Precipitation Changes and Their Impacts on the Water Resources Management in Taiwan

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Abstract

Records of precipitation for 21 stations of Taiwan have been examined for the past 60 years. Although the mean long-term trend of whole Taiwan has remains a rather stable state, the regional heterogeneity in amount is gradually increasing through years between the northern and southwestern Taiwan, especially during the wet season. The days of precipitation are equally important to the amounts of precipitation when dealing with water resource management. A continual decreasing trend is clearly observed for the entire Taiwan. There are contrast variations in areas and seasons for the precipitation-day records in Taiwan. Major reductions are found in regions of southwestern and eastern Taiwan, while only minor change for northern Taiwan. More declines are found in the wet season for regions of northern and southwestern Taiwan, but a reversal trend is observed for the eastern Taiwan. This reduction in the precipitation days has generated many hydrological difficulties and problems, namely shortage of surface water supply, severe and frequent droughts and floods in Taiwan, particularly for the last twenty years. The precipitation intensity defined by the ratio of amount and day suggests that higher risks fall in northern and eastern Taiwan as evidenced for the past decade. Further interdisciplinary studies and appropriate strategies for the effective management of water resources in Taiwan are urgently needed in dealing with these gloomy precipitation trends in the future.

Introduction

Precipitation is the primary water resource in Taiwan. An annual average amount of 2500mm brings much bless to the island (CWB, 1991). However, recent hydrological fluctuations tend to vary greatly and cause immense difficulties in the management of water resources in Taiwan. Many reports have discussed the precipitation patterns in different time scales (Wan, 1973; Wang et al., 1984; Wang et al., 1994; Wu, 1992), but a clear trend is not observed due to the great fluctuations and high variances in the precipitation record. The days of precipitation are also important to the amounts of precipitation when dealing with water resource management. However, few studies have been discussed in this context.

In this report, observations for the precipitation records of 21 meteorological stations in Taiwan for the past 60 years are presented. Certain unfavorable trends of precipitation patterns are very evident and become the major factors in generating the recent hydrological problems in Taiwan. A multidisciplinary effort is needed to decipher the complicating relationships among possible parameters. In the mean time, an appropriate strategy for the effective management of water resources in Taiwan is urgently needed in perceiving these persistent and gloomy trends of precipitation patterns in the future.

Data and Methods

Data from twenty-one Taiwan meteorological stations operated by the Central Weather Bureau (CWB, 1940-2003) with records dated back to 1940 are used as the basis for analyses of long-term trends. The details and locations of these stations are listed in Table 1 and shown in Figure 1.

Four water resources divisions have been designated by the Water Resources Agency (WRA) in Taiwan: north, central, south and east (WRA, 2002). In this study, the central and south divisions are merged into one section (i.e. southwestern) due to their high similarity on climatic and hydrologic properties. Thus twenty-one meteorological stations are grouped into three sections when discussing the regional variations relating to water resources management: 8 stations at the northern section; 9 stations at southwestern section and 4 stations eastern stations.

In dealing with seasonal variations, the annual records are divided into wet (May to October) and dry (November to April) seasons, because on the long-term average about 79% precipitation falls within the wet season in Taiwan (WRA, 2002). Two 20-year intervals (1941-1960; 1981-2000) are also chosen to compare their pattern shift and difference in illustrating their changes through time.

Results and Discussion

1. The Long-Term Change of Precipitation

The long-term changes of precipitation in Taiwan and respective sections for different seasons are shown in Figure 2. In short, there is a great variation in the precipitation amount annually, ranging from 1577mm (in 2003) to 3841 mm (in 1947), with an average of 2549mm for the past 60 years (left plot). Though there is no apparent trend for the annual means of whole Taiwan, regional heterogeneity is very evident. Northern Taiwan has shown a gradually increasing trend, whereas southwestern Taiwan experiences a declining tendency. The difference between the northern and southwestern Taiwan is enlarged gradually through years indicating that the regional difference is deteriorating. The shift of this precipitation pattern may be related to global warming. Many studies have indicated that due to rising sea surface temperature, the intense evaporation in the tropics pushes the precipitation further northward in the northern hemisphere (IPCC, 1995, 2001).

The precipitation changes between the first and last 20-year intervals are illustrated in Figure 3. In the interval of 1941-1960, the part higher than 2000-mm contour was about 78% in Taiwan (left plot), but the same fraction was reduced to 68% in the period of 1981-2000 (middle plot). Consequently, about 68% area of Taiwan has shown a precipitation-reduction between these two intervals (right plot). Apparently, one hydrological line is separating Taiwan from Hualien to Miaoli into wet and dry regions.

2. The Long-Term Change of Pprecipitation Days

In dealing with the water resource management, the precipitation days are equally important with the precipitation amount. The long-term changes of Taiwan's precipitation-day in different sections and seasons are shown in Figure 4. Taiwan has a mean value of 158 days annually for the past 60 years with extensive fluctuations ranging from 195 days (in 1947) to 117 days (in 2003), a difference of more than 2 months (left plot).

