# Evidence of climate change impact on stream low flow from the tropical mountain rainforest watershed in Hainan Island, China

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## ABSTRACT

Stream low flow estimates are central to assessing climate change impact, water resource management, and ecosystem restoration. This study investigated the impacts of climate change upon stream low flows from a rainforest watershed in Jianfengling (JFL) Mountain, Hainan Island, China, using the low flow selection method as well as the frequency and probability analysis technique. Results showed that low flow at this watershed over a period of 18 years (1990–2007) was 0.58 $m^3$/s and its recurrence probability and recurrence interval were, respectively, 99% and 1.01 years for low flow with a 60-day duration. Low flow rate decreased linearly both as time increment elapsed ($R^2 = 0.62$, $p < 0.01$) and as air temperature rose ($R^2 = 0.60$, $p < 0.05$), whereas the recurrence intervals of low flow were shorter (or occurred more frequently) as time increment elapsed. In contrast, no correlation existed between annual rainfall and low flow for this watershed, indicating that rainfall was not a factor influencing stream low flows. Since there were little to no anthropogenic activities rather than air temperature rise over time at this watershed, we attributed the decreased rate and frequent occurrence of low flow to the warming air temperature as time elapsed.

**Key words** | air temperature, climate change, Jianfengling, low flow, tropical rainforest

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## INTRODUCTION

Climate change is a long-term change in statistical distribution of weather patterns over periods of time that range from decades to millions of years (Houghton *et al.* 2001). Climate change over the past several decades has been linked to changes in large-scale hydrological cycles including: increasing atmospheric water vapor content; modifying precipitation patterns with intensity and extremes; reducing snow cover and melting ice; and changing soil moisture and surface runoff (Bates *et al.* 2008). In the last century, precipitation has increased over land in high northern latitudes, but has decreased from 10 °S to 30 °N since the 1970s. The frequency of heavy precipitation events has increased over most areas, while the area of land classified as very dry has more than doubled globally since the 1970s. Shifts in the amplitude and timing of runoff in glacier- and snowmelt-fed rivers, and in ice-related phenomena in rivers and lakes, have been observed (Bates *et al.* 2008). It has been predicted that temperatures in 2100 are expected to be 1.1–6.4 °C higher than temperatures in 1900, accompanied by changes in rainfall intensity and amount (Tank *et al.* 2009). Each of the past three decades has been successively warmer at the Earth's surface than any previous decades based on instrumental records, and the decade of the 2000s has been the warmest (Tank *et al.* 2009).

doi: 10.2166/wcc.2016.149

In climate vulnerability assessment, hydrologic characteristics such as low flow are an important indicator of water responses to climate change (NRC 2008). Low flow is defined as a flow of water in a stream during prolonged periods of little, or no, precipitation (WMO 1974). It is a seasonal phenomenon and an integral component of the flow regime of any river (Smakhtin 2001). Low flow is affected by climate, topography, geology, soil, land use, and human activity (Smakhtin 2001; Ryu *et al.* 2011; Ouyang 2012). Low flows are normally derived from groundwater discharge or surface water discharge and usually occur in the same season each year. The magnitude of annual low flows, the rate and variability of low flows in the absence of precipitation, the duration of continuous low flow events, and the relative contribution of low flows to the total stream flow hydrograph are widely used characteristics in hydrological analysis.

Estimates of river low flow characteristics in forest ecosystems are central to investigating variations in regional climate, water resource management, and water supply planning because forests and water are inextricably connected. The movement, distribution, quality, and quantity of water in forest lands are regulated by forests (NRC 2008). Forests process water that not only sustains ecological functions, but also is used for agriculture and human consumption. However, no effort has been devoted to investigating the impacts of climate change on stream low flows in forest ecosystems in watersheds from JFL, Hainan Island, China.

Several studies have been performed to estimate whether low flows have changed as a result of variations in climate. Lins & Slack (1999, 2005) reported significant increasing trends in annual minimum and 10th percentile flows between 1940 and 1999 at most sites in the Appalachian-Cumberland, Mississippi Alluvial Valley, and Mid-South ecoregions of the southeast US, but many sites in the coastal plain and piedmont ecoregions exhibited significant decreasing trends in low flow. Ryu *et al.* (2011) investigated the impacts of climate change on local hydrology and low flow frequency in the Geum River Basin, Korea, using a general circulation model (GCM). These authors found that a more severe low flow of 0.03 $m^3/s$ is predicted by the GCM as opposed to that of 1.54 $m^3/s$ obtained by the 7Q10 method. Recently, Ouyang (2012) developed a potential approach for low flow selections and applied this approach to estimate low flow characteristics in Big Sunflower River, Mississippi and St. Johns River, Florida. This author showed that the level of low flow from these two rivers have decreased over the last several decades, which means that these rivers are becoming drier. As a result, the estuary part of the lower St. Johns River near Jacksonville City, Florida is potentially susceptible to salt water intrusion from the Atlantic Ocean. This author also found that the recurrence probability of low flow increased while the recurrence interval of low flow decreased in both rivers, indicating that low flows occurred more frequently in these rivers as time elapsed. Although these studies have provided valuable insights into low flow estimations, our knowledge of the interaction between low flow and variation in climate is still fragmented and has not yet been thoroughly evaluated. Therefore, a need exists to assess the impacts of climate variations on low flows and the potential consequences of changes in low flows on water supply, terrestrial and aquatic life, and forest ecosystems.

