALS AND METHODS

### Site description

The Lienhuachih area (Fig. 1) commonly refers to the experimental forest of the Lienhuachih Research Center of the Taiwan Forestry Research Institute (TFRI) and its vicinity. Its blurred boundary is generally equivalent to that of Taomi Village which is about 600 ha in area and administrated by Yuchih Township. However, if we expand the scope of its area, the entire Shuili Creek watershed can also be considered as the Lienhuachih area. Elevations of the Lienhuachih area range 610~920 m. The main land use types are forests, orchards, betel nut plantations, tea plantations, and villages. There is a meteorological station managed by the TFRI located at the Lienhuachih Research Center at 120°54’E, 23°56’N and 744 m in elevation. This station is classified as a second rank meteorological station for agricultural use. Rainfall, air temperatures (including the daily average, maximum, and minimum temperatures), relative humidity, solar radiation, and wind velocity and direction are monitored (Lu et al. 2000). The yearly average temperature is about 21.0℃, and the average yearly total rainfall is about 2400 mm. Other climatic conditions can be referenced from Lu et al. (2000).

### Materials

Historical rainfall records of the Lienhuachih station were used for an analysis of the long-term tendency of change and fre-

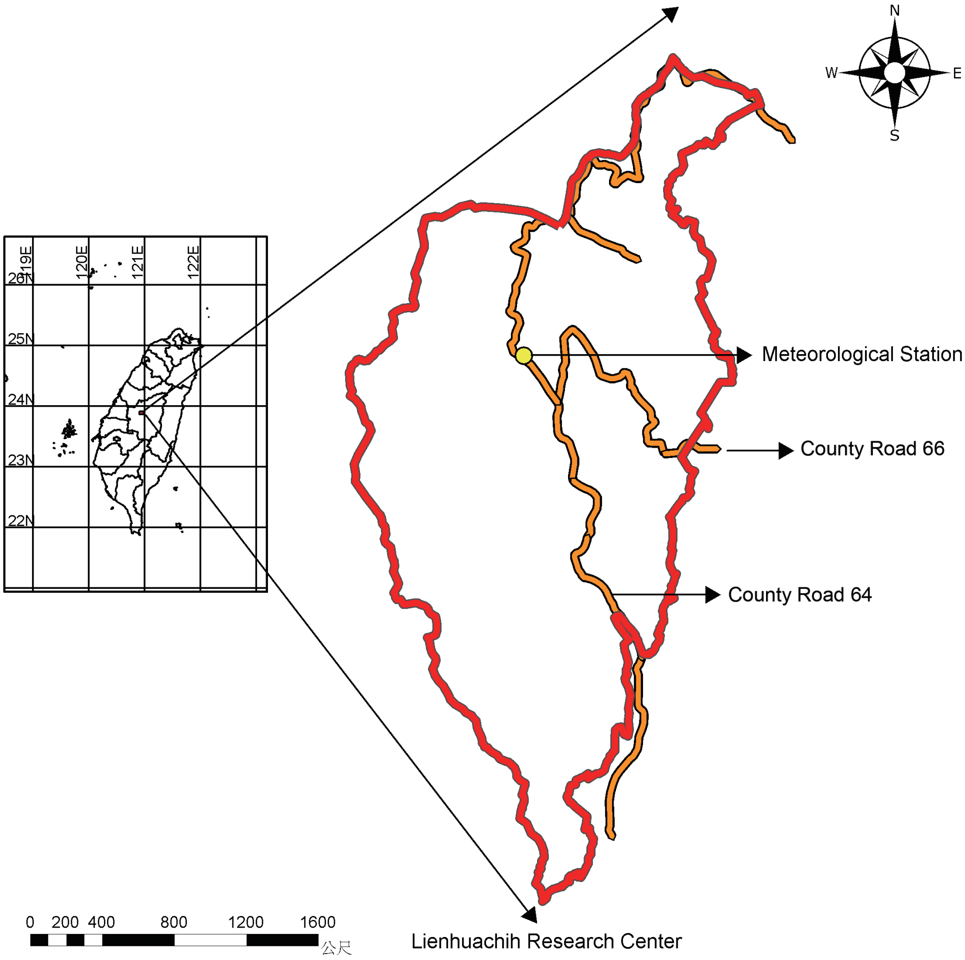


**Fig. 1. Location of the Lienhuachih area.**

quency in this study. Records of rainfall date back to April 1928. Records before 1993 were manual records monitored by a standard rainfall gauge with resolution of 0.1 mm, because there were no automatic monitoring systems available at that time. For the manual records, daily rainfall records were observed at 09:00 each day. Automatic records were monitored by a tipping bucket rain-gauge with a resolution of 0.5 mm, and the daily rainfall is the total rainfall amount within a day (0:00 to 24:00). Different measurement resolutions will not influence measured rainfall amounts because it is believed that loss to evaporation in the bucket and that in the standard rainfall gauge did not significantly differ.

**Long-term change analysis**

In dealing with seasonal rainfall variations, annual records were divided into wet and dry seasons, because on the long-term average about 79% of precipitation falls within the wet season in Taiwan (WRA 2002). If the rainfall amount exceeded 0.1 mm $d^{-1}$, then that day was considered a rainy day, and the number of rainy days in each month was calculated. The monthly average rainfall, rainfall-days, and the average of the entire dataset were calculated. Departure was considered the difference in the yearly amount (rainfall and rainfall-days) with the average of the entire dataset. Departure diagrams (annual, wet season, and dry season rainfall and rainfall-days) were drawn to compare pattern shifts and differences to illustrate changes through time for both rainfall and rainfall-days.