Quite different with the precipitation-amount pattern, the long-term changes of precipitation-day show a steadily decreasing trend from 1940 to the present. With regards to regional variations, the northern part has experienced the least declining rate (slope = -0.12); the eastern area has the highest one (slope = -0.72) and the southwestern Taiwan in the middle (slope = -0.56). In short, Taiwan has shown a holistic downtrend in the precipitation days for the past decades. This phenomenon is a serious and alarming signal for Taiwan. The causes of the precipitation-day shortening are complicated and may relate to global warming, aerosols and sand storms (Liu et al., 2002).

In terms of seasonal variability, the southwestern Taiwan shows a major reduction in the wet season (slope = -0.42; middle plot) whereas the eastern Taiwan exhibits the opposite (dry season slope = -0.41; right plot). It is noted that the eastern Taiwan has a precipitation-day record consistently lower than that of the 60-year mean value after 1990. This unusual feature needs a further study to explore the causes.

The changes of precipitation-day in Taiwan between the 1941-1960 and 1981-2000 intervals are presented in Figure 5. The extent higher than 140-day contour in Taiwan was about 72% in the interval of 1941-1960 (left plot); but was lessened to 52% in the interval of 1981-2000 (middle plot). Major reduction happened in the western part of Taiwan. Except the station Jihyuehtan, all other 20 stations show uniformly drop in the precipitation-day records between the intervals comparison; with northern section the least (<8%) and southwestern section the highest (>12%) (right plot).

3. The Long-Term Change of Precipitation Intensity

The precipitation intensity that is defined as the ratio of amount over time (day) represents an index of the rainfall extremity. The intensity records of Taiwan from 1940 to 2003 are shown in Figure 6. On average, Taiwan has a value of 16.1 mm/day with high fluctuations (left plot); the highest intensity is found in 1998 (21.8) and the lowest in 1980 (11.8). Given the area of Taiwan is about 36,000 km^2, 1-mm difference of the precipitation is equivalent to a quantity about $36x10^6$ m^3 that is a significant figure in terms of flood prevention. The precipitation intensity is gradually increasing (slope = 0.04) due to the rather stable trend of precipitation amount but a decreasing tendency of precipitation-day for the past 60 years.

Regarding to regional difference, the northern and eastern sections have the high risks in flooding in wet seasons (slope >0.06; middle plot). The southwestern Taiwan retains the same intensity during the studied period due to the simultaneously reduction of both precipitation amount and days, but still carries a high average value (21.5) in wet season. The rising trends observed for the precipitation intensity in Taiwan indicate that the occurrences of flood and drought would more likely increase toward hydrological extremes.

The comparisons between the first and last 20-year intervals are shown in Figure 7. In the interval of 1941-1960 (left plot), the coverage of area higher than 16 mm/day contour in Taiwan was about 37%, but this same extent was increased to 44% in the later interval of 1981-2000 (middle plot). The northeastern part enclosed by the yellow contour (intensity increase >16%) shows the most risky area of hydrological extremes (right plot).

4. Impacts on Water Resources Management

(I) Immense Difficulty in the Water Resources Management

Case 1: Taiwan surface water usage record (Figure 8)

The rapid declines both in precipitation amount and days in southwestern Taiwan for the past 60 years have resulted serious difficulty in the water resources management. For example, the extraction of surface water for the water usage in Taiwan has been diminished from $150x10^8$ m^3 in late 1970 to about $120x10^8m^3$ in 1990s, a 17% shortage of average annual demand (~$180x10^8m^3$). The major water deficiency occurs in the southwestern region that has been suffered the heavy reduction of precipitation for the past decades. Groundwater has been forced to significantly increase to meet the overall water demand every year. Consequently, over-exploitation of groundwater since 1980 caused chain-series effects, such as groundwater level waning, land subsidence, seawater intrusion along the coast and groundwater quality deterioration (Wang et al., 2004). River pollution is another critical problem for the southwestern Taiwan partly due to the drop of precipitation of the past decades.

Case 2: Groundwater level falling in foothill regions (Figure 9)

The chain-reaction effect of precipitation reduction in the southern Taiwan can be demonstrated from records in river flow and groundwater level. For example, the drop of precipitation in the Pingtung region (top panel) has resulted the constant plunge of river flow of Kaoping Chi (middle panel), and further affected the foothill groundwater level (lower panel) of Chimei well which locates at an altitude of 44.2m in the Pingtung area. Similar phenomena can be seen in other foothill groundwater levels of southwestern Taiwan (Wang et al., 2004).