The goal of this study was to assess the impacts of climate change upon low flows in a mountain rainforest watershed from JFL, Hainan Island, China. Our specific objectives were to: (1) determine low flow, (2) estimate recurrence probabilities of low flow, and (3) assess recurrence intervals of low flow, as affected by climate change at the mountain rainforest watershed from JFL.

## MATERIALS AND METHODS

### Study site and data acquisition

JFL is located in the southwest of Hainan Island, China, between 18°20′ and 18°57′ N and between 108°41′ and 109°12′ E (Figure 1) with an area of 636.84 $km^2$ and a rainforest coverage of 93.18% (Li *et al.* 2002). The rainforests at this location were further divided into three major watersheds, namely the primary forest watershed, the secondary forest watershed, and the plantation watershed (Figure 1). Several gage stations have been initiated to monitor stream discharge and water quality for the three watersheds since the 1990s. However, the monitoring activities for most

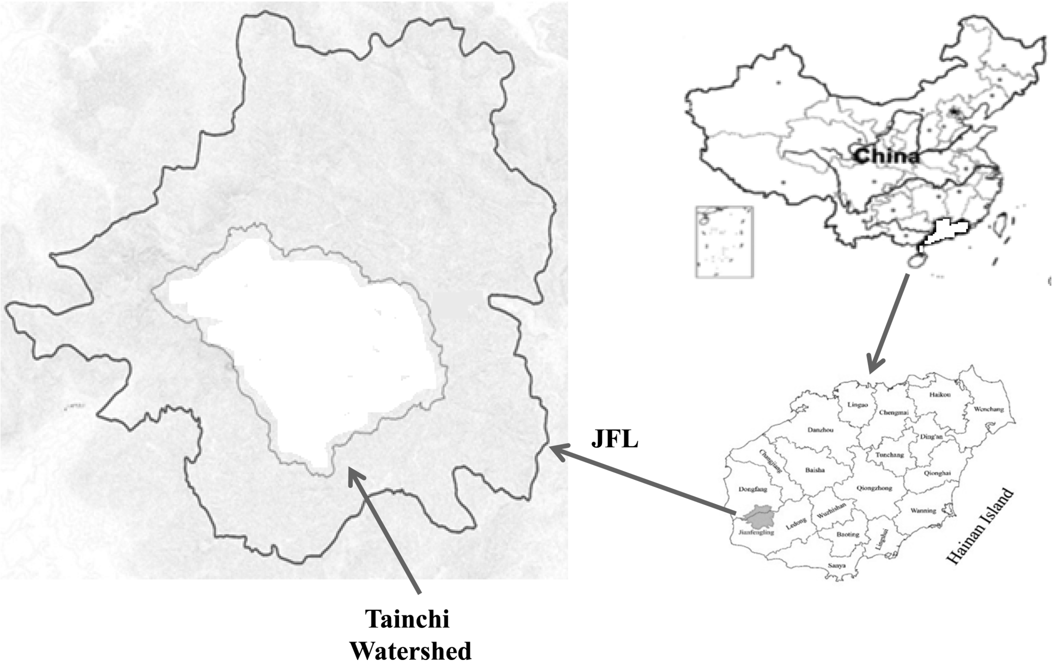

**Figure 1** | Location of weir surface water monitoring station at Tainchi secondary forest watershed in Jiangfengling (JFL), Hainan Island, China.

of them have been discontinued, are intermittent or of short duration due to budget constraints. In this study, the gage station located at the secondary forest (Tainchi) watershed (Figure 1) was selected partly because the station has a relatively long-term (1990–2007) and continuous monitoring stream discharge data and partly because this area is undisturbed land covered with naturally regenerated forests. The primitive rainforests from this watershed were clear cut in 1964 and the current (or secondary) forests have naturally regenerated since then and matured in 1980 with the dominant tree species of *Castanopsis fissa, Sapium discolor*, *C. tonkinensis, Syzygium tephrodes* and *Schefflera octophylla* (Huang *et al.* 1986; Zeng *et al.* 1997; Xu *et al.* 2009). The watershed has an elevation ranging from 800 to 900 m above sea level, an average annual precipitation of 2,449 mm, a mean annual temperature of 19.8 °C, an average slope of 30%, and a dominated lateritic yellow soil (Zhou *et al.* 2009). Our hypothesis is that since little to no anthropogenic activities took place and no natural forest and stream channel modifications occurred after 1980 at this secondary forest watershed, any change in stream low flow would be attributed to climate change impacts. The historical discharge data from this station were used to select low flows, estimate recurrence probabilities of low flows, and assess recurrence intervals of low flows, while the air temperature and rainfall data obtained from the local weather station were used to estimate the climate change conditions.

## Selection of low flow

There are currently a number of methods for low flow analysis, including flow duration curve (FDC) analysis, low flow frequency curve (LFFC) analysis, analysis of flow recessions, and storage-yield analysis (Riggs 1976; McMahon & Mein 1986; Vogel & Fennessey 1995; Smakhtin 2001; Laaha & Bloschl 2007). The most commonly used methods for low flow estimation are the FDC and LFFC analyses. The FDC method expresses the relationship between any given discharge value and the percentage of time that this discharge is equaled or exceeded (Smakhtin 2001), