Research paper

Study of Rainfall Characteristics and Their Changes on the Hengchun Peninsula

Shiang-Yue Lu[1,2)]

【Summary】

Rainfall characteristics including types, regimes, frequency behaviors, long-term changes, and design storm distributions were analyzed for the area of the Hengchun Peninsula in this study. The mechanism of rainfall in the study area can mainly be classified as frontal rain, thunderstorms, and typhoon rain. Each of these mechanisms dominates the type and characteristics of rainfall. Rainfall is extremely unevenly distributed in the annual cycle. About 91.03% of the rainfall is concentrated in the period from May to October (wet season), and the rest (8.97%) is in the period from November to April (dry season). There was a total of 121.7 days on average which had at least 0.1 mm d^{-1} rainfall in the yearly cycle of the study area. The percentage of rainy days in the wet season of the total rainy days in a year was 71.41%, and that of the dry season was 28.59%. This phenomenon indicates that rainfall in the wet season is relatively strong when it occurs, and that in the dry season is usually in smaller amounts. Annual and wet season rainfall totals have significantly increased in the last 4 decades. Annual rainfall has increased about 14.6 mm $decades^{-1}$ and that in the wet season has increased about 12.8 mm $decades^{-1}$. However, the rainfall amount in the dry season has slightly decreased at a rate of -2.5 mm $decades^{-1}$. This phenomenon indicates that there is an increasing trend of rainfall, but the increase is mainly in the wet season. Long-term changes of rainfall-days show a steadily decreasing tendency. Rainfall-days were obviously reduced after 1990. Annual rainfall-days showed the largest declining rate, while rainy days in the dry season showed the least decline. The number of days with a rainfall amount exceeding 30 mm showed an increasing tendency in both the wet and dry seasons. In addition, the Extreme Value Type I distribution was used in this study to estimate magnitudes of 2-, 5-, 10-, 25-, 50-, and 100-year return intervals for 10-min, 1-h, 6-h and 24-h rainfall events. Design storm distributions for 3, 6, and 12 hours were also been analyzed. Results of the design storm analysis combined with those of the frequency analysis can provide a reference for designing hydraulic structures and water control works on the Hengchun Peninsula.

Key words: rainfall characteristics, Hengchun Peninsula, long-term changes, design storm.

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[1)] Division of Watershed Management, Taiwan Forestry Research Institute, 53 Nanhai Rd., Taipei 10066, Taiwan. 林業試驗所集水區經營組，10066台北市南海路53號。

[2)] Corresponding author, e-mail:shiang@tfri.gov.tw 通訊作者。

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研究報告

恆春半島降雨特性及其變遷之研究

陸象豫[1,2)]

摘　要

本研究探討恆春半島降雨分佈、型態、變遷趨勢等特性，並進行頻率及設計降雨量分析。恆春半島降雨機制主要可分為鋒面雨、雷陣雨及颱風雨三大類，每一機制決定降雨型態及特性。該地區雨量在時間上的分佈極為不平均，約91.03%年雨量集中在5~10月(濕季)，其餘8.97%則分布於11月至翌年4月(乾季)。一年中平均約121.7天的降雨量超過0.1 mm，濕季的降雨天數約佔總降雨日數的71.41%，而乾季則佔28.59%。降雨量過度集中於濕季，但降雨天數則否，顯示濕季的降雨強度通常較大且較集中。年降雨量及濕季的降雨量在過去40年間，均有顯著增加的現象，然而乾季的降雨量卻以每十年2.5 mm的微幅減少；全年降雨量約以每十年14.6 mm的幅度增加，濕季降雨量每十年則增加12.8 mm。證實恆春地區降雨量有增加的趨勢，但增加的雨量多集中於濕季。降雨日數長期變化呈現穩定減少的趨勢，減少的幅度在1990年後更為明顯。全年降雨日數減少的幅度最大，乾季的降雨天數減少幅度則較緩，而一年中日降雨量超過30 mm的天數，無論乾濕季均顯示有增加的趨勢。此外，本報告亦以極端值第一型分佈法進行頻率分析，求得2、5、10、25、50及100年回歸週期之10分鐘、1、6及24小時延時之降雨量；亦由歷年降雨紀錄，求得3、6及12小時延時的設計降雨歷線。期望這些研究結果，可做為恆春地區水利工程構造物及防洪工程設計之參考。

