Research paper

Climatic and Hydrological Characteristics of the Liukuei Experimental Forest

Shiang-Yue Lu,[1)] Ming-Yuan Sun,[2,3)] Jia-Bin Tsai,[2)] Hui-Hsueh Huang[1)]

【Summary】

The Liukuei Experimental Forest (LEF) is the largest experimental forest in Taiwan in which about 10,000 ha of natural and artificial forestlands are administered. To understand the climatic and hydrological conditions of this vast area so as to provide necessary information for forestry management, phenology, hydrology, afforestation, and ecological conservation, the Division of Watershed Management has successively set up 3 second-grade agricultural weather stations in the northern, central, and southern parts of the LEF since 1980 respectively named the Fonkang, Shanping, and Donna stations, as well as 5 gauged watersheds in the Shanping area since 1964. This report summarized the effective electronic records of these 3 stations from 1986 to 2017, and presents LEF's climatic conditions in monthly resolution. Average annual rainfall amounts in the Fonkang, Shanping, and Donna areas were 3429.8, 3435.9, and 3536.1 mm, respectively. The average annual rainfall for the entire area was close to 3500 mm (3467.3 mm), which was much higher than that for Taiwan as a whole (about 2500 mm) and indicates that the LEF receives abundant rainfall. However, rainfall in the LEF mostly occurs in April to October, and this period can be defined as the wet season. Rainfall in the wet season accounted for 92.8, 94.5, and 94.7% of the total annual rainfall for the Fonkang, Shanping, and Donna areas, respectively. This shows that rainfall is extremely temporally unevenly distributed. There are a clear wet season and dry season in the LEF. Numbers of rainfall-days (defined as a day with ≥ 0.5 mm of rainfall) in a year for the Fonkang, Shanping, and Donna areas were 142.5, 135.1 and 126.0 d, respectively. The number of rainfall-days in the northern part of LEF was greater than that of the southern part, while the rainfall amount in the north was less than that in the southern part, indicating that rainfall was more unevenly temporally distributed in the southern part of the LEF. Annual average temperatures in the Fonkang, Shanping, and Donna areas were 16.7, 20.7, and 19.7℃, respectively. The entire LEF area belongs to a cool climate zone, based on the annual average temperature. The difference in annual average temperature is mainly determined by elevation. The average monthly temperature differences for the Fonkang, Shanping, and Donna areas in a year cycle were 7.7 (12.3~20.0), 8.3 (15.8~24.1), and 8.6 (14.7~23.3)℃, respectively. Compared to the monthly average temperature difference of the Fushan, Lienhuachih and Taimali experimental forest of ITRI, the average monthly temperature difference of the LEF was relatively low. The highest monthly average temperature for the entire LEF area was in July, and the lowest average monthly temperature was in January. Average daily temperature differences in January for the Fonkang, Shanping, and Donna areas were 7.04, 6.87, and 6.42℃, respectively; and those of July were 5.73, 6.50, and 7.32℃, respectively. Other meteorological parameters monitored in the LEF were humidity, solar radiation, wind speed and direction, and evaporation. The physical quantities of these meteorological factors are also presented in monthly statistics. In addition, the yearly average temperatures of the air, streamflow, topsoil at 5, 30, and 50 cm in depth of the riparian zone of Chungliao Creek were 19.53, 19.04, 18.99, 19.39, and 19.38℃, respectively, for the monitoring period of 2005~2008. The yearly average rainfall, streamflow discharge, and baseflow for the period 2000~2003 of the Shanping no. 2 experimental watershed were 3316.5, 2043.1, and 487.3 mm, respectively. It was also noted that streamflow discharge in the period from November to April mainly originated from deep seepage water and groundwater and was approximately equal to that of baseflow.

Key words: Liukuei Experimental Forest, rainfall amount, temperature difference, streamflow discharge, riparian zone.

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研究報告

六龜試驗林氣象及水文特性之研究

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摘　要

六龜試驗林為台灣地區最大的試驗林，擁有將近1萬公頃的天然及人工林，為能掌握此一廣大地區的氣候狀況，以供林業經營、物候、水文、育林、生態保育等方面的研究所需，林業試驗所所集水區經營組早在1980年起即陸續在試驗林北中南三區設置了鳳岡、扇平及多納等三座氣象觀測站並於1964年起在扇平地區陸續設置了五座試驗集水區。本報告彙整1986年起至2017年該三測站的有效電子紀錄，以月為單位呈現六龜試驗林北中南三區域的氣候狀況。六龜試驗林鳳崗、扇平、多納三測站的年平均降雨量分別為：3429.8、3435.9及3536.1 mm，總平均年降雨量接近3500 (3467.3) mm，高於台灣年平均2500 mm甚多，顯示該試驗林雨量甚為豐富。然而主要的降雨多發生在4至10月(濕季)，鳳岡、扇平及多納此期間的降雨量分別佔全年總降雨量的92.8、94.5及94.7%，顯示降雨極為不平均，有明顯的乾濕季之分。鳳岡、扇平及多納地區年平均降雨天數(單日降雨量≥ 0.5 mm)分別約為142.5、135.1及126.0天；而北部鳳岡林區年雨量稍低於南部區域，顯示試驗林南部地區降雨比北部區域在時間分布上較為集中。試驗林鳳崗、扇平及多納三林區的年均溫分別為16.7、20.7 及19.7℃，由年均溫觀之，全境均屬於偏涼的氣候區，而年均溫的差異主要係受海拔高度的影響。鳳岡、扇平及多納全年度月平均溫差分別為7.7 (12.3~20.0)、8.3 (15.8~24.1) 與8.6 (14.7~23.3)℃，相較於林試所福山、蓮華池及太麻里等其他試驗林的月均溫差，六龜試驗林月均溫差相對地為低。三林區最高月均溫均以7月為最高，最低月均溫則均為1月份。鳳岡、多納及扇平1月平均日溫差分別為：7.04、6.87及6.42℃；7月平均日溫差則分別為：5.73、6.50及7.32℃。其他與氣候相關且進行觀測的氣象因子尚有：濕度、日照輻射、風速與風向、蒸發量等項目，均以月統計的方式呈現該等氣象因子的物理量。此外，試驗林中寮溪濱水帶亦在2005年至2008年進行溪流水溫、大氣及土壤表層溫度監測測，獲知大氣、溪流水及5、30與50 cm深處土壤的年均溫分別為：19.53、19.04、18.99、19.39及19.38℃。扇平二號試驗集水區在統計期間年降雨、逕流及基流量分別為：3316.5、2043.1及487.3 mm，並獲知在十一月至翌年四月間，溪流水主要源自基流。