### Frequency analysis

In determining threshold quantities of extreme rainfall and consecutive days of no rainfall for drought, the Extreme Value Type I (EVI) probability distribution function was used in this study. The EVI distribution is often used as an approximation to model the maxima of long (finite) sequences of random variables. Extreme values of hydrologic variables are of interest for frequency analyses, and also storm rainfalls are most commonly modeled using this distribution function (Tomlinson 1980). The probability function is:

$F(x) = \exp\{-\exp[-(x - \mu) / \alpha]\}$;

where F(x) is the accumulative probability for variable x,

$\alpha = 6^{0.5}\ s / \pi = 0.7796\ s$, and

$\mu = \mathrm{Ave}(x) - 0.5572\alpha$, with

s as the standard deviation (SD).

The magnitude of $X_T$ of a hydrologic event for a different return period (T) can be estimated by

$X_T = \mu + \alpha y_T$,

with $y_T = -\ln[\ln(T/(T - 1))]$.

The first step in studying extreme hydrologic events involves selecting a sequence of the largest or smallest observations from a dataset. In this study, the annual maximum 24-h rainfall and the annual driest period were established by selecting the largest rainfall amounts and the greatest number of consecutive days with no rainfall in each year from historical records. Then the means, SDs, frequency factors (factors used in the frequency analysis which are functions of the return period and the type of probability distribution), and other parameters were calculated from the equations described above (Chow 1953, Lu 2016).

## RESULTS

### Rainfall characteristics and regimes

The average monthly rainfall, the recorded maximum daily rainfall, rainfall-days, and number of days which had daily rainfall exceeding 50 mm are tabulated in Table 1. It can be noted that rainfall in October is relatively low and in April is relative high compared to values in other parts of Taiwan (Lu et al. 2000, Chen and Chen 2003). About 85.9% of the annual rainfall, 67.5% of rainy days, and 94.1% of days with daily rainfall exceeding 50 mm were concentrated from April to September. Therefore, we defined the wet season in the study area as occurring from April to September rather than from May to October as it is generally defined in Taiwan (Wang 2004, Lu 2016). This kind of temporal distribution is related to the rainfall mechanism in spring, the presence of southwesterly flow in higher elevations, the cold, dry northeasterly flow in low elevations, and the effects of the spring transition and barrier effects of the Central Mountain Range.

