Observed magnified runoff response to rainfall intensification under global warming

Jr-Chuan Huang, Tsung-Yu Lee and Jun-Yi Lee

Department of Geography, National Taiwan University, Taipei, Taiwan

E-mail: riverhuang@ntu.edu.tw

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Abstract
Runoff response to rainfall intensification under global warming is crucial, but is poorly discussed due to the limited data length and human alteration. Historical rainfall and runoff records in pristine catchments in Taiwan were investigated through trend analysis and cross temperature difference analysis. Trend analysis showed that both rainfall and runoff in the 99.9-percentile have been significantly increasing in terms of frequency and intensity over the past four decades. Cross temperature difference analysis quantified that the rainfall and runoff extremes (including the 99.0–99.9-percentiles) may increase by 69.5% and 99.8%, respectively, under a future scenario of 1°C increase in temperature. This increase in intensity resembles the increase in intensity observed between 1971–1990 and 1991–2010. The amplified runoff response can be related to the limited catchment storage capacity being preoccupied by rainfall extremes. The quantified temperature effect on rainfall and runoff intensification can be a strong basis for designing scenarios, confirming and fusing GCMs’ results. In addition, the runoff amplification should be a warning for other regions with significant rainfall intensification. Appropriate strategies are indispensable and urgently needed to maintain and protect the development of societies.

Keywords: global warming, rainfall intensification, runoff amplification, water resource management

1. Introduction
Global warming will increase the water capacity in the atmosphere and accelerate global water cycling processes (Gerten et al 2008, Bates et al 2008). The changing water cycle inevitably re-allocates precipitation and the consequent streamflow which is the main concern for water resources (Vörösmarty et al 2000, Oki and Kanae 2006). In addition, the accelerated rainfall–runoff process may induce more frequent and more violent hydro-geomorphic disasters, which are ranked second by the WMO (World Meteorological Organization) in terms of loss of human life (Bengtsson 2007). So far, rainfall intensification has been found in the Asian Monsoon region (Liu et al 2002, Goswami et al 2006, Fujibe et al 2005), though the change of annual precipitation is insignificant. The significant intensification in the upper extreme of precipitation is likely to be temperature-dependent because the Clausius–Clapeyron thermal scaling means that a unit temperature increase can lead to an increase of ~7% in the atmospheric water-holding capacity (Trenberth 1998). However, the intensification is much higher than modeling works have predicted (Liu et al 2009). The additional latent heat can further invigorate the intensification (e.g., Allan and Soden 2008, Min et al 2011). Meanwhile, the speedy circulation of water vapor enhanced by the warming may result in more frequent and intense precipitation, particularly in tropical and high elevation areas (Shiu et al 2009, Chou et al 2013).
In contrast to rainfall, signals of change in streamflow are obscure. Only a few studies have identified significant increase of runoff amount in ‘melting’ regions (e.g., glacier-dominant and high-latitude areas) (Lammers et al. 2001, Peterson et al. 2002, Shiklomanov et al. 2006). In those regions, global warming plays a primary role in melting snow or glaciers and sequentially increases streamflow. However, in the Asian Monsoon region the change of annual runoff is indistinct and sometimes inconsistent on regional scales due to the limited data length, data quality, and human alteration (Miller and Russell 1992, Lins and Slack 1999, Kundzewicz et al. 2005, Wilby 2006). Besides, whether the occurrence of flooding is enhanced by rainfall intensification or global warming is still in debate. For example, Milly et al. (2005) and Pall et al. (2011) argue that the increased frequency of catastrophic floods may result from global warming, although others have shown that the severity of flooding is highly correlated to population and urban growth (Mudelsee et al. 2003). Obviously, the issue of runoff change in terms of trend or flood frequency is important for areas where the population growth is high; however, the solution is not easy to find due to the limitations of data length and quality (Peel and McMahon 2006, Alkama et al. 2011) and hydraulic manipulation (e.g., river division or dams/reservoirs) (Milly et al. 2005, Oki and Kanae 2006).