關鍵詞：六龜試驗林、降雨量、溫差、溪流流量、濱水帶。

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INTRODUCTION

The Liukuei Experimental Forest (LEF) under the jurisdiction of the Liukuei Research Center (LRC) of the Taiwan Forestry Research Institute (TFRI) encompasses about 9882 ha of forestlands that range 250~2600 m in elevation and is one of the most important experimental forest sites in Taiwan. To understand climatic conditions of such a vast and complex forest terrain ecosystem so as to provide for forestry management and research needs, the Liukuei Branch (the former name of the LRC) conducted rainfall observations as early as 1955 at the Shanping Work Station and also has subsequently monitored other meteorological factors such as temperature, relative humidity (RH), evaporation (using a Type A evaporation pan), and cloud cover at the Shanping and Donna Work Stations since 1980. As electronic monitoring devices of various parameters came out one after another in the late 1980s, the Division of Watershed Management of TFRI successively set up 5 second-grade agricultural weather stations at the Liukuei, Fonkang, Shanping, Donna, and Senshin Work Stations (Table 1) after 1986. The monitored items include wind speed and direction, solar radiation, temperature (including the maximum and minimum of daily records), RH, rainfall, etc., and initiated an era of automatic detection and storage of digital records. At present, all weather stations in the LRC are monitored by Campbell's CR1000 system. Each monitored parameter is detected every 10 min, and then the average (or total), and the highest and lowest recorded values of the period are stored in a data logger.

The Joint Commission on Rural Reconstruction (a former institute of the Council of Agriculture) invited Prof. Rebert Dils of Colorado State University (USA), a watershed research expert, to visit Taiwan in 1963. He pointed out in his inspection report that Taiwan has steep terrain and frequent slope disasters. Therefore, he strongly suggested that the government should carry out catchment studies as early as possible. In 1964, the TFRI received financial support from the Joint Commission on Rural Reconstruction and Forest Bureau and successively constructed 5 experimental watersheds in the Shanping area. Those gauged watersheds initiated experimental watershed studies in Taiwan. Although they were installed very early, due to the poor geological conditions (mostly interbedded shale and gneiss) and frequent heavy rainfall, weirs of these watersheds were often fully filled with silt, and observations were often interrupted.

Stream systems occupy a large portion of the LEF. The interface between uplands and streams is the riparian zone, which is important in ecology, environmental management, and civil engineering because of its role in soil conservation, its habitat biodiversity, and its influence on fauna and aquatic ecosystems including grasslands, woodlands, wetlands, and even non-vegetated areas. The Division of Watershed Management also monitored temperatures of the air, streamflow, and topsoil layers at 5, 30, and 50 cm in depth, and RH in the riparian area of Chungliao Creek, a tributary of Shanping Creek, in 2005~2008.

In this report, physical quantities of meteorological factors in the northern, central, and southern parts of the LEF, streamflow and rainfall records of the Shanping no. 2 experimental watershed, and temperatures of streamflow and topsoils in riparian zones of Chungliao Creek are presented as monthly statistics. Hopefully such information will be useful to better understand environmental conditions of the LEF.

Table 1. Information of weather stations in the Liukuei Experimental Forest

Name	Location	Elevation (m)	When established
Liukuei	120°38′46”E 22°59’30”N	251	Aug. 1980 (Oct. 1995 AM[1])
Shanping	120°41’08”E 22°58’04”N	692	Aug. 1980 (Jan. 1991 AM)
Fonkang	120°42’36”E 23°00’00”N	1637	Jan. 1986 (Jan. 1986 AM)
Donna	120°44’16”E 22°53’17”N	1050	May 1986 (May 1986 AM)
Senshin	120°41’43”E 22°57’32’N	1202	Oct. 1991 (AM)

[1] Automatic monitoring.

MATERIALS AND METHODS

Study area

The LEF is located in southwestern Taiwan in the upstream portion of the Laonong River watershed (Fig. 1). Besides the stream and road systems, buildings of 3 work stations, and bare landslide areas, all of the other land is covered by forests. The area of artificial forestland is about 1560 ha, and other forestlands are natural hardwood forests. The geology of the entire area has an interbedded structure of shale and gneiss. Due to the latitude of LEF ranging from 23°00’31”N in the north to 22°50’06”N in the south, and the large elevation difference, it is difficult to express climatic conditions with only average values of records of those meteorological stations. However, it is reasonable to divide the LEF into three major forest areas, namely the Fonkang, Shanping, and Donna areas from north to south, respectively. The Senshan and Shanping weather stations are located close together. Due to the shorter period of record of the Senshan station, we used records of the Shanping station to express climatic conditions of the central area of the LEF. Because of the inconvenient traffic conditions on the east coast of Hot-Spring Creek (9 to 25 forest compartments), no weather station has been set up in this large region. Weather conditions in that area are poorly understood.