### Analysis of long-term changes in rainfall

Long-term changes in rainfall and rainfall-days from 1928 to 2016 in the Lienhuachih area are shown in Figs. 2 and 3, respectively. Departure diagrams of rainfall amounts showed a declining tendency for annual, wet-season, and dry-season values during the study period. Rainfall amounts showed great fluctuations from year to year (annual rainfall ranged 1410.0~4302.5 mm, that in the wet season ranged 1043.0~4002.0

**Table 1. Average monthly rainfall and rainy days in the Lienhuachih area (1928~2016)**

| | Total rainfall (mm) | Max. daily rainfall[1)] (mm) | Rainfall-days (d) | Days of rainfall >50 mm [2)](d) |
|---|---|---|---|---|
| Jan. | 47.6 | 78.0 | 8.6 | 4 |
| Feb. | 78.2 | 110.7 | 9.6 | 12 |
| Mar. | 109.1 | 120.1 | 10.6 | 26 |
| Apr. | 145.6 | 211.5 | 11.8 | 45 |
| May | 340.7 | 275.0 | 17.3 | 155 |
| June | 532.1 | 566.3 | 20.5 | 273 |
| July | 410.6 | 582.4 | 18.2 | 161 |
| Aug. | 436.2 | 735.0 | 18.1 | 168 |
| Sept. | 203.8 | 584.0 | 11.7 | 68 |
| Oct. | 42.0 | 158.5 | 5.9 | 8 |
| Nov. | 26.2 | 110.5 | 5.6 | 1 |
| Dec. | 36.9 | 85.4 | 6.7 | 4 |
| Total | 2409.0 | | 144.6 | 925 |

[1] The maximum daily rainfall in historical records.
[2] Total days of daily rainfall exceeding 30 mm in historical records.

mm, and that in the dry season ranged 97.5~969.7 mm) with a decreasing tendency of about 28.0, 29.2, and 1.7 mm decade$^{-1}$, for the annual, and wet and dry seasons, respectively. A greater decline in the rainfall amount was found in the wet season, while there was only a minor decrease in the dry season, and the decline in the annual rainfall amount was attributed to the significant decrease in quantity in the wet season.

The Lienhuachih area has a mean annual value of 145 rainfall-days for the past 89 yr with great variations ranging from 286 (in 1993) to 86 d (in 1995), a difference of more than half a year. Long-term changes in rainfall-days showed a steadily decreasing tend in the Lienhuachih area. Annual rainfall-days showed the largest declining rate (slope = -0.46 d yr$^{-1}$), where rainy days in the wet season showed the least reduction (slope = -0.23 d yr$^{-1}$). It was noted that rainfall-days showed 2 peaks in the 1930s and 1950s. It is difficult to explain the reason for the appearance of these 2 peaks, and reasons for the decrease in rainfall-days are complicated and unclear. Most scientists ascribe this phenomenon to global warming, aerosols, and sand storms (Liu et al. 2002).

**The threshold of extreme rainfall amounts**

Following the procedures of the EVI frequency analysis, the estimated quantities of daily rainfall for the 2-, 5-, 10-, 50-, and 100-year return periods were 209.5, 337.4, 422.1, 608.6, and 687.4 mm, respectively. From the definition of extreme rainfall, 24-h or daily rainfall must exceed 600 mm before it can be identified as an extreme rainfall event in the Lienhuachih area. However, the threshold of extreme rainfall is a blurred value and changes from region to region. The estimated threshold is relatively high compared to that in most other places in the world, but this illustrates that Taiwan is an area with abundant rainfall.

There were 6 rainfall events which reached the extreme rainfall threshold in recorded history in the Lienhuachih area.