關鍵詞：降雨特性、恆春半島、長期變遷、設計降雨。

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INTRODUCTION

Characteristics of precipitation, i.e., the amount, types, and distribution in space and time, play important roles in ecosystem operations, agriculture activities, social structures, economic development, meteorological applications, and design of hydraulic structures. Therefore, studies of regional precipitation are important for a variety of agricultural, hydrological, and meteorological applications. These characteristics combined with the associated discharges of creeks and streams are the main study topics for hydrologists from the initial study of hydrology. Many researchers have studied these topics and discussed precipitation patterns in Taiwan (Wang et al. 1994, Yeh and Chen 1998, Chen and Chen 2003, Wang 2004, Cheung et al. 2008). Their works mainly focused on rainfall categories, temporal and spatial distributions, and the influence of typhoons on the entire island-scale basis. However, recent hydrological fluctuations tend to vary greatly due to influences of global warming, and rainfall characteristics have significantly been affected (Hsu and Chen 2002, Wang 2004, NCDR 2011). In addition, few studies have been carried out so far on temporal distributions and other rainfall characteristics on the Hengchun Peninsula, and this situation is unfavorable for water resources management. In this report, rainfall records of the Hengchun Meteorological Station managed by the Central Weather Bureau

(CWB) for the past 45 yr and the Kueitsaiiyue Station managed by the Taiwan Forestry Research Institute (TFRI) for the past 23 yr were analyzed for their characteristics, long-term change tendencies, frequency behaviors, and design storm distributions to help deal with water resources and ecological system management in this area.

MATERIALS AND METHODS

Site description

The Hengchun Peninsula is located at the southernmost tip of Taiwan and is surrounded by the Taiwan Strait to the west, the Bashi Channel to the south, and the Pacific Ocean to the east, and only the northern part of this peninsula converges with the mainland of Taiwan. Most of the terrain of this peninsula is < 800 m in height and is classified as the southernmost part of the Central Mountain Range (CMR). Weather patterns of this peninsula are classified as a tropical climate and greatly differ from that of other parts of Taiwan which are mostly in a subtropical climate zone. It has long summers and winters are not obvious. The average temperature of the coldest month (January) is 19.0℃, that of the hottest month (July) is 27.3℃, and year-round there is a warm climate. Other climatic conditions can be referenced from Lu et al. (2002). The northeast monsoon brought by continental cold fronts is particularly strong during the period from October to March, and wind speeds during that period can reach to 17 m sec^{-1}. The strong northeast monsoon is known as "Taiwan's chinook".

Materials

Historical rainfall records from the Hengchun Meteorological Station managed by the CWB and the Kueitsaiiyue Meteorological station managed by the TFRI were used as the basic materials of this study. The Hengchun Station is located at 120°44′17″E, 22°00′20″N and 22.1 m above sea level, and the Kueitsaiiyue Station is at 120°49′E, 21°57′N and 230 m above sea level. They are respectively located in downtown Hengchun City and in the Kenting National Tropical Botanical Garden. The straight line distance between these 2 stations is about 8.2 km. Historical daily records (including daily maximum 10-m, 1-h and 6-h records) of rainfall dating from 1970 to 2014 of the Hengchun Station were used for long-term tendency and frequency analysis in this study. Rainfall pattern (design storm distribution) analyses were based on the archived half hourly data records from the Kueitsaiiyue Station which has records from 1992 to 2014.

Long-term change analysis

Historical records of rainfall from the Hengchun Station were first tested for outliers to eliminate any unseasonable records from the dataset. Any record greater than the high outlier or less than the low outlier was considered to be an unseasonable record, and the procedures for calculating the higher and lower outliners are from US WRC 1981. In dealing with seasonal variations, annual records were divided into wet (May to October) and dry (November to April) seasons, because on the long-term average about 79% of the 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 also calculated. If the rainfall amount exceeds 30 mm d^{-1}, then that day was considered to be a heavy rainy day. The monthly average rainfall, rainy days, and heavy rainy days and the average of the entire dataset were calculated. The departure was considered as the difference of the yearly amount and the average of the entire dataset in wet or dry season. Departure diagrams were drawn to compare pattern shifts and differences to illustrate the changes through time.

Frequency analysis

The Extreme Value Type I (EVI) probability distribution function was used in this study because 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). Its probability function is:

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

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

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

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

s as the standard deviation.