In order to understand the relationship between rainfall and streamflow amount of watersheds in the LEF, the Shanping no. 2 experimental watershed was selected as the study area. The area, main stream length, average slope, minimum and maximum elevations, and aspect of this gauged watershed are 49.95 ha, 3980 m, 74%, 693 m, 1362 m, and SW, respectively (Lu et al. 2009). The geological formation is mainly mudstone and

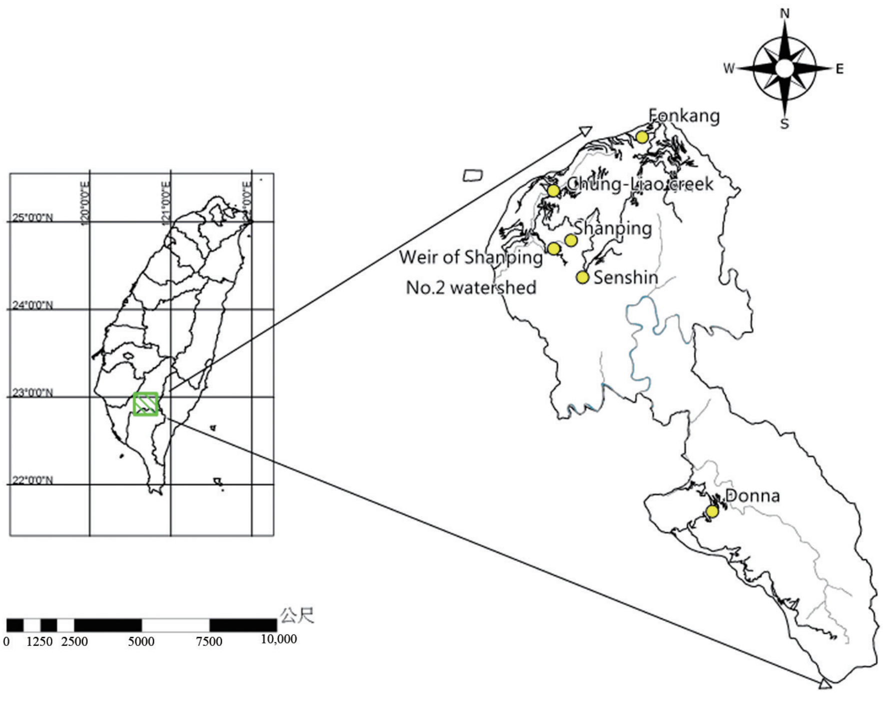

Fig. 1. Location of meteorological stations, the weir of the Shanping no. 2 watershed, and monitoring site of temperatures in the riparian zone of the Liukuei Experimental Forest.

slate which is characterized as easy to friable and hard to weather. The topsoil is an acidic reddish-yellow Podzolic soil with a shallow organic layer, and the deeper soil is a clayey loam mixed with plenty of Podzolic fragments. The vegetative cover is almost completely closed by plants of the Lauraceae and Fagaceae families, and groundcover plants are mainly ferns, large lineolate *Elatostema* and dwarf Lilyturf (Koh et al. 1978).

Materials

Valid self-recorded meteorological records of these 3 stations were the basic material for explaining the climatic conditions of the LEF. Data periods of these stations are: 1986~2017 for the Fonkang Station, 1991~2017 for the Shanping Station, and 1987~2017 for the Donna Station. Daily streamflow and its corresponding rainfall records of the Shanping no. 2 gauged watershed were used to explain the hydrological conditions of Shanping Creek. Reliable records were collected from 2001 to 2003. Temperature records of air, streamflow, and top soils from 2005 to 2008 of the riparian zone of Chungliao Creek were used to describe the heat budget and temperature relationships among air, streamflow, and topsoils of the riparian zone.

Data collection and analysis

Data collection followed the sequence of hydrologic measurement that is sensing, recording, transmission, translation, editing, storage, and retrieval, and then the data could be used. All records before editing had to be treated by an outlier test to delete or modify unreasonable records (Chow et al. 1988). Data were stored by establishing a database which contained files of a year's record in Microsoft Excel and ASCII formats. Data were retrieved using a self-created program in ASCII formatted data or with Microsoft Excel for Excel formatted data. Selected data were statistically analyzed for totals, means, etc., to present monthly and annual records of each desired factor.

Baseflow separation

Many techniques of baseflow separation were generally developed by rules of thumb and involve subjective judgment. The commonly used baseflow separation methods are: the straight-line method, fixed-base-length method, and variable-slope method. The variable-slope method was adopted in this report because it considers that the value of baseflow is related to that of discharge and can give more-accurate estimates. The baseflow curve before the surface runoff begins is extrapolated forward to the time of peak discharge, and the baseflow curve after surface runoff ceases is extrapolated backward to the time of the point of inflection on the recession line. A straight line is used to connect the endpoints of the extrapolated curves (Bethalhmy 1972, Chow et al. 1988). Detailed techniques were also referenced from Lu et al. (1995).

RESULTS

Climatic conditions of the LEF

Climatic conditions of a region are mainly determined by rainfall and temperature. Average annual rainfall amounts of the Fonkang, Shanping, and Donna areas of the LEF were 3429.8, 3435.9, and 3536.1 mm, respectively, with the average approaching 3500 mm (3467.3 mm), which is much higher than the annual average of 2500 mm for Taiwan in general, indicating that rainfall in this experimental site is very abundant. The average numbers of rainfall-days (defined as daily rainfall of $\geq$ 0.5 mm) in Fonkang, Shanping, and Donna were 142.5, 135.1, and 126.0 d, respectively. The number of rainfall-days in the northern part of the LEF was slightly higher than that in the southern region, indicating that rainfall in the southern part of the experimental forest was more concentrated than that in the northern region.

Average annual temperatures of the Fonkang, Shanping, and Donna areas of the LEF were 16.7, 20.7, and 19.7℃, respectively. According to the average annual temperature, the entire area belongs to a colder climatic zone. Monthly average temperature differences in an annual cycle for the Fonkang, Shanping, and Donna areas were 7.7 (12.3~20.0), 8.3 (15.8~24.1), and 8.6 (14.7~23.3)℃, respectively. The average temperature difference of the LEF is relatively low compared to those of the Fushan, Lienhuachih and Taimali experimental forests of the TFRI (Lu et al. 2000). Monthly average temperatures including maximum and minimum temperatures and rainfall amounts of the Fonkang, Shanping, and Donna areas are shown in Figs. 2~4. The lowest average monthly temperatures of these stations all occurred in January with a few years having lowest monthly average temperature in February due to the late arrival of a cold air mass. The highest average monthly temperatures of these stations all occurred in July without exception.