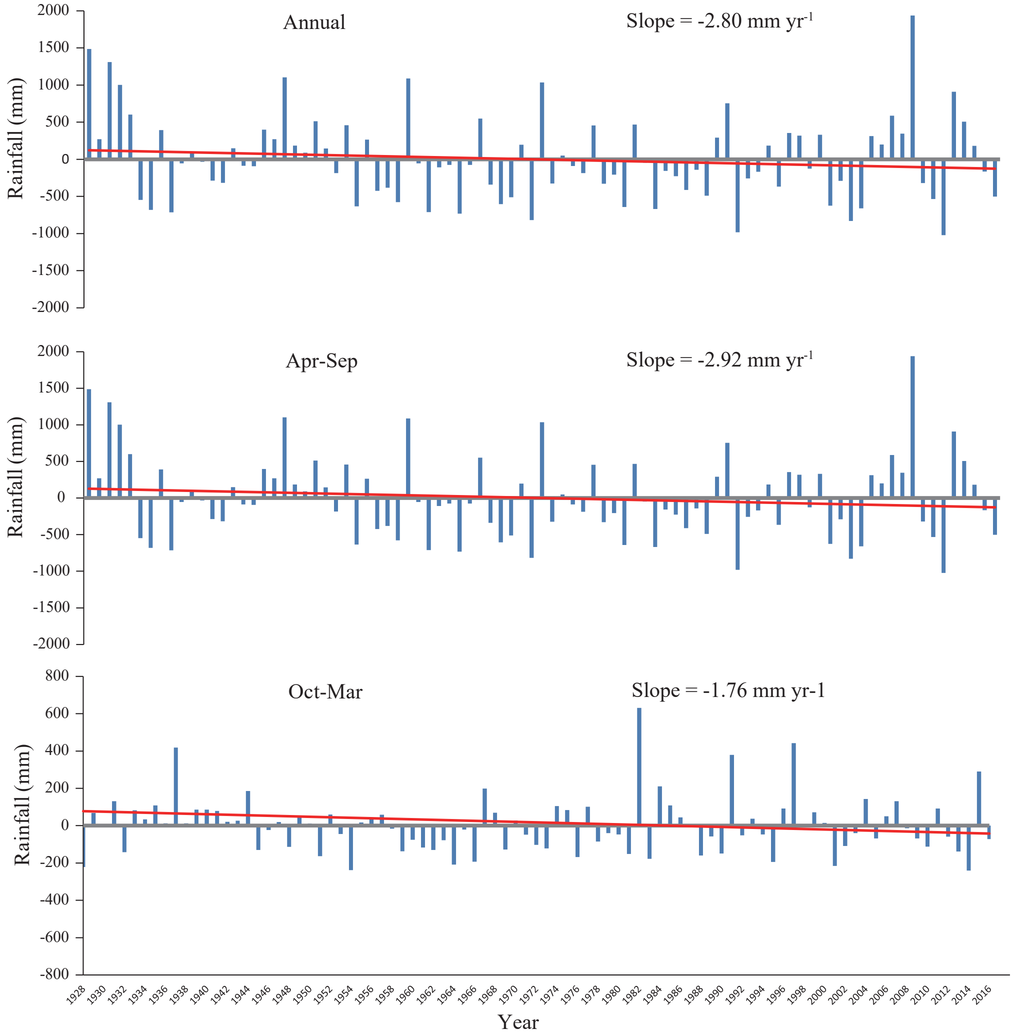


**Fig. 2. Long-term linear trends of rainfall amounts for the Lienhuachih area.**

They occurred on 14 June 1976, 19 August 1990, 31 July to 1 August 1996, 3 to 4 July 2004, 14 to 15 September 2008, and 8 to 9 August 2009 and all occurred during periods when typhoons were hitting Taiwan. There are 22 rainfall events which can be classified as extremely torrential rain in the historical records. It was found that the occurrence of torrential rains was more frequent after 2004 as shown in Fig 4. This phenomenon indicates that the frequency of heavy rainfall has recently increased.

**The threshold of extreme drought events**

When determining the longest period of consecutive days of no rainfall, the hydrological year was selected to run from November to September of the following year, by considering that it may occur in a period that occurs in 2 calendar years. In addition, the threshold amount for rainy days was selected as rainfall amount exceeding 0.5 mm in a day, not only because this quantity would have no contribution to streamflow (Lu and Tang 1995) but also for consistency with the