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 for studying extreme hydrologic events involves selection of a sequence of the largest or smallest observations from a set of data. In this study, the annual maximum series of 10 min, 1 h, 6 h and 24 h was established by selecting the largest rainfall amounts for the specified period during each year from historical records of the Hengchun Station. Then the means, standard deviations (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.

Design storm analysis

A design storm is a precipitation pattern defined for use in the design of a hydrologic system. It is commonly a temporal precipitation amount distribution of a storm for a specified region and serves as the input data of rainfall-runoff and flow routing procedures. In this report, the rainfall distribution of a design storm was created from observed storm events. Storms of 3, 6, and 12 h duration were selected from hourly and 10-min resolution records of the Kueitsaiiyue Station, and amount distributions in each time sequence for those different durations were analyzed. The time gap of storms of longer than 2 h was subjectively considered as the threshold of different storms. The percentage of the rainfall amount at each time interval to the total rainfall amount and the time to the peak hyetograph were calculated for each storm, and then the average was taken as the design storm distribution (DSD) for those different durations and considered as the rainfall patterns in the study area.

RESULTS AND DISCUSSION

Rainfall characteristics and regimes

The average monthly rainfall, the recorded maximum daily rainfall, rainy days, and number of days which had daily rainfall exceeding 30 mm are tabulated in Table 1. It can be seen that rainfall in the Hengchun Peninsula had an extremely uneven distribution in the annual cycle. About 91.03% of the rainfall was concentrated in the wet season, and the rest (8.97%) was in the dry season. This phenomenon is in accordance with known study results that the further south in Taiwan, the more uneven is the temporal distribution of rainfall (Chen and Chen 2003). The uneven timely distribution of rainfall is unfavorable in terms of water resources management and flood prevention work.

The rainfall mechanism in the Hengchun Peninsula can be classified as frontal rain,

Table 1. Average monthly rainfall and rainy days on the Hengchun Peninsula (1970~2014)

	Total rainfall (mm)	Max. daily rainfall[1)] (mm)	Rainy days (d)	Days of rainfall > 30 mm[2)] (d)
Jan	22.2	36.7	6.8	2
Feb	25.2	67.9	6.1	4
Mar	18.7	68.8	4.4	5
Apr	37.4	111.8	5.7	12
May	162.9	206.3	10.8	64
June	363.4	311.5	16.5	167
July	387.9	395.0	16.0	171
Aug	510.1	615.0	18.4	224
Sept	315.3	348.1	15.4	137
Oct	124.8	339.0	9.8	38
Nov	53.5	430.5	6.3	18
Dec	26.6	144.5	5.5	9
Total	2048.0		121.7	851

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

thunderstorms, and typhoon rain. During the cold season (generally October to April), the northeasterly monsoon bring enough moisture generally causes small to moderate rainfall in this area. The southwesterly monsoon from the South China Sea during the warm season (May to August) also cause rainfall with high intensity. During the *mei-yu* season (generally from 15 May to 15 June), frontal systems from southern China and convective systems embedded within the southwesterly monsoon flow frequently bring heavy precipitation to the entire island including the Hengchun Peninsula (Yeh and Chen 1998, Chen and Chen 2003). Frontal systems commonly bring heavy rainfall in this area during the *mei-yu* season. Hot weather over all of Taiwan after the *mei-yu* season, at which time thunderstorms are prone to occur due to strong convective in the afternoon. The beginning of thunderstorm activities in the Hengchun Peninsula generally occurs in March, and the number of thunderstorm days achieves an annual peak during the period from June to August. Thermally driven circulation during the diurnal heating cycle is important in producing of heavy rainfall in this area. Thunderstorms have characteristics of a short duration, small scale, and high intensity. In summer and early autumn, tropical storms (typhoons) frequently affect Taiwan and result in another major rainfall peak. 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). All 3 of these mechanisms of rainfall occur during the wet season on the Hengchun Peninsula, and this explains the uneven distribution of rainfall in the annual cycle. Although orographic rain is another type of rainfall in most areas of Taiwan, the CMR on the Hengchun Peninsula is relatively low, and rainfall caused by topographic effects is not significant.

There is a total of 121.7 d on average which have at least 0.1 mm d^{-1} rainfall in the yearly cycle of the Hengchun Peninsula. The distribution of rainy days is not as uneven as that of rainfall throughout the year. The percentage of rainy days in the wet season to total rainy days in a year is 71.41% and that of the dry season is 28.59%. This phenomenon indicates that rainfall in the wet season is relatively strong when it occurs, while that in the dry season is usually of small amounts. The number of days which have a daily rainfall > 30 mm in the historical database also was larger in months of the wet season. Months with higher numbers of rainy days (June to September) were generally caused by the mechanisms of typhoon, and thunderstorms.

Frequency analysis

The EVI distribution was used in this study to find the magnitudes of the 2-, 5-, 10-, 25-, 50-, and 100-y return interval rainfall events for 10-min, 1-h, 6-h, and 24-h rainfall events on the Hengchun Peninsula. In fact, rainfall events do not exactly fit any one specific known statistical distribution. It is not known which of the many available distributions is the "true" distribution. However, to make the problem of defining rainfall probabilities tractable, it is necessary to assign a distribution. Although there is no goodness of fit for this distribution, storm rainfalls were most commonly modeled by the EVI distribution in previous studies (Chow 1953, Tomlinson 1980). Because if we assume that precipitation depth for any given storm is random and independent of each other, then the maxima of the total annual precipitation, being the sum of random events, should follow an EVI distribution. The quantiles of rainfall with different recurrence intervals were tabulated and are shown in Table 2.

The purpose of determining the rainfall frequency is to know the rainfall depth that can be expected to occur in a given period of time on average once every so many years. These quantiles are important design variables for many hydraulic structures. In addition, hydrologic systems are usually impacted by extreme events. The magnitudes of those extreme events are inversely related to their frequency of occurrence, with very severe events occurring less frequently than more-moderate events. The frequency analysis expresses hydrological data on a probability basis, so that the frequency of exceeding of some magnitude for a selected variable can be determined. Such works are used in many hydrological analyses such as in the design of water control works, determining conservation storage requirements, and flood plain delineations. Heavier rainfall generally creates larger stream discharges. The estimated rainfall amounts of different return intervals can provide a reference for designing hydraulic structures and water control works.

Long-term changes in rainfall

Long-term changes in rainfall, rainy days, and days with a rainfall amount exceeding 30 mm d^{-1} from 1970 to 2014 on the

Table 2. Results of EVI frequency analysis for records of the Hengchun Station

Return period	Frequency	Estimated rainfall (mm)			
Year	factor	10 min	1 h	6 h	24 h
2	0.165	20.9	66.8	145.3	231.2
5	0.719	25.5	90.8	202.9	323.5
10	1.305	28.6	106.7	241.1	384.6
25	2.044	32.5	126.8	289.3	461.8
50	2.592	35.4	141.7	325.1	519.1
100	3.137	38.3	156.5	360.6	576.0

Hengchun Peninsula are shown in Figs. 1~3, respectively. Departure diagrams of rainfall amounts indicate that annual and wet-season rainfall totals significantly increased during the last 45 yr on the Hengchun Peninsula. Rainfall amounts showed great fluctuations from year to year (annual rainfall ranging 888.7~3470.4 mm) with a tendency to increase in the last 20 yr. The annual rainfall amount increased about 14.6 mm decade^{-1} and that in the wet season increased about 12.8 mm decade^{-1}. However, the rainfall amount in the dry season slightly decreased at a rate of -2.5 mm decade^{-1}. This phenomenon indicates that there is an increasing trend of rainfall, but the increase is mainly in the wet season, when there is no shortage of water resources.

Long-term changes in rainfall-days showed a steadily decreasing tendency from 1970 to 2014 on the Hengchun Peninsula. It was noted that rainfall-day were obviously reduced after 1990 in both the wet and dry