Other meteorological factors in addition to rainfall and temperature that are closely related to climate include humidity, solar radiation, wind speed and direction, evaporation, etc. The monthly statistical results of those factors are tabulated in Table 2.

Temperatures of the air, streamflow, and top soil layers of the riparian zone under study

Monthly average temperatures for air, streamflow, and soils at different depths from 2005 to 2008 of the riparian zone of Chungliao Creek are tabulated in Table 3. Soil types of the monitored spots were classified

Table 2. Monthly average statistics of relative humidity (RH), solar radiation, wind speed, and evaporation amounts of the Liukuei Experimental Forest

Month	RH (%)			Solar radiation (MJ m^{-2})			Wind speed (m s^{-1})			Evaporation (mm)	
	FK	SP	DN	FK	SP	DN	FK	SP	DN	SP	DN
Jan.	86.6	85.8	84.3	355.0	288.1	329.6	0.67	0.70	0.57	79.5	71.0
Feb.	88.1	86.0	83.4	326.0	292.3	314.2	0.67	0.72	0.62	71.5	94.5
Mar.	88.7	84.7	85.1	373.6	354.1	375.4	0.65	0.71	0.63	99.3	95.5
Apr.	91.0	86.9	86.2	354.4	401.4	384.2	0.61	0.76	0.67	100.5	102.6
May	92.6	89.8	89.2	336.1	420.0	409.2	0.58	0.76	0.64	115.4	114.9
June	93.3	89.6	89.8	340.0	432.3	418.3	0.67	0.74	0.70	92.9	93.6
July	93.5	89.6	89.0	345.7	479.2	452.9	0.67	0.77	0.80	104.1	114.7
Aug.	93.3	90.2	91.2	313.1	411.5	373.4	0.70	0.71	0.78	89.1	101.1
Sept.	94.2	90.3	90.8	297.4	394.8	372.0	0.56	0.66	0.70	82.2	77.8
Oct.	92.8	89.5	90.0	316.5	354.3	342.6	0.52	0.64	0.60	82.0	74.9
Nov.	89.0	88.1	88.1	330.2	283.4	303.4	0.57	0.63	0.59	77.2	71.5
Dec.	87.1	87.0	86.1	319.6	254.5	295.6	0.61	0.65	0.55	72.0	69.5
Avg.	90.9	88.1	87.8				0.62	0.70	0.65		
Sum				4007.5	4366.0	4370.7				1065.7	1081.6

FK, Fonkang; SP, Shanping; DN, Donna.

Table 3. Average monthly temperatures of the air, streamflow, and top soil layers at 5, 30, and 50 cm deep, and relative humidity (RH) in the riparian zone of Chungliao Creek

	Temperature (℃)					RH (%)
	Air	Streamflow	5 cm	30 cm	50 cm	
Jan.	15.44	16.46	17.31	15.86	16.33	89.42
Feb.	15.84	16.79	17.56	16.02	16.87	88.28
Mar.	17.38	17.32	17.89	17.30	17.39	86.18
Apr.	20.02	19.29	18.80	19.91	19.66	88.72
May	21.51	20.52	19.56	21.23	21.02	89.59
June	22.05	20.48	19.90	21.39	21.08	93.10
July	23.02	20.99	20.32	22.17	21.73	94.02
Aug.	21.98	20.34	20.16	21.77	21.40	94.31
Sept.	21.86	20.62	20.03	21.64	21.35	92.93
Oct.	20.76	20.02	19.92	20.71	20.35	92.19
Nov.	18.68	18.88	19.37	18.93	18.96	91.24
Dec.	15.89	16.72	17.08	15.69	16.36	90.58
Avg.	19.53	19.04	18.99	19.39	19.38	91.08

as sandy to sandy loam with a characteristic of the percentage of sand decreasing with increasing depth. There was no vegetation at the monitoring spots or it had been removed; therefore, no solar energy was consumed by photosynthesis. All maximum monthly average temperatures for air, streamflow, and soil layers at all monitored depths occurred in July. The minimum monthly average temperatures of the monitored items all occurred in January. The occurrence of maximum and minimum monthly average temperatures was consistent with that of air temperature. Hourly temperature fluctuations in January and July for the studied riparian zone are shown in Figs. 7 and 8, respectively.

Rainfall and corresponding discharge for the Shanping no. 2 experimental watershed

Daily records of streamflow discharge and rainfall for the Shanping no. 2 experimental watershed from November 2000 to December 2003 were used to analyze and express hydrological characteristics of the LEF. Monthly statistics are tabulated in Table 4. The annual rainfall and discharge for the period were 3316.5 and 2043.1 mm, respectively. The ratio of the annual discharge to rainfall was 61.62%, and that for periods from May to October and from November to April were 60.46% and 91.86%, respectively. The average yearly baseflow of the target watershed was 487.28 mm, which accounted for about 23.9% of the annual discharge and 14.7% of annual rainfall. It was noted that discharge in the dry period (November to April) was nearly all attributed to baseflow, and the ratio of baseflow to discharge in the period from May to October was about 19.1%.

DISCUSSION

Rainfall characteristics and extreme events

Rainfall in the LEF mostly occurs in May to September, and rainfall amounts in this period accounted for 85.0, 86.8, and 87.5% of the total annual rainfall in the Fonkang, Shanping, and Donna areas, respectively.

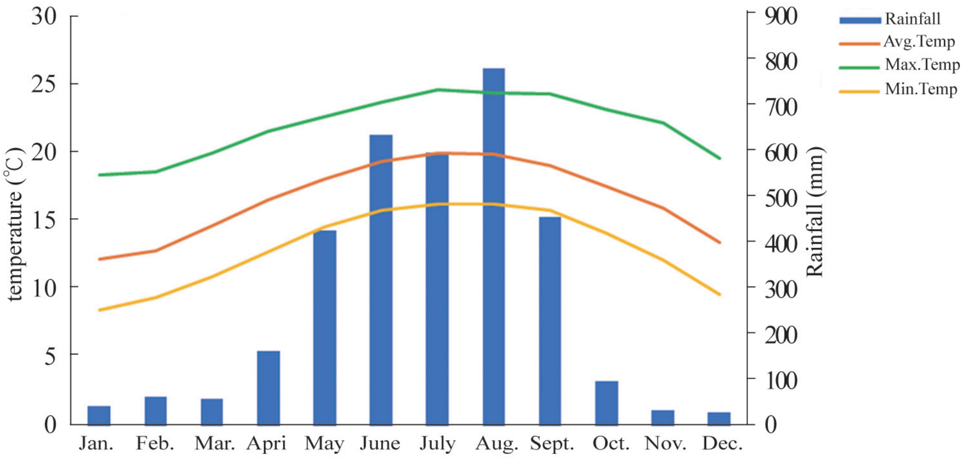

Fig. 2. Monthly average temperatures and rainfall amounts for the Fonkang area.

Table 4. Monthly average discharge and rainfall of the Shanping no. 2 watershed

Month	Rainfall (R; mm)	Discharge (D; mm)	D/R (%)	Baseflow (mm)
Jan.	36.2	24.75	68.37	24.75
Feb.	6.8	13.23	194.56	13.23
Mar.	31.5	10.45	33.17	10.45
Apr.	32.5	16.40	50.46	16.40
May	854.9	378.75	44.30	61.49
June	431.0	274.37	63.66	65.34
July	663.8	396.27	59.70	65.19
Aug.	428.3	284.51	66.43	55.89
Sept.	675.0	434.31	64.34	62.35
Oct.	110.5	147.77	133.73	56.23
Nov.	19.5	49.56	254.15	43.26
Dec.	26.5	12.70	47.92	12.70
Sum	3316.5	2043.07		487.28

If we expanded the calculation period from April to October, percentages of rainfall in those 7 mon compared to annual rainfall amounts would account for 92.8, 94.5, and 94.7% for the Fonkang, Shanping, and Donna areas, respectively. This fact indicates that the temporal distribution of rainfall in the LEF is very uneven, and the period from November to March is extremely dry.

During the period from February to April of each year, cold air masses from the northern mainland encounter unstable warm air masses from the southern sea, and an unstable interface is formed (called the southern Yunnan cloudiness area) which is conducive to the development of clouds and rain in Taiwan (Chen and Chen 2003). The rainfall in this period is called the spring rains. The spring rain is the first rainfall mechanism after the dry season, and its amount accounts for about 7.8% of the total annual rainfall in the LEF.

Another rainfall mechanism is the plums rains (*mei-yu*), which mainly occur in the

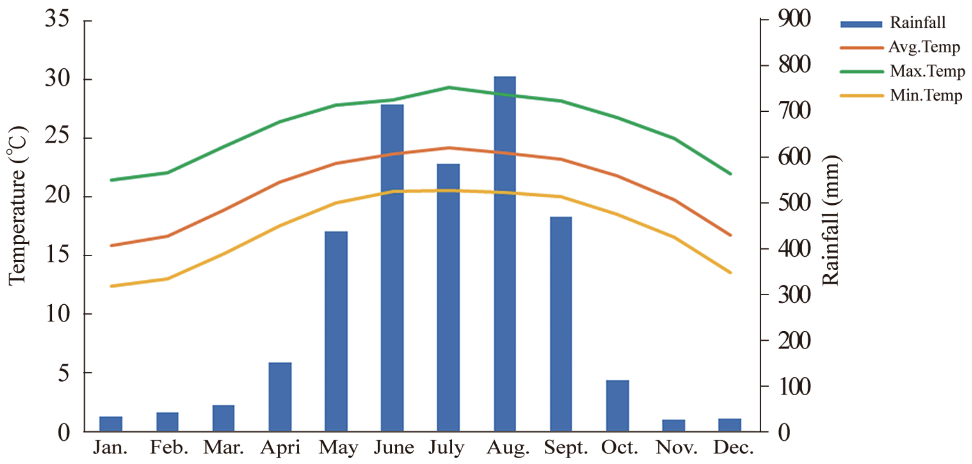

Fig. 3. Monthly average temperatures and rainfall amounts for the Shanping area.

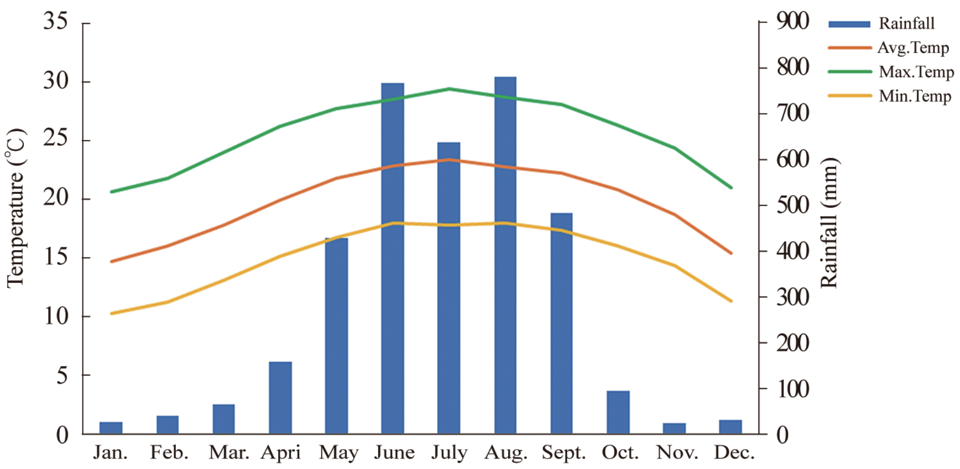

Fig. 4. Monthly average temperatures and rainfall amounts for the Shanping area.

period between spring and summer generally from 15 May to 15 June. Since the northeasterly monsoon gradually weakens and the southwesterly monsoon from the southern tropical oceans gradually increases (southwesterly airflow) at this time, cold and warm air masses with equivalent force are encountered in the area of southern China to Taiwan, and fronts are created in this area. These frontal systems bring intensive rainfall to southern China and Taiwan. About 30~37% of the annual rainfall in the LEF is concentrated in the plum-rain period, which is the second largest rainfall type after typhoon rainfall in the experimental forest. Although typhoons may also affect the LEF during this period, the number of typhoons that hit Taiwan in May and June only account for about 15% of the total number of typhoons. Therefore, the main rainfall mechanism in May and June is the plum rains.