(II) Drought Severity

Case 1: Taiwan long-term drought tendency (Figure 10)

Worsening drought and water restrictions have been widely featured in news reports in Taiwan during recent years. Drought serves as a reminder of society's vulnerability to water resources and its enormous economic impact. Four major drought periods have been observed for the past 60 years in Taiwan (green arrows in Fig.10). They are: (1) mid 1960s; (2) late 1970s and early 1980s; (3) early 1990s and (4) early 2000s. On the contrary, only one minor drought was found from 1900 to 1950 (i.e. around 1910s). This phenomenon shows that not only the precipitation fluctuation increases but also the hydrological extremes worsen for the latter half of twenty century in Taiwan. Some possible factors have been proposed, such as global warming, volcanic activities (Wang et al., 1997; Li et al., 1997; Chang and Wang, 2003); but a further interdisciplinary study is certainly needed.

Case 2: Tseng-Wen Reservoir (Figure 11)

The Tseng-Wen Reservoir is the largest one among tens of reservoirs in Taiwan for storage of river water and serves as a regulator for water resources management in the Chia-Nan Plain of southwestern Taiwan. The water level record in this reservoir since the summer of 2001 is illustrating the enhanced difficulty in the daily operation. After the reservoir reached to a historical maximum level (~6.3 x$10^8$$m^3$) in the September 2001, the water storage showed a unvarying decrease for almost 3 years and arrived at the historical low (~0 m^3) in the early summer of 2004. In July 2004, the ultra-heavy rainfall brought by the Typhoon Mindule filled the reservoir up to a quantity of 5x$10^8$$m^3$ (85% of its capacity) within only 4 days. It was very fortunate that the reservoir was empty before the astonishing pouring of rainfall at that event. However, this dangerous situation might happen more often in the future if the increasing trend of precipitation intensity persists in Taiwan.

(III) Flood Intensity

Case 1. Flooding records of the past decade (Figure 12)

The growing trends observed in the precipitation intensity of Taiwan also pose greater risks for flooding in northern and eastern Taiwan. Though the southwestern remains a steady tendency (Fig.6), the high value of the southwestern section indicates the intrinsic danger of flooding. On the whole, hydrological extremes seem to become more and more common in Taiwan. In the past decade, Taiwan has experienced repeated occurrences of flood and drought. For instance, the monthly precipitation records in August 1994, October 1998 and September 2001, all broke the historical accounts in sequence. These events may be the dreadful signs of the coming of hydrological extreme periods in Taiwan.

Case 2: Typhoon Nari (Figure 13)

The notorious Typhoon Nari slashed Taiwan with unprecedented rainfall for the past 100 years. In the right plot of Figure 13, the precipitation contour of Typhoon Toraji (July 30, 2001) shows that the extent greater than 300-mm precipitation covered about 23% area of Taiwan, a typical feature in the past. However, the Nari (September 16-18, 2001; left plot) not only brought a total amount more than 12,000-mm during its invasion to Taiwan, but also reached a unparallel 55% area of Taiwan in its affecting coverage higher than 300-mm precipitation. The severe damage caused by the Nari in Taiwan would not be the last one if the precipitation intensity continues to rise in the future.

Summary

(1) The regional heterogeneity of precipitation-amount between northern and southern Taiwan is deteriorating due to the opposite long-term trends observed for the past 60 years. The big negative slope found in the southwestern region heralds an alarming signal and implies a greater difficulty in the water resource management.

(2) The holistic reduction of precipitation-day in Taiwan is a serious problem and has generated many problems and difficulties in the hydrological environment. The immediate impact is that the quantity taken from the rivers and dams has been reduced for the past 20 years. Consequently, the draft of groundwater has been raised

and exceeded the natural recharge limit for the past two decades.

(3) The growing trends of precipitation intensity in Taiwan indicate the hydrological extremity gets worse through time. The repeated occurrences of drought and flood observed in the last decade faithfully reflect this alarming phenomenon. Appropriate measures and further interdisciplinary studies need to be promptly implemented to deal with these hydrological extreme problems.

Acknowledgements

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Table 1. List of 21 meteorological stations with their station number, name, latitude, longitude, and altitude.

Station No.	Station Name	North Latitude	East Longtitude	Elevation (M)
466900	Tanshui	25 09 56	121 26 24	19.0
466910	Anpu	25 11 11	121 31 13	825.8
466920	Taipei	25 02 23	121 30 24	6.1
466930	Chutzehu	25 09 54	121 32 11	607.1
466940	Keelung	25 08 25	121 43 56	26.7
466990	Hualien	23 58 37	121 36 18	16.0
467060	Suao	24 36 06	121 51 52	24.9
467080	Ilan	24 45 56	121 44 53	7.2
467410	Tainan	22 59 43	120 11 49	13.8
467440	Kaohsiung	22 34 04	120 18 29	2.3
467480	Chiayi	23 29 52	120 25 28	26.9
467490	Taichung	24 08 51	120 40 33	84.0
467530	Alishan	23 30 37	120 48 18	2413.0
467540	Tawu	22 21 27	120 53 44	8.1
467550	Yushan	23 29 21	120 57 06	3844.8
467571	Hsinchu	24 49 48	121 00 22	34.0
467590	Hengchun	22 00 20	120 44 17	22.1
467610	Chengkung	23 05 57	121 21 55	33.5
467650	Jihyuehtan	23 52 59	120 53 60	1014.8
467660	Taitung	22 45 15	121 08 48	9.0
467770	Wuchi	24 15 31	120 30 54	7.2