This study attempts to reveal the change in rainfall and runoff extremes in Taiwan. Meanwhile, the rainfall and runoff intensification due to temperature increase is hypothesized and assessed quantitatively. A total of 16 rain gauges and 28 pristine catchments in Taiwan with 40 years of records were used. The rainfall and runoff extremes represented by the 99.0–99.9-percentiles were analyzed by trend analysis. In addition, a cross temperature difference analysis was applied to reveal the temperature effect on rainfall and runoff extremes. The quantified rainfall and runoff intensifications were compared with the historical change between 1991–2010 and 1971–1990. This study provides insight into the magnified runoff response to rainfall intensification and demonstrates the potential crisis that might have to be faced in a warming world.

2. Rainfall and runoff characteristics

Taiwan is geographically located at the crossroads of many climate influences, including (1) monsoonal shifts, (2) ENSO phases, (3) the Kuroshio warm ocean current, and (4) typhoon alley. Meanwhile, frequent orogenic activity and plate oscillation characterize the rugged landscape and abundant mass wasting (Milliman and Syvitski 1992, Hilton et al. 2008). Thus, the rainfall/runoff here is an important indicator for these climate and geomorphic influences. Data from 16 rain gauges (daily precipitation from 1970 to 2010 by Taiwan Central Weather Bureau) and 28 discharge stations (1970–2010, Taiwan Water Resource Agency and Taipower Company) were used in this study. The 16 rain gauges were selected from 436 available records for the sake of adequate record length. The 28 discharge stations (out of 120) were selected with the criteria of free-of-artificial manipulation (e.g., no major water supply devices or dams) and no significant human disturbance (e.g., land use change) within watersheds. The distribution of the selected rain gauges and catchments is illustrated in figure 1(a).

Figure 1. The locations of the 16 rain gauges and 28 selected pristine catchments in Taiwan (a). The integrated daily rainfall (b) and runoff (c) over the past four decades.

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multiplied by 365, figure 1(b)). The mean resembles the average of 2639 ± 433 mm derived from 436 monitoring stations over the past 20 years, showing acceptable representativeness. In fact, the annual and monthly precipitation have no significant temporal trends over the past four decades (Liu et al. 2002). However, the daily precipitation is very spiky. On approximately 1.8 days per year the island-wide daily rainfall can exceed 100 mm, which is induced by periodic typhoon invasions. In general, 3–5 typhoons per year invade Taiwan, mostly between June and September. An individual typhoon event generally brings > 300 mm of total rainfall within one or two days and a cumulative rainfall reaching as high as 1000 mm is not rare. Such concentrated torrential rainfall often results in catastrophic landslides, flooding and sediment transport.

For runoff, the annual arithmetic average among the 28 watersheds was 2314 mm (derived from 6.34 mm multiplied by 365, figure 1(c)). The annual and monthly runoff over the four decades also have no significant trend through Mann–Kendall analysis, though some individual stations show notable local increasing trends for annual and maximum discharge. In general, the long-term annual runoff is steady with considerable fluctuation. Notably, 73% of the annual runoff flows into the ocean in the wet season (May–October). Highly-variant seasonality and steep landscape is common in mountainous watersheds in the Asian Monsoon region. The extreme effects are masked by the seemingly stable annual rainfall and runoff mask on an annual timescale.

3. Increase of rainfall and runoff extremes

The frequency and intensity of rainfall and runoff extremes that were represented by the 99.0–99.9-percentiles over the past four decades were retrieved and illustrated (figure 2). The 99.9-percentile of rainfall indicated the most intense 15 daily rainfalls over the four decades. Twelve out of the 15 occurred after 1990 (figure 2(a)). The frequency of 99.9-percentile rainfall is statistically increasing through the Mann–Kendall analysis, with $p < 0.05$, while the 99.0-percentile and 99.5-percentile rainfall are scattered. In addition to frequency, the intensity of 99.9-percentile rainfall increasing from 163 to 210 mm is also supported by trend analysis, with $p < 0.05$. Although the frequency and intensity of 99.9-percentile rainfall have significant increasing trends, they are highly fluctuating and are not well correlated with the global temperature anomaly. For rainfall extremes, convective precipitation and typhoon associated rainfall are the dominant sources. Convective precipitation may only affect local rainfall, though the warming temperature significantly speeds up the convection (Del Genio et al. 2007). Instead, typhoons, for which the radius of 15 m s$^{-1}$ is approximately 200 km, covering almost the whole island, are the primary contributors. The number, track, size and translation speed of typhoons, therefore, alter the island-wide precipitation significantly. Although a change in the number of typhoons is not clear, it is relatively evident that the track is shifting northward (IPCC AR4), implying that typhoons may affect northeast Asia more frequently. Meanwhile, an increase of typhoon intensity (e.g., size) (Tu et al. 2009) and/or slow translation speed (Chien and Kuo 2011) can result in rainfall intensification. Recent studies have further stated that the rainfall intensification is more severe in the ‘wet’ region (e.g., low latitude and the West Pacific region) (Chou et al. 2013). The significance of our statistical analysis in examining rainfall extremes (frequency and intensity) confirms the findings of these studies.
Figure 3. $\Delta R / \Delta T$ of the 99.0-percentile (a) and 99.9-percentile (b) of rainfall intensity as a function of $\Delta T$. The 99.0-percentile and 99.9-percentile of runoff intensity are shown in (c) and (d), respectively. $\Delta R$ (rainfall) and $\Delta D$ (runoff) are the differences between any two years in 1970–2010, and $\Delta T$ is the difference between the global temperatures of the two corresponding years. Each horizontal bar represents the range in $\Delta T$ for a group of 10% data points. The vertical bar denotes the range between the maximum and the minimum for the data points of an individual group.

The frequency and intensity of 99.9-percentile runoff also showed a significant increasing trend, with $p < 0.05$. Twelve out of 15 floods (99.9-percentile runoff) occurred after 1990 and the intensity increased from 150 to 250 mm d$^{-1}$ gradually. The frequency and intensity of 99.9-percentile runoff increased and intensified as well as rainfall. Comparing 1991–2010 with 1971–1990, the frequency of rainfall/runoff extremes increased four-fold. Meanwhile, the intensity of rainfall and runoff increased 1.28-fold and 1.67-fold, respectively. For rainfall–runoff, runoff corresponds with precipitation changes in response to short- and long-term atmospheric–oceanic signals (Milliman et al. 2008). This connection in meso-scale catchments ($10^6$ km$^2 <$ drainage area $< 10^3$ km$^2$) should be tight particularly for short-term extremes because of shorter travel time and limited storage resulting in near-synchronous stream responses (Huang et al. 2012). Our runoff change resembles the rainfall change in terms of both frequency and intensity, showing synchronous response. However, the larger increase in runoff (1.67-fold) than rainfall (1.28-fold) deserves a great deal of attention in that runoff is the main concern and is the basis for water resource management.