The peak high-intensity rainfall of the LEF is concentrated in July to September and is mainly due to typhoons. According to statistics of the Central Weather Bureau (CWB), an average of about 3.4 typhoons has hit Tai-

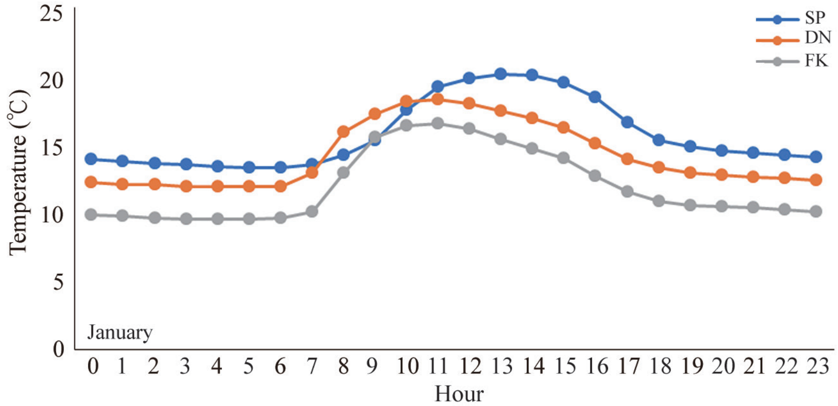

Fig. 5. Hourly average temperature fluctuations in January for 3 areas of the Liukuei Experimental Forest. SP, Shanping; DN, Donna; FK, Fonkang.

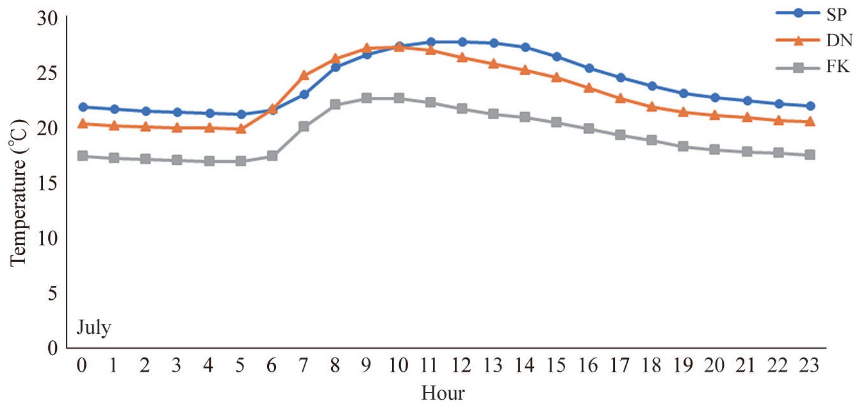

Fig. 6. Hourly average temperature fluctuations in July for 3 areas of the Liukuei Experimental Forest. SP, Shanping; DN, Donna; FK, Fonkang.

wan each year over the past 100 yr, and about 80% are concentrated in July to September. The LEF is a hot area where strong rainfall occurs when typhoons invade Taiwan. The long duration of heavy rainfall brought by typhoons is the main factor causing landslides and road collapse in the experimental forest. The amount of rainfall brought by typhoons is often the deciding factor in the amount of annual rainfall. Another rainfall mechanism in summer is orographic (or relief) precipitation. Moisture-rich air currents from the sea off southwestern part of Taiwan are forced to ascend due to blockage by mountains, and during their ascent, the moisture cools and condenses creating rainfall. This kind of rainfall mostly occurs on summer afternoons and is the main rainfall mechanism in the LEF during summertime. Summer rainfall is also an important water resource of the experimental forest, and it accounts for about 55% of annual rainfall. Rainfall in October is partly brought by thunderstorm which is mostly occurred early of this month and the other part is caused by autumn typhoons. However, that generally accounts for only a small amount.

The largest 24-h rainfall record in the LEF was 1290.0 mm which occurred from

02:00 on 8 August to 01:00 on 9 August 2009 in the Fonkang area (due to typhoon Morakot), and the second largest was 1065.5 mm which occurred from 12:00 on 18 July to 11:00 on 19 July 2005 in the Donna area (due to typhoon Haitang), both of which were memorable events of heavy rain.

According to the definition of extreme torrential rain events by the CWB (i.e., 24 h cumulative rainfall exceeding 350 mm), there were over 12 extreme torrential rain events in the LEF during the recording period. They occurred almost every 2 yr, and all were brought by typhoons. Huge torrential rains brought by typhoons in the experimental forest frequently occur and are the main reason for slope failure and road damage in the LEF.

Average periods of the most consecutive days without rain in a year in the Fonkang, Shanping, and Donna areas were 32, 31, and 38 d, respectively. The most consecutive days without rainfall occurred in the Donna region from 10 October 1995 to 18 January 1996 with 70 consecutive days in total with no rainfall recorded. The most consecutive no-rainfall days in the Fonkang and Shanping regions were 65 and 62 d, respectively. Continued time with an absence of rainfall is one of the indicators of drought. The results indicated that the southern parts of the LEF are more vulnerable to drought than are other parts of the LEF.