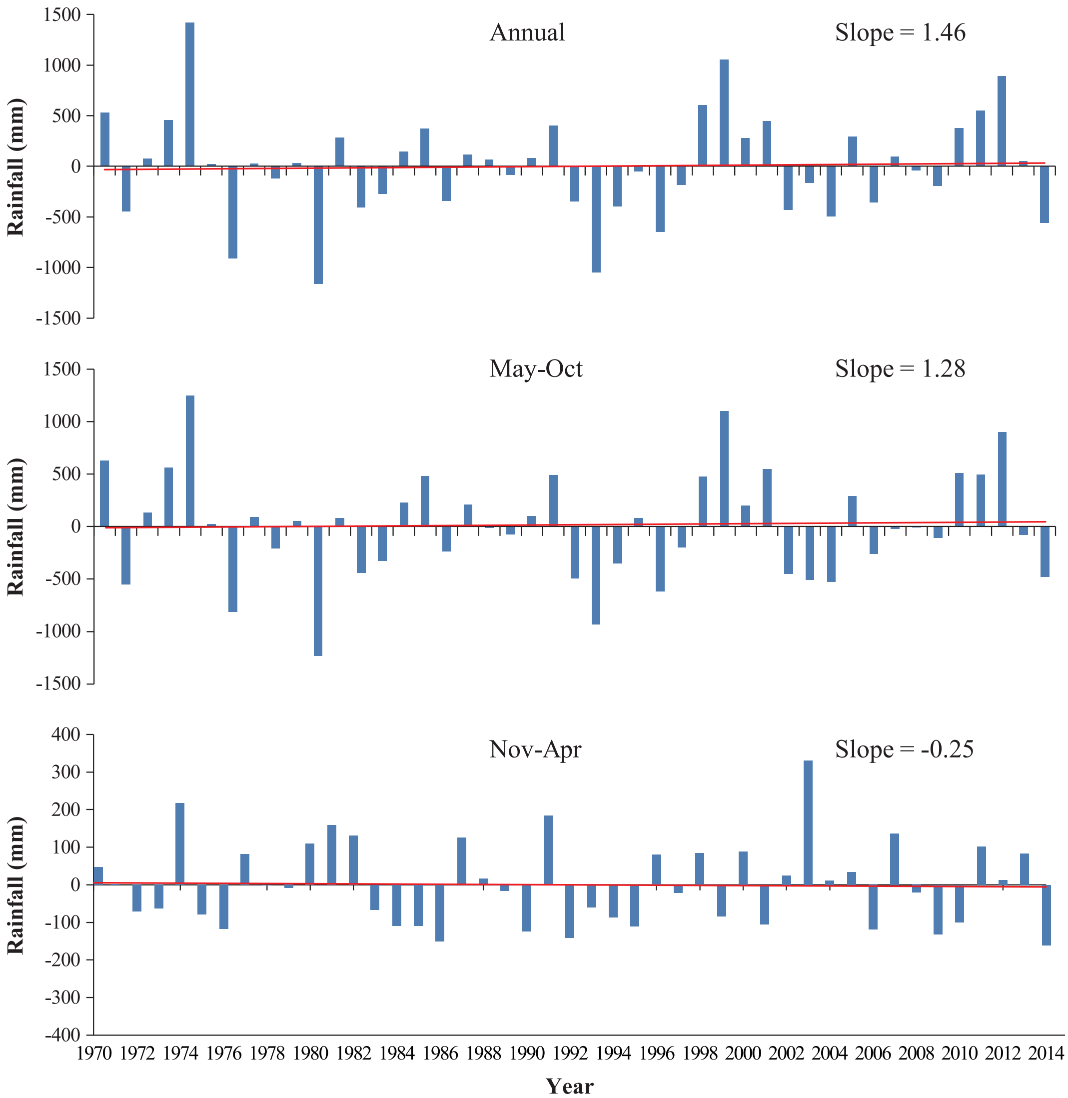

Fig. 1. Long-term linear trends of rainfall amounts for the Hengchun Peninsula.

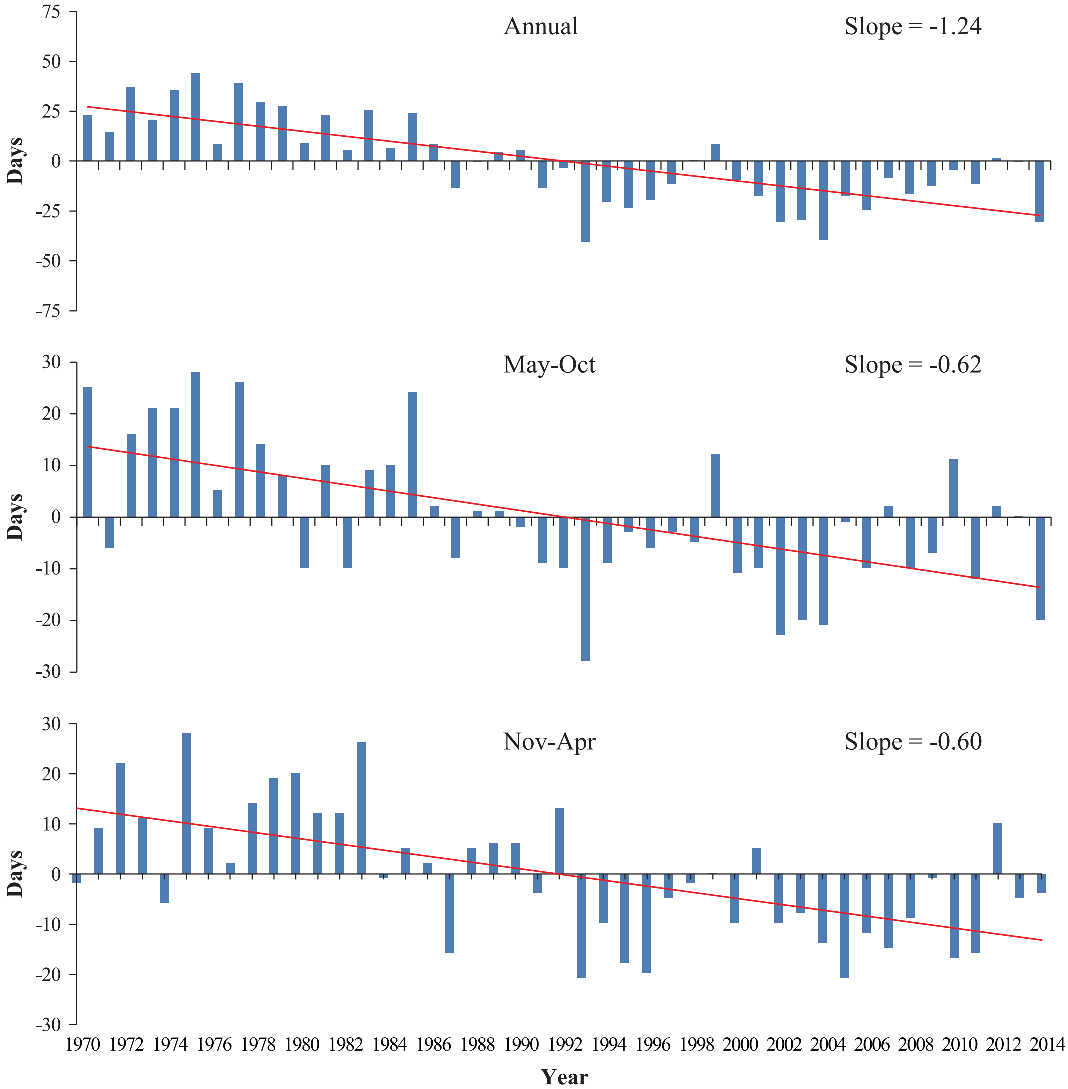

Fig. 2. Long-term trends of rainfall-days for the Hengchun Peninsula.

seasons. Annual rainfall-days showed the largest declining rate (slope = -1.24) where as rainy days in the dry season showed the least decline (slope = -0.60). 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. This kind of rainfall of a low amount has little contribution to water resources utilization. If the threshold were raised to 0.5 mm d^{-1}, the declining tendency would be further obvious. The reasons for the decrease in precipitation-days are complicated and unclear, and most scientists ascribe this phenomenon to global warming.

The number of days with a rainfall amount exceeding 30 mm d^{-1} showed an increasing tendency in both the wet and dry seasons. Any day with a rainfall amount exceeding 30 mm is defined as a heavy rainfall day. Heavy rain in the wet season is generally caused by typhoons and thunderstorms, and