Figures

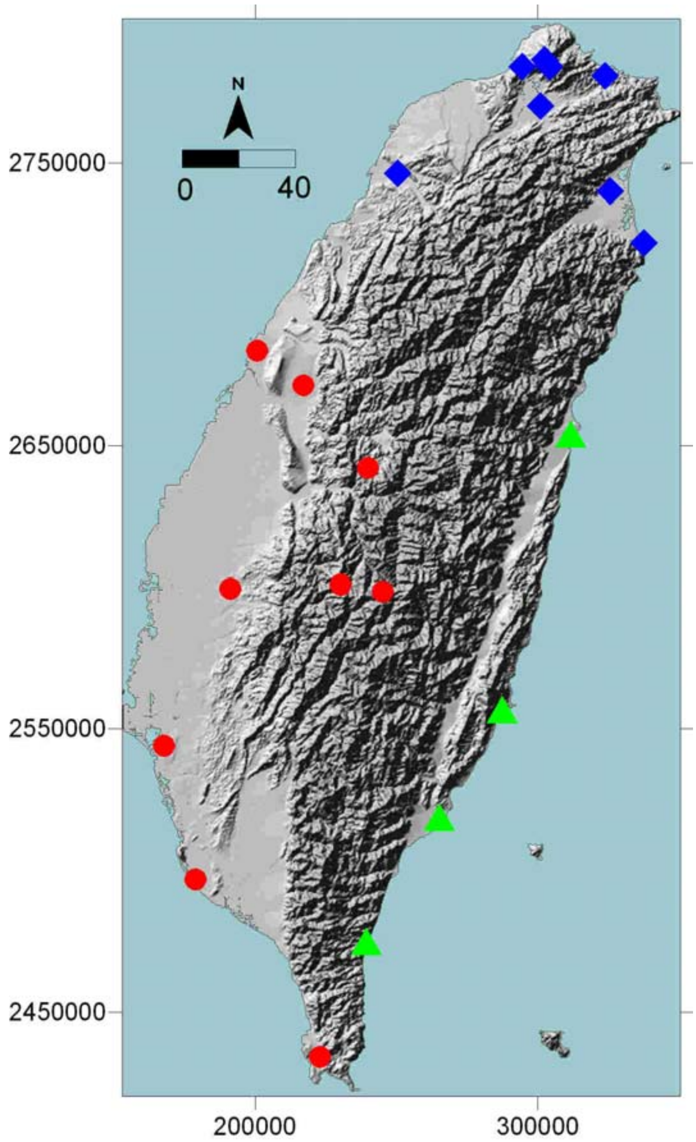

Figure 1. Schematic map of 21 meteorological stations in Taiwan. These meteorological stations are grouped into three sections: 8 stations at the northern section (blue squares); 9 stations at southwestern section (red dots) and 4 stations eastern stations (green triangles).

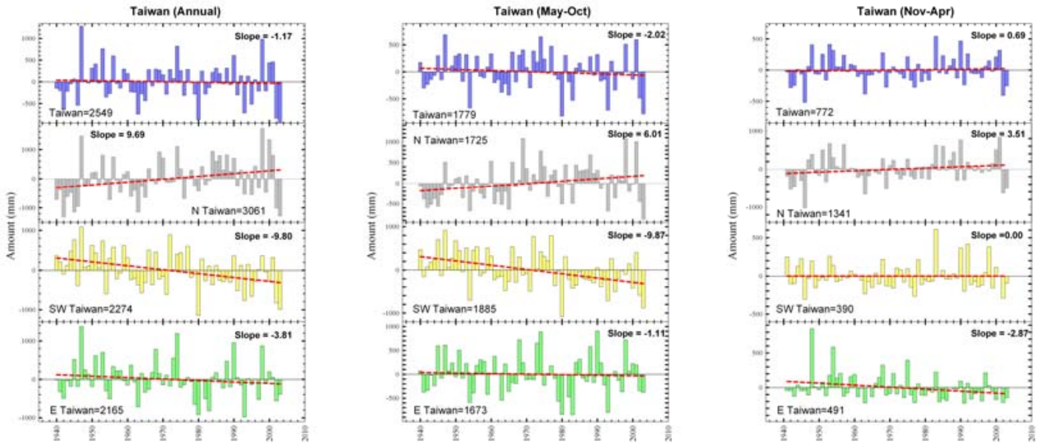

Figure 2. The annual anomalies and long-term linear trend of precipitation-amount in Taiwan. Left plot: annual average; Middle plot: wet season; Right plot: dry season. Each plot includes four panels: (top) Taiwan; (upper middle) northern section; (lower middle) southwestern section; (lower) eastern section.

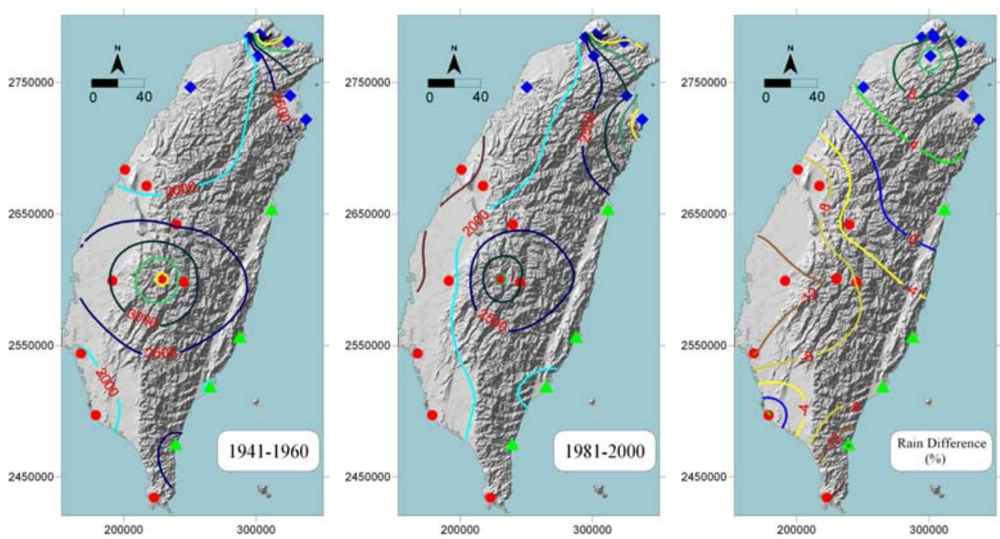

Figure 3. The 20-year interval comparison of Taiwan precipitation-amount contours. Left plot: 1941-1960; Middle plot: 1981-2000; Right plot: the percent difference between the two intervals.

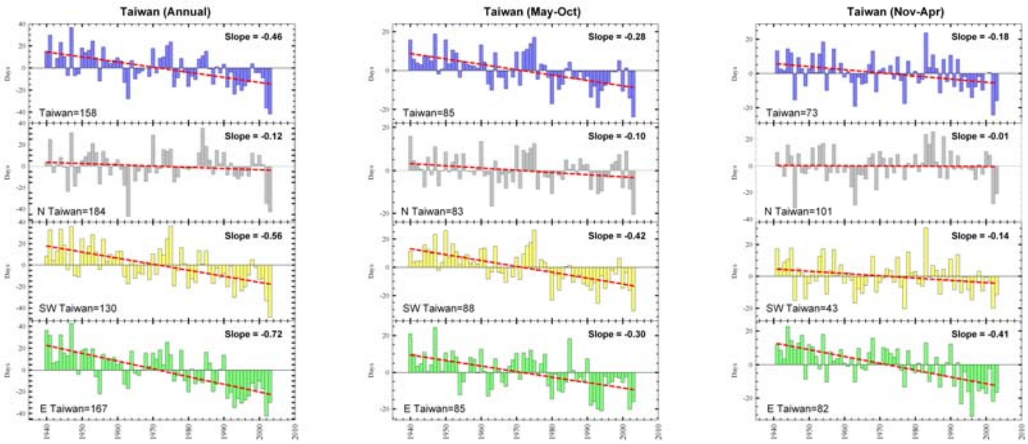

Figure 4. The annual anomalies and long-term linear trend of precipitation-day in Taiwan. Left plot: annual average; Middle plot: wet season; Right plot: dry season. Each plot includes four panels: (top) Taiwan; (upper middle) northern section; (lower middle) southwestern section; (lower) eastern section.

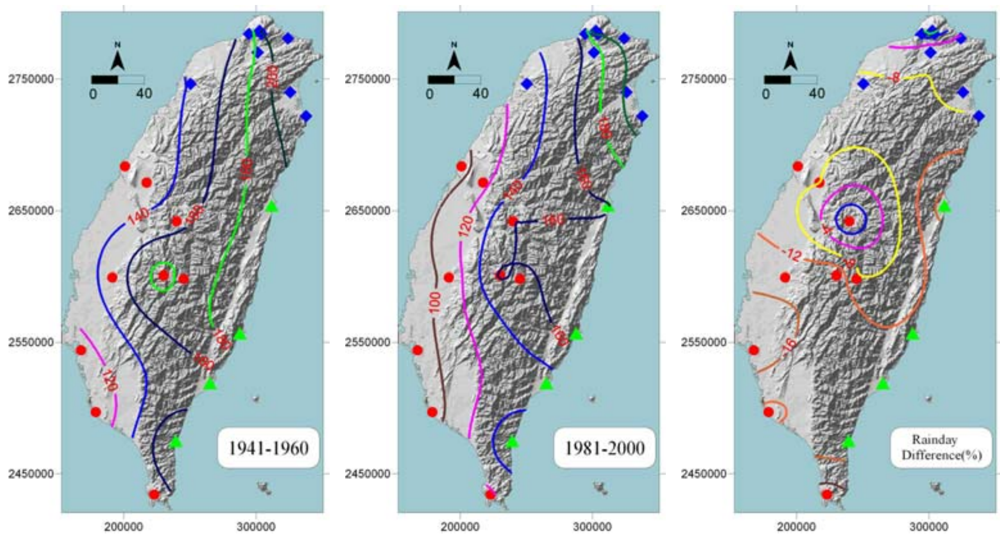

Figure 5. Figure 3. The 20-year interval comparison of Taiwan precipitation-day contours. Left plot: 1941-1960; Middle plot: 1981-2000; Right plot: the percent difference between the two intervals.

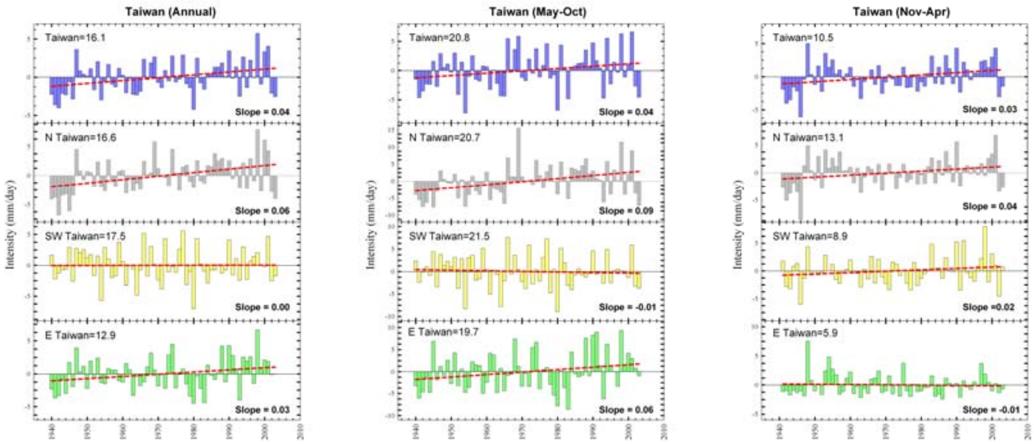

Figure 6. The annual anomalies and long-term linear trend of precipitation-intensity in Taiwan. Left plot: annual average; Middle plot: wet season; Right plot: dry season. Each plot includes four panels: (top) Taiwan; (upper middle) northern section; (lower middle) southwestern section; (lower) eastern section.

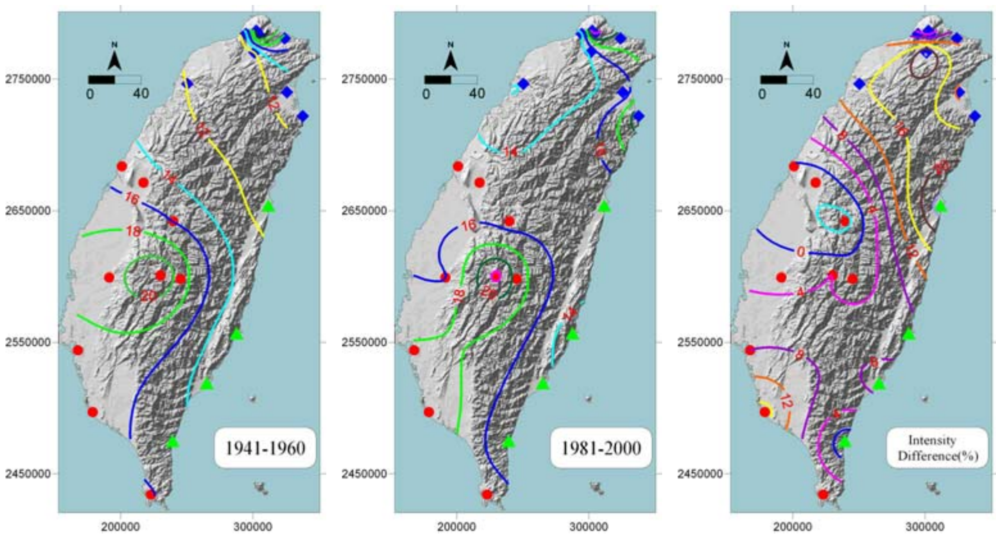

Figure 7. The 20-year interval comparison of Taiwan precipitation-intensity contours. Left plot: 1941-1960; Middle plot: 1981-2000; Right plot: the percent difference between the two intervals.