Extreme temperatures and daily temperature variations

Factors that affect temperatures of the LEF are mainly elevation and the presence of air masses. Low temperatures in winter in the LEF are mainly affected by continental cold air masses from China mainland. When a center of high atmospheric pressure reaches the Yangtze River or even further south, central and southern Taiwan will be affected by it, and low temperatures will occur. The lowest recorded instantaneous temperatures for the Fonkang, Shanping, and Donna areas were -1.2, 3.0, and -0.1℃, respectively. These historical lowest temperatures all occurred in the early morning after a cold air mass had reached Taiwan. High temperatures in summer in the LEF are associated with the amount of solar radiation and also with high sea temperatures in the western Pacific Ocean, which is the result of the El Niño phenomenon. The highest recorded instantaneous temperatures in Fonkang, Shanping, and

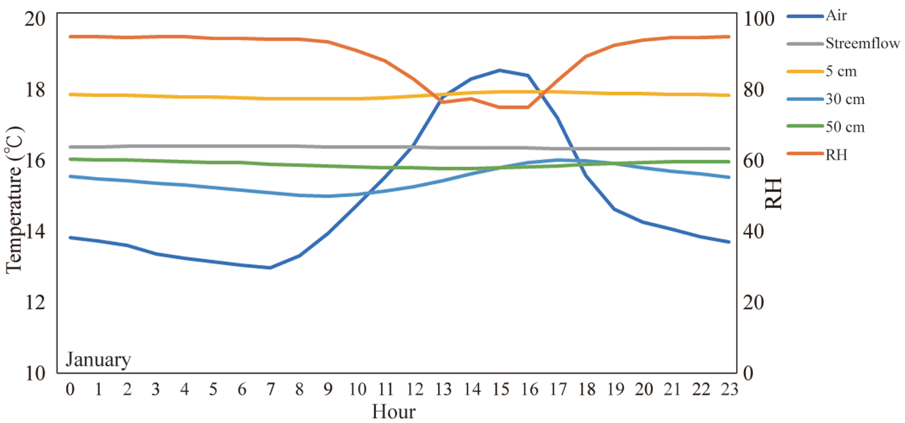

Fig. 7. Hourly average temperature and relative humidity fluctuations in January for Chungliao Creek.

Donna regions were 36.6, 37.8 and 37.9℃, respectively. All of those highest temperatures occurred at noon in July. These highest and lowest temperatures are all thought to have reached thresholds of extreme temperature values. The highest temperatures of these three regions occurred in July, and their lowest temperatures all occurred in January.

Daily temperature changes in January and July are respectively shown in Figs. 5 and 6. Occurrences of the highest daily temperatures of the Fonkang, Shanping, and Donna regions in January occurred at 12:00, 14:00, and 12:00, respectively, and those of the lowest temperatures occurred at 06:00, 07:00, and 07:00, respectively. Occurrence of the highest daily temperatures of the Fonkang, Shanping, and Donna regions in July were 11:00, 13:00, and 11:00, respectively, and those of the lowest temperatures all occurred at 06:00. The time of the occurrence of highest daily peak temperature has a significant relationship with the slope direction. The Shanping Station is located on a southwestern slope, and it is still exposed to direct sunlight in mid-afternoon. Therefore, the occurrence of the maximum daily temperature was delayed by about 2 h compared to the other 2 stations. However, the lowest temperature generally occurred before the sun rose and was mostly at 06:00 in the dawn.

Characteristics of RH, solar radiation, and evaporation

Humidity is the amount of moisture in the atmosphere, and although its content will not exceed 5% at the most, it will have significant impacts on the climate in a region. There are various definitions of humidity, including the mixture ratio of water vapor (the ratio of water vapor to dry air mass in a unit weight of air), specific humidity (the ratio of water vapor in the air to air mass containing water vapor in a unit weight of air), vapor pressure (the pressure of water vapor in the air), absolute humidity (the weight of moisture in a unit volume, generally expressed as g/m^3), RH (the percent of actual vapor density to the saturated vapor density or the ratio of partial pressure of water vapor to the equilibrium vapor pressure of water at a given temperature), and so on. TFRI weather stations all use RH to represent humidity. The average monthly RH of LEF ranges 83.4~93.5% which is relatively dry

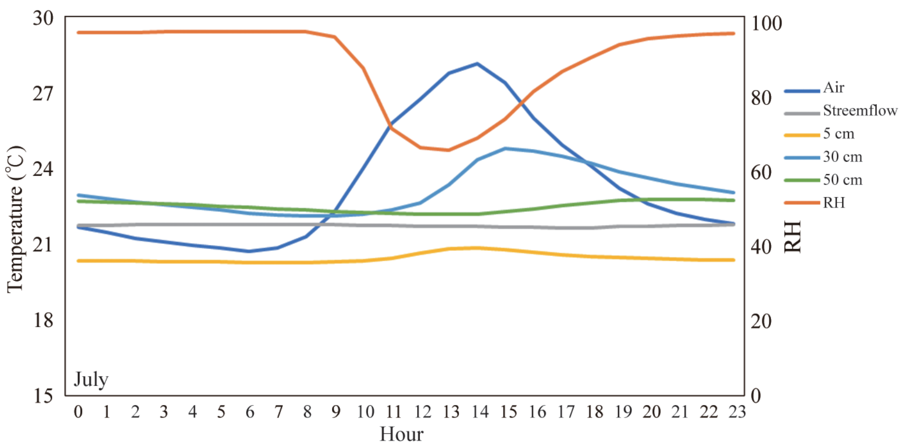

Fig. 8. Hourly average temperature and relative humidity fluctuations in July for Chungliao Creek.

compared to other TFRI experimental forests (Lu et al. 2000). The Donna area has the lowest average monthly RH for almost all months of the year, while the Fonkang area has the highest, generally indicating that the more southward the more drought of the LEF.

Solar radiation is the radiation energy of the near-ultraviolet (at wavelengths of about 0.3~0.4 μm) to the near-red (at wavelengths of about 3~4 μm) of sunshine. The amount of solar radiation is usually represented as the cumulative amount of radiation per unit of time (hour or day), and is usually expressed as MJ m^{-2} (million joules per square meter) or cal cm^{-2}, where 1 MJ m^{-2} = 23.9 cal cm^{-2}. Solar radiation in the Fonkang area is significant lower than levels in the Shanping and Donna areas, which is mostly is affected by the amount of cloudiness. The Fonkang area has an average elevation of >1500 m, and forests there can be classified as fog forests.