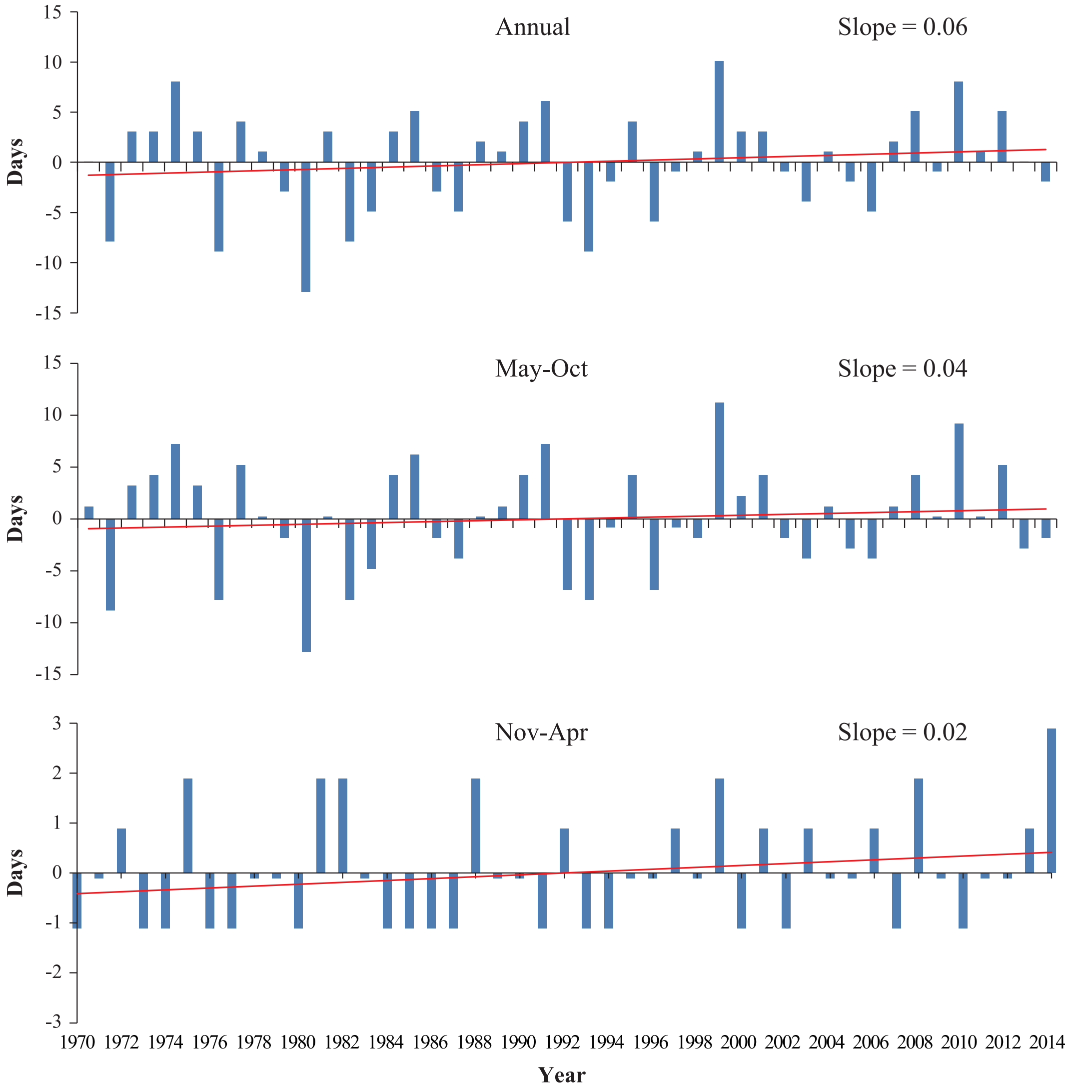

Fig. 3. Long-term linear trends of heavy rainfall-days for the Hengchun Peninsula.

that in the dry season is caused by northeasterly monsoon. It was noted that the number of heavy rainfall days obviously increased after 1990. This phenomenon indicates that big storms occurred more frequently, and rainfall was more concentrated in certain rainy days. Due to the frequency of light rain decreasing but that of the heavy rain increasing, their contributions to the total rainfall amount canceled each other out, and rainfall amount changes were insignificant. Unfavorable trends of rainfall are very evident and have become major factors in generating the recent water management and hydrological problems in this area.