4. Temperature dependence of rainfall/runoff extremes

The temperature effect on the rainfall/runoff was further quantified through cross temperature difference analysis. This method is used to determine the temperature effect for limited data length by calculating the differences in the parameter of interest between any two years against the corresponding differences in the temperature anomalies (figure 3). As a previous study has demonstrated, ‘one distinct advantage of this method over the time series method was the reduction of the scattering of points and the convergence of the mean value’ (Liu et al. 2009). In this study, the $\Delta R / \Delta T$ values of 99.0- and 99.9-percentile rainfall move toward 28.05 and 52.62 mm d$^{-1}$ when the $\Delta T$ reaches approximately 0.59 (figures 3(a) and (b)). This means that the daily rainfall for the 99.0- and 99.9-percentiles would increase to 47.5 and 89.2 mm (derived from 28.05/0.59 and 52.62/0.59) with an increment of 1 °C. Larger variation can be found when the $\Delta T$ is smaller. This large variation merely reflects the natural variation which is a complex issue involving temporal scaling, and Earth
dynamics. With an increase of the temperature difference, the reduced variation and the converged mean value can shed light on the temperature effect. The temperature-induced increments for rainfall/runoff percentiles are shown in table 1. The 99.0–99.9-percentiles of rainfall vary from 70.55 to 157.22 mm d\(^{-1}\) and the \(\Delta R/\Delta T\) increments of the individual percentiles increase from 47.54 to 89.19 mm d\(^{-1}\) °C\(^{-1}\) with an average of 68.42 mm d\(^{-1}\) °C\(^{-1}\). In general, the average rainfall change ratio is 69.5% °C\(^{-1}\). This much greater rainfall change ratio, approximately 10-fold greater than the Clausius–Clapeyron thermal scaling, is consistent with studies that have also documented the unexpected rainfall intensification (Liu et al 2009, Tu and Chou 2013). As mentioned above, the additional latent heat and the speedy circulation of water vapor may contribute to the rainfall intensification.

Furthermore, the runoff extremes were analyzed by the same method as well (figures 3(c) and (d)). The \(\Delta D/\Delta T\) values of the 99.0- and 99.9-percentile runoffs move toward 21.80 and 75.66 mm d\(^{-1}\) when the \(\Delta T\) reaches ~0.59. For all percentiles, the 99.0–99.9-percentiles of runoff vary from 45.77 to 136.57 mm d\(^{-1}\). Meanwhile, the \(\Delta D/\Delta T\) increments of the percentiles increase from 36.95 to 128.23 mm d\(^{-1}\) °C\(^{-1}\) with an average of 79.20 mm d\(^{-1}\) °C\(^{-1}\). The average of runoff change ratios is 99.8% °C\(^{-1}\). This means that with a temperature increase of 1 °C, the runoff responses would be doubled while the runoff extremes would merely increase by 69.5%. The cross temperature difference analysis shows that both the rainfall and runoff responses are temperature-dependent, but the increment and change ratios for runoff, in terms of absolute and relative quantities, are larger than those for rainfall.

5. Magnified runoff response

A straightforward scenario of 0.5 °C temperature increment, based on the temperature-dependent relation, was applied to the whole dataset. Meanwhile, the observed rainfall and runoff change between 1991–2010 and 1971–1990 was illustrated as the reference. The mean global temperature anomalies of the two periods are 0.147 and 0.482 °C, representing a temperature increase of 0.335 °C. The relative changes of rainfall and runoff percentiles for the scenario and the reference are shown in figure 4. The relative change of rainfall for the reference is gradually increasing from 17.6% to 30.3% with an average of 22.6% or 67.5% °C\(^{-1}\) (= 22.6%/0.335 °C). The relative change is consistent with a previous study (Tu and Chou 2013) that concluded that the relative change of typhoon rainfall between 1990–2009 and 1970–1989 was approximately 30%. For the scenario of 0.5 °C increment, the relative change of rainfall varies from 28.5% to 43.5% with an average of 34.8% or 69.5% °C\(^{-1}\). The rainfall intensifications from the observations and the scenario are 67.5 and 69.5% °C\(^{-1}\) respectively. The mechanism of such intensification, particularly for the extremes, should be explored, since rainfall extremes are the forcing for many surface processes.

The observed relative change of runoff increases from 27.4% to 62.2% with an average of 43.1% or 128.7% °C\(^{-1}\) (=43.1%/0.335 °C). For the scenario, the relative change of runoff varies from 40.5% to 58.3% with an average of 49.9% or 99.8% °C\(^{-1}\). The runoff intensifications from the observations and the scenario are around 128.7 and 99.8% °C\(^{-1}\), respectively. Meanwhile, the increase between the 99.9- and 99.5-percentiles is higher than that for the 99.5- to 99.0-percentile, indicating that the runoff response to extreme rainfall is magnified. We further determined the water yield (defined as runoff-percentile/rainfall-percentile) against rainfall for these percentiles (figure 4(b)). As expected, the rainfall percentiles for the periods of 1971–1990, 1991–2010, and the scenario move toward larger values on the x-axis. At the same time, the water yield increases from 0.6 to 1.0 and remains at 1.0 when rainfall is >180 mm d\(^{-1}\).