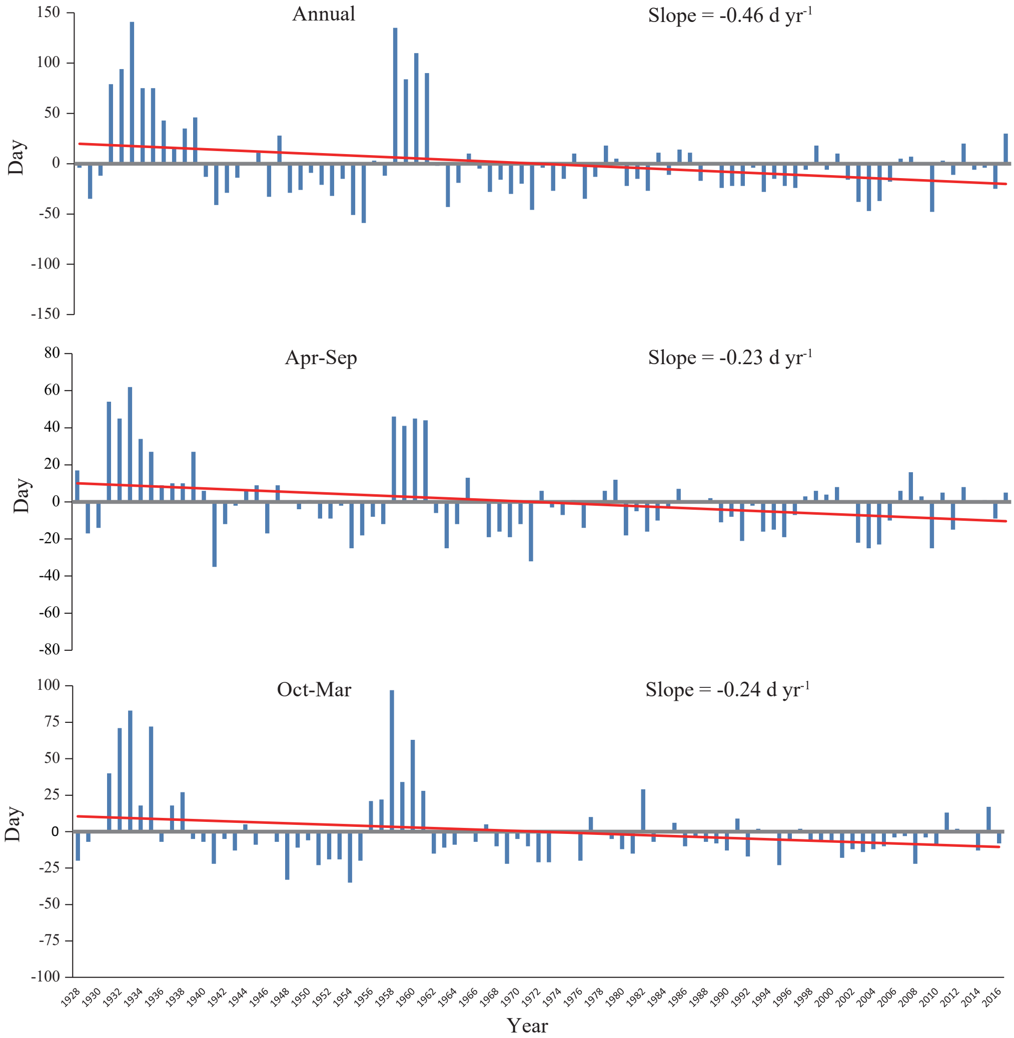


**Fig. 3. Long-term linear trends of rainfall-days for the Lienhuachih area.**

record's resolution. The average consecutive days of no rainfall in historical records of the Lienhuachih area was 35.0 d with a range of 16~86 d. The most and fewest consecutive days of no rainfall amount exceeding 0.5 mm occurred in 1948 and 1938, respectively.

If consecutive no-rainfall days followed the EVI distribution, then the estimated quantities of consecutive days without rainfall for the 2-, 5-, 10-, 25-, 50-, and 100-year return periods would be 38.3, 48.7, 55.5, 64.2, 70.6, and 77.0 d, respectively. The extreme drought threshold estimated by the 50-yr return period from the EVI distribution was about 70 d. If we considered that the distribution of consecutive days with no rainfall followed a normal distribution, the estimated threshold would be about 65 d.

# DISCUSSION

## Rainfall characteristics

Rainfall mechanisms in the Lienhuachih area can roughly be classified as frontal rain,