Design storm analysis

Design storms can be defined by a value for precipitation depth at a point, by a design hyetograph specifying the time distribution of precipitation during a storm, or by an isohyetal map specifying the spatial pattern of the precipitation. In this study, the development of design storms was based upon historical precipitation data of the Kueitsaiiyue Station due to its fine resolution records and is represented as the time distribution of rainfall for a specified duration of a storm. There were 378, 300, and 130 storms with durations of 3, 6, and 12 h, respectively, which were selected for the design storm analysis. Total rainfall amounts ranged 2.0~160.5, 2.5~190.0, and 6.0~214.0 mm for durations of 3, 6, and 12 h, respectively. The percent of rainfall at each time interval for these durations were tabulated and are shown in Table 3. It can be seen that rainfall with short durations, i.e., 3 and 6 h of duration, was phone to have a single peak, and that of longer durations generally had more than 1 peak. There are many factors, including type of rainfall, vapor concentration in the atmosphere, and topographic and meteorological conditions that can influence the distribution of rainfall of a storm. The mechanisms of rainfall with a duration of longer than 12 h were all nearly frontal and typhoon types in the study area. It is a complex process for vapor to condense and drop down, and generally there are no rules to follow. Therefore, it is unrealistic that the shape of the hyetograph is triangular for longer-duration rainfall events. However, rainfall with a duration of < 6 h analyzed in this study commonly had triangular hyetograph. The average storm advancement coefficients (defined as the ratio of the time before the rainfall peak to the total duration) for 3- and 6-h duration rainfall in the study area were 0.50 and 0.33, respectively. This shows that storms with a short duration on the Hengchun Peninsula tend to be of the advanced type.

Table 3. Design storm distributions (DSDs) for 3-, 6-, and 12-h duration storms on the Hengchun Peninsula

Time	Design storm distribution (%)		
(h)	3 h	6 h	12 h
0.5	8.82	4.35	1.27
1.0	21.80	8.14	2.20
1.5	30.25	10.25	3.85
2.0	19.79	16.49	5.24
2.5	10.45	14.35	7.35
3.0	8.89	11.36	6.47
3.5		10.26	5.50
4.0		8.23	4.86
4.5		6.58	4.26
5.0		4.72	4.67
5.5		3.21	5.66
6.0		2.06	6.19
6.5			5.32
7.0			4.71
7.5			3.69
8.0			6.25
8.5			4.81
9.0			4.39
9.5			3.72
10.0			3.59
10.5			3.21
11.0			1.13
11.5			0.94
12.0			0.72

Numerous procedures have been developed for designing storms, including SCS rainfall distributions, triangular hyetograph method, intensity-duration-frequency relationships, and scale-invarant Gauss-Markov model (Yen and Chow 1980, Chow et al. 1988, Chen and Hsu 2010). However, most of these methods are used for regions with no observed precipitation available. Since available data records can be used for a design storm analysis, this study used the more reliable and straight forward way to create design storm distributions by calculating historical records.

The application of design storms ranges from the use of point precipitation values in the rational method for determining peak flow rates in storm sewers and highway culverts, to the use of storm hyetographs as inputs for rainfall-runoff analyses of urban detention basins or for spillway design in large reservoir projects. With obtained quantiles of different return periods combined with the results of design storms, the hyetographs of different recurrence intervals can be created and used in hydrologic simulations.

CONCLUSIONS

Rainfall characteristics are crucial factors that influence ecosystem operations, agriculture activities, social structures, and economic development, and they are also the main factors in the design of hydraulic structures. This report further proved that the further south the more uneven is the temporal distribution of rainfall in Taiwan, since about 91.03% of rainfall was concentrated in the period from May to October in the annual cycle for the Hengchun Peninsula. There was a total in average 121.7 d on average which had at least 0.1 mm d^{-1} of rainfall in the yearly cycle of the study area. Rainfall-days was not as unevenly distributed (71.41% in the wet season) as that of rainfall amount, and this phenomenon means that rainfall in the wet season is relatively strong when it is occurs, and that in the dry season is usually in small amounts in the peninsula area. Although rainfall amounts showed a slight increasing tendency, the days of heavy rainfall showed significant decreasing tendencies in the last 4 decades. This phenomenon indicates that big storms occurred more frequently, and rainfall was more concentrated on certain rainy days. The unfavorable trends of rainfall are very evident and have become major factors in generating recent water management and hydrological problems in this area. In addition, frequency and design storm analyses are also presented in this report.

Magnitude of 2-, 5-, 10-, 25-, 50-, and 100-y return interval rainfall events for 10-min, 1-, 6-, and 24-h rainfall events on the Hengchun Peninsula were also estimated in this report. Quantiles of estimated rainfall for 100-yr return period were 38.3, 156.5, 360.6, and 576.0 mm for 10-min, 1-, 6-, and 24-h durations, respectively. These values of rainfall amounts can be used as a reference when designing hydraulic structures for flood prevention. Design storm distributions for 3-, 6-, and 12-h duration storms on the Hengchun Peninsula are also presented in this report. The designed hyetographs can be used in hydrologic simulations and in estimating peak rainfall events for the most commonly occurring rainfall durations in the study area.

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