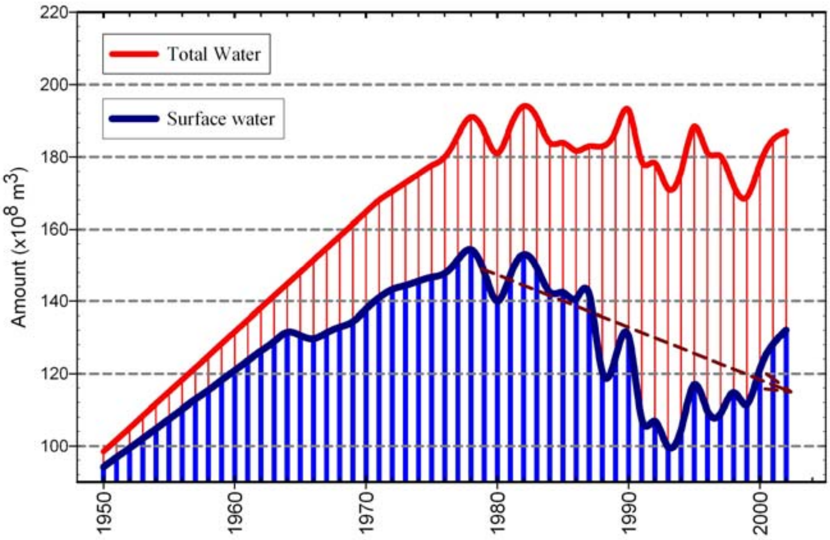

Figure 8. Taiwan water usage record since 1950 to 2002. The solid red line represents the total amount and solid blue line for the surface water. The brown dashed arrow indicates the decreasing trend of surface extraction for the past two decades.

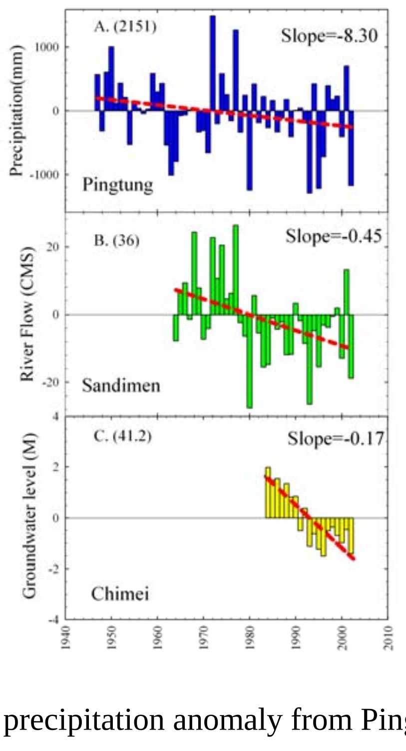

Figure 9. Top panel: Annual precipitation anomaly from Pingtung city station and its linear regression line; Middle Panel: Annual flow rate of Sandimen station from Kaoping Chi and its linear regression line; Lower panel: Annual groundwater level anomaly from Chimei well of the Pingtung foothill region and its linear regression line.

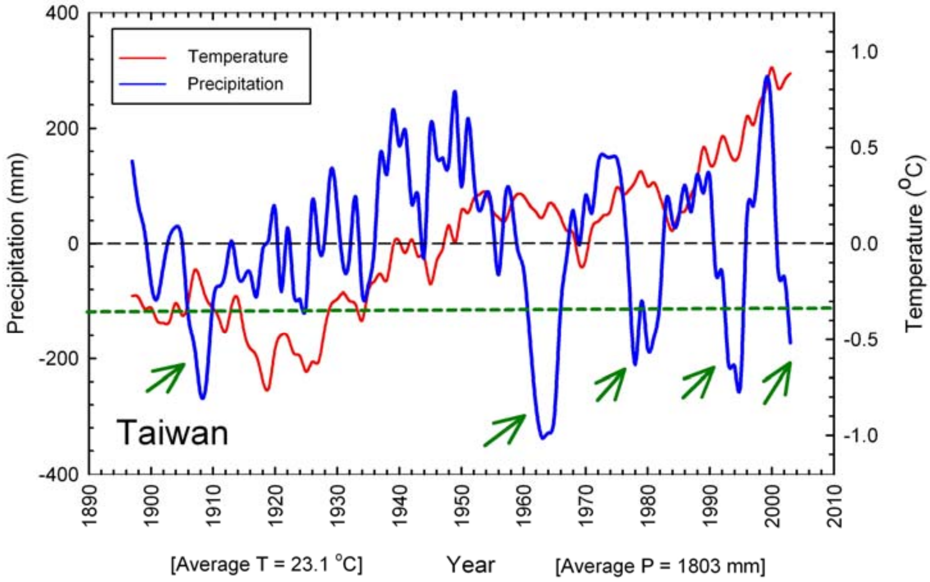

Figure 10. Time series of five-year running mean precipitation and temperature anomalies averaged from eight station records for the period from 1897 to 2003. The green dashed line represents the threshold of meteorological drought. Green arrows point up the occurrences of drought periods in Taiwan.

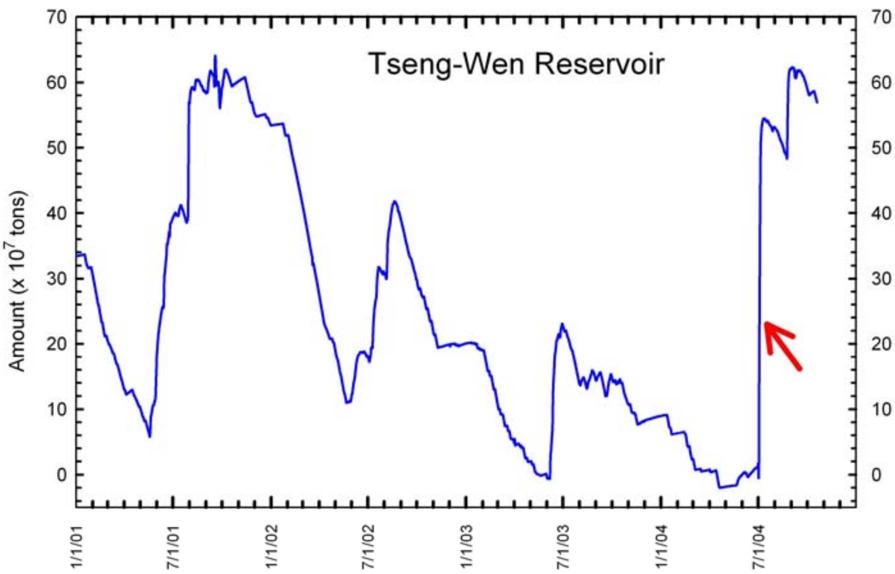

Figure 11. The water storage record of the Tseng-Wen Reservoir from the January 2001 to the present. The red arrow indicates the speedy rising of water by the Typhoon Mindule in early July 2004.

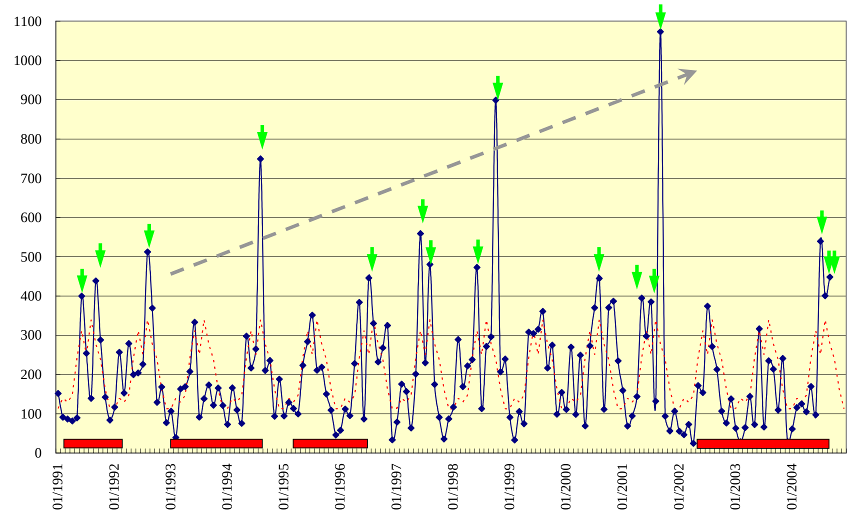

Figure 12. The recent hydrological extremes occurred in Taiwan since 1991. The y-axis represents the precipitation amount (in mm) of Taiwan. The solid blue lines are observed monthly records and red-dotted lines are long-term monthly mean values for comparison. Green arrows are flood events and red bars on the bottom are drought periods. The gray dashed arrow indicates the increasing extremity for the past decade.

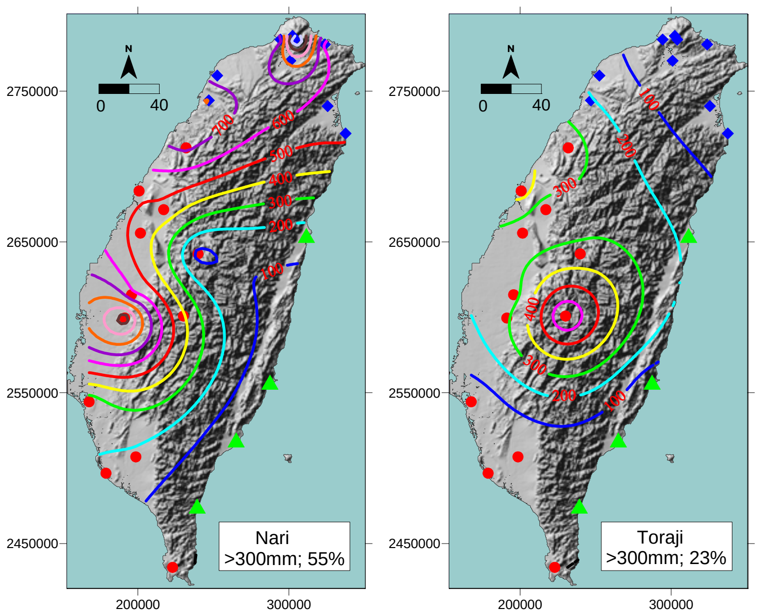

Figure 13. Precipitation contours in two typhoon events of 2001. Left plot: Typhoon Nari; Right plot: Typhoon Toraji.