Evaporation is a phenomenon of liquid or solid water becoming gaseous water, and the amount of water lost due to evaporation from the surface of the soil or from free water is called evaporation. Observations of evaporation were made at Shanping and Donna using a 120-cm evapotranspiration pan from 1980 to 1990 and were measured in mm d^{-1}. The average daily evaporation was 2.9 mm for the LEF, which is lower than the average daily evaporation amount in southern Taiwan as measured by Yeh et al. (2008) due to the cooler climate. The amounts of evaporation in dry months (October to April) for the Shanping and Donna areas were 582.0 and 579.5 mm, respectively, while respective total rainfall amounts in those months were 452.9 and 441.8 mm. It is clear that the amount of evaporation in the dry season is greater than the amount of rainfall of the same period for the LEF. The fact indicates that the LEF in the dry months is vulnerable to drought.

Temperatures of the riparian zone

The riparian zone is the interface between land and a river or stream. Due to the steep topography, the cross-sections of streams are mostly V-shaped, and the distance from the stream bank to upland areas is very small. There is no distinct floodplain on most sections of streams, and riparian zones are generally narrow and not obvious in the LEF. Despite this, riparian zones still play important roles in hydrology and ecology in the LEF because of their roles in soil conservation due to buffering effects, habitat biodiversity, and the influence they have on fauna and aquatic ecosystems, including grasslands, woodlands, wetlands, and even non-vegetated areas.

Among all environmental factors, temperature is an extremely important factor in the ecosystem, because it plays an important role in soil chemical reactions, development of physical characteristics, and biological interactions. Therefore, temperature exerts a major influence on biological activities and growth, water chemistry, soil structure and aeration capacity, decomposition of organic matter, and phenological phenomena. The primary important temperatures in forestry ecosystems and riparian zones are air temperature, topsoil temperatures, and stream temperatures. These temperatures in ecosystems affect each other and temporally and spatially vary in response to exchanges in radiant, thermal, and latent energies which take place primarily in the top layers of the soil surface (Abdul et al. 1986).

It was noted that the lowest annual average temperature of the monitored items occurred in the top soil layer of 5 cm deep instead of in streamflow as those in central and northern regions of Taiwan (Lu et al. 2010, 2014). Higher air temperatures, low soil water contents, and strong radiation in southern

Taiwan are possible reasons for streamflows having higher temperatures. However, after further examination of monthly average temperatures for riparian zones of the LEF, it was found that the temperature at 5 cm deep in topsoil was the lowest among all soil layers in months with plenty of rainfall (April to October). In addition, the texture of top shallow soils in the study area is coarse sandy with large soil pores and low porosity, and therefore little water can be stored in the top soil layer. The low specific heat of sandy soil holds less heat, and the temperature of the sandy soil layer will be significantly affected by thermal energy in the surrounding environment. It can be inferred that cooler rain water will reduce the temperature of the soil surface. However, in deeper layers, less heat can be exchanged between the infiltrating water and soil. Therefore the temperature of deeper soil layers will be less affected by the cooling effects of rainfall.

Streamflow temperature is mainly associated with air temperature, ground and soil water temperatures, and solar radiation. Heat contained in streamflow generally comes from 2 sources, i.e., from the sun by means of solar radiation and from inside the earth by means of conductivity. However, heat from the latter is far less than that from the first for topsoils and streamflow during the daytime under most conditions and can be considered insignificant for streamflow and topsoils (Greening 1995). The basin of Chungliao Creek receives the strongest solar radiation from May to August (Table 2), and the occurrence of higher monthly average temperatures for all monitored items paralleled that of the maximum solar radiation. In addition, when air temperature is less than about 16℃, the temperature of streamflow is higher than that of air; otherwise air temperature is higher than that of streamflow. The inconsistency of regional temperature occurrences is associated with the heat capacity and transmission and should be further investigated.

Stream discharge in the LEF

Although experimental studies were initiated early in the LEF and 5 gauged watersheds were set up as early as 1964, the poor geological conditions and frequently heavy rainfall resulted in weirs often being filled with silt, and moreover, severe leakage also forced some experimental watersheds to abandon observations. Reliable and complete observation records would be valuable for understanding the relationship between rainfall and streamflow in the LEF, but they are rare. Discharges of creeks in the Shanping no. 2 watershed rapidly respond to rainfall, and most of them contain direct runoff in wet seasons and baseflow in dry periods. Although the studied watershed is fully covered by vegetation and has a high potential for infiltration, the amount of water detained and retention storage are insignificant compared the amount of concentrated rainfall in the rainy season, and most rainfall quickly flows into the aboveground stream network in the form of direct runoff. The interbedded shale and gneiss geological formation of the LEF means that more water can be stored in deep soil layers and the aquifer, and most of that water will eventually drain into streams in the form of baseflow during dry periods. Characteristics of discharge of creeks in the LEF can be inferred from those of the Shanping no. 2 gauged watershed due to similar topographic, geological, and vegetative cover conditions. Discharges of other watersheds in the LEF can be estimated by comparing areas with the area of the Shanping no. 2 watershed because discharges of different watersheds in the same region have a linear relationship with the watershed area.

CONCLUSIONS

Climatic conditions of the LEF can be classified as a cool climate with plenty of rainfall and sunshine. However, the temporal distribution of rainfall is extremely uneven with more than 90% of annual rainfall concentrated in the period from April to October. The cool climate is attributed to the high elevation and abundant rainfall which is mostly brought by typhoons and the plum rains. The concentrated rainfall also affects the distribution of stream discharge. Characteristics of discharge of creeks in the LEF can be inferred from those of the Shanping no. 2 gauged watershed. Discharges of creeks in the LEF quickly respond to rainfall, and most of the creeks contain direct runoff in wet seasons and baseflow in dry periods. Temperatures of air, streamflow, and topsoil layers in riparian zones of the LEF exhibited a special circumstance of the lowest annual average temperatures of the monitored items occurring in the top soil layer 5 cm deep instead of in streamflow as occurs in central and northern regions of Taiwan. This phenomenon is related to the soil type and thermal exchange between the soil and raindrops and needs further investigation.

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