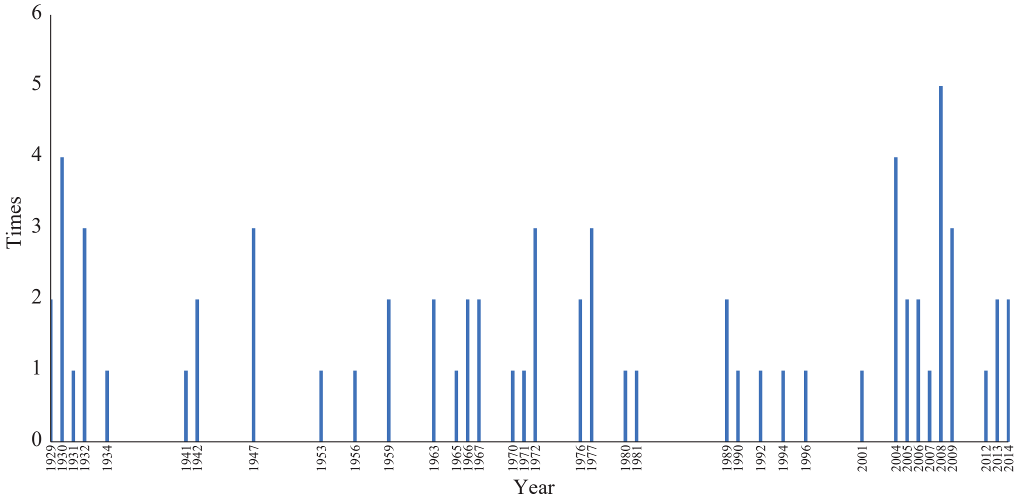


**Fig. 4. The number of times the 24-h rainfall amount exceeded 200 mm in the Lienhuachih area.**

thunderstorms, and typhoon rain. During the cold season (generally from October to April), the northeasterly monsoon brings sufficient moisture to cause small to moderate rainfall on upwind slopes of Taiwan. Rainfall in the cold season is generally caused by the northeasterly monsoon in this area. The northeast monsoon and high-altitude westerly flow are quite strong in the region of South China to Taiwan in spring, and is prone to creating tangential cyclone winds, and rainfall areas mostly occur on the southern edge of the wind tangent line. The edge of the wind tangent line is close to central Taiwan, and with the presence of southwesterly flow at the 850-hpa level and the relative cold, dry northeasterly flow at lower levels, it generally brings more rains in the early spring and causes more rains in April on the western slopes of central Taiwan. April is also the time of the spring transition when rainfall gradually changes from stable precipitation to convective-type precipitation, and rainfall is unevenly distributed over Taiwan (Chen and Chen 2003). In addition of the Lienhuachih area having high monthly rainfall in April, the nearby Sun Moon Lake station managed by the Central Weather Bureau (CWB) also has high monthly rainfall in April (185.9 mm, average of records in 2009~2017). However, the Wuchi station also managed by the CWB on the central Taiwanese coast has a monthly rainfall of 106.5 mm (average in 2009~2017) which is relatively low compared to that of slope areas. These facts indicate that rainfall in April on the western slopes of central Taiwan is relatively high.

During the *mei-yu* (plum rain) season (frontal rainfall that typically occurs between May and June), frontal systems occurring in South China, the East China Sea, and Taiwan bring heavy rainfall to the entire island including the study area. *Mei-yu* rainfall, which on average contributes more than 25% of the annual rainfall, is a major source of rainfall in this area. During hot weather throughout Taiwan after the *mei-yu* season, thunderstorms are prone to occur in summer due to strong afternoon convection. The number of thunderstorms achieves an annual peak during the period from June to August. A short duration, small scale, and high intensity are characteristics of thunderstorms, and they generally produce heavy rainfall in the study area. Typhoon rain is another mechanism of rainfall in Taiwan. About 3.6 typhoons per year hit Taiwan on average, and cause heavy rainfall over the area as they move across (Shieh et al. 1998). Typhoons combined with *mei-yu* rains comprise the 2 rainfall peaks in the Lienhuachih area.

**Long-term changes in rainfall patterns**

Departures of rainfall amounts showed no consistency and also exhibited great variations, mainly because of the influence of extreme rainfall events. In short, overall changes in rainfall in the study area showed a gradually decreasing trend, and the decrease mainly occurred in the wet season. The shift in this rainfall pattern is highly thought to be affected by global warming. One study indicated that due to the rising sea surface temperature caused by global warming, the intense evaporation in the tropics pushes precipitation further northward in the northern hemisphere (IPCC 2001), causing declines in rainfall in Taiwan (Wang 2004).