For rainfall–runoff, a catchment is a storage-limited medium, like a sponge, which plays the role of absorbing precipitation and yielding discharge depending on the storage status. However, the functionality of the sponge would be minimized when the rainfall was too heavy and concentrated. In our study, approximately 60% of rainfall converts to runoff when the daily rainfall is less than 75 mm d\(^{-1}\). In other words, the storage keeps around 40% of the rainfall within the catchment. However, when the rainfall increases,
Figure 4. Relative changes in rainfall and runoff (a). The blue triangles and circles respectively represent the rainfall and runoff change between 1991–2010 and 1971–1990. The red triangles and circles respectively indicate the rainfall and runoff change between the scenario of 0.5 °C increment and the whole data period (1971–2010). The water yield of the individual percentile groups during 1971–1990, 1991–2010, and the scenario is shown in (b). The green, blue and red circles are derived from 1971–1990, 1991–2010 and the scenario, respectively.

the water yield increases in an accelerated manner due to the storage being occupied by the abundant precipitation, i.e. reaching saturation. When it is saturated, the catchment transfers all the excess rainfall into runoff completely. Once rainfall extremes become more frequent and intense, the runoff will be generated by a water yield factor of 1.0. This implies that the current estimated flood quantities based on historical rainfall–runoff records may underestimate the warming effect. The overlooked response will then threaten hydraulic constructions, increase the risk of hydro-geomorphic disasters (Huang et al. 2006, Kao et al. 2011) and reduce crop productivity (Nearing et al. 2004, Zhang and Nearing 2005). The effect may be more challenging than expected due to population growth. The runoff amplification in this study could be analogous to many Asian countries such as China, Japan and India (Liu et al. 2005, Fujibe et al. 2005, Goswami et al. 2006, Qian et al. 2007) where similar rainfall intensification has been experienced.

6. Remarks

The change of rainfall/runoff extremes is becoming a severe challenge for water resource management under global warming and population growth conditions. Our study found that only extreme cases (e.g., 99.9-percentile of rainfall/runoff records over the past four decades) have increased significantly in terms of frequency and intensity. Although trend analysis confirmed that the rainfall/runoff extremes have increased, the quantitative temperature effect on rainfall/runoff is not clear due to insufficient extreme cases within the limited data length. Cross temperature difference analysis was applied to quantify the temperature effect on rainfall/runoff intensification. In general, rainfall/runoff extremes (including the 99.0–99.9-percentiles) may increase by 69.5% and 99.8% with an increment of 1 °C, individually. On the other hand, the observed increments between 1991–2010 and 1971–1990 are 67.5% and 128.7% for rainfall and runoff, respectively. The consistent increments between historical and cross temperature difference analysis may underline the warming effect. In addition to the greater increment (~70%) in rainfall extreme, the magnified increment in runoff extreme deserves a great deal of attention. The magnified runoff response can be attributed to the increase of water yield with the increase of rainfall. An important implication is that current flood risk assessments based on historical rainfall–runoff records may underestimate the warming effect. The magnified runoff response may be analogous for other regions with similar rainfall intensification. The quantified rainfall/runoff intensification can also be a basis for designing scenarios or confirming and integrating the results of GCMs. According to the latest IPCC Fifth Assessment Report, a projected 1 °C increase in global mean surface air temperature is likely to occur during 2046–2065 unless CO2 emission follows the worst Representative Concentration Path (RCP8.5) (IPCC 2013). Appropriate strategies are indispensable to maintain and protect the development of societies.

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