A rainfall-day is defined with a low threshold as a rainfall amount exceeding 0.1 mm within a day. It excludes days of drizzle and immeasurable rains. Although this kind of rainfall contributes little to water resources utilization, it generally indicates that the day is cloudy. However, the type of rain gauge was changed from a standard rain gauge to a tipping-bucket rain gauge in January 1993. The resolution of rainfall measured by the tipping-bucket rain gauge is 0.5 mm; therefore, only an accumulated amount exceeding 0.5 mm could be recorded after 1993. If the threshold of a rainfall-day was raised to 0.5 mm $d^{-1}$, the average number of rainfall-days was 127, and the tendency of yearly rainfall-days showed a little increase of about 0.164 d $yr^{-1}$. This phenomenon indicates that the number of days with moderate to heavy rainfall has increased, but that of light rainfall events has decreased. Light rainfall helps maintain soil moisture and growth of vegetation, while strong rainfall more easily forms surface runoff and is prone to cause erosion problems. An increased rainfall intensity but not total rainfall means that water resources available to plants and humans are reduced and may bring more challenges for water resources management.

The Lienhuachih area has experienced reductions in both rainfall amounts and rainfall-days over the last 90 yr. The primary declines in rainfall amounts were found in the wet season, while there is worrying about too much water possibly causing erosion and flooding. The reduction in rainfall in the wet season seems to outweigh the benefits. Declines in rainfall-days are generally minor in all seasons in this area, but the increase in heavy rainfall may cause serious problems for hydrological and water resources management.

**Thresholds of extreme rainfall amounts and drought events**

In studying the occurrence of extreme rainfall events and determining thresholds of extreme rainfall events, frequency analyses are commonly adopted. There is no suitable probability distribution that can exactly interpolate the occurrence of a hydrological or meteorological event. However, hydrologists and meteorologists agree that the Weibull probability distribution and the EVI distribution are most suitable for rainfall events. The estimated quantity of daily rainfall through the EVI frequency analysis may be considered reliable for this study area. In addition, if the period of record is sufficiently long, precipitation and meteorological phenomena within a certain time interval can also be analyzed using a normal distribution, and events lying outside the 95% confidence level can be categorized as extreme events.

The CWB has classified 24-h rainfall events as heavy rain, extremely heavy rain, torrential rain, and extremely torrential rain for disaster prediction and prevention. Heavy rain events are 24-h cumulative rainfall exceeding 80 mm, and at least 1 h of intensity exceeding 40 mm. Extremely heavy rain events are 24-h cumulative rainfall exceeding 240 mm or 3-h cumulative rainfall exceeding 100 mm. Torrential rain events are 24-h cumulative rainfall exceeding 350 mm, and extremely torrential rain events are 24-h cumulative rainfall exceeding 500 mm. Therefore, an extremely torrential rain event is a rainfall event with about a 15-yr return period in the Lienhuachih area. Torrential rain events occur almost every year in Taiwan, and extremely torrential rain events may not occur every year in low-elevation areas but will occur nearly every year in mid-elevation areas of Taiwan. However, those 2 kinds of rainfall events do not qualify as extreme rainfall in the Lienhuachih area. In terms of rainfall, the threshold of extreme rainfall in Taiwan is quite high.

Drought events are judged by the number of consecutive days with no rainfall as defined by statistical extremes in this report. It ignores the soil moisture conditions at the beginning of the consecutive days of no rainfall, because soil moisture will be exhausted through drainage into steams or evapotranspiration into the atmosphere when the period of no rainfall is sufficiently long. Drought is described as a natural phenomenon that occurs due to insufficient precipitation over a prolonged period and is also defined as an inequality of water accessibility. The drought threshold value can be determined by the precipitation amount, level of streamflow, and consecutive days of no rainfall (Edossa et al. 2010, Yusof and Mean 2012). Regardless of which indicator is used to estimate the drought threshold, it involves subjective judgment and should consider the local environment. Historically, extreme drought events as judged by the EVI distribution approach occurred twice in 1946 and 1948. People in the Lienhuachih area seem to feel no or little threat of drought, but they do suffer from water shortages in the dry season.

## CONCLUSIONS

The Lienhuachih area has experienced reductions in both rainfall amounts and rainfall-days over the last 90 yr. Consistent with other studies in Taiwan, an increase in the proportion of heavy rainfall in recent years was detected in this report. The increase in heavy rainfall should remind water resources managers that they may face serious problems and management difficulties in the future. In addition, the thresholds of extreme rainfall and drought events were estimated and expressed by rainfall amounts and continuous days of no rainfall. They are about 600 mm $d^{-1}$ and 2 consecutive months of no rainfall for extreme rainfall and drought thresholds, respectively. Those thresholds seem quite high, but extreme rainfall and drought do occur in the study area and are expect to occur more frequently in the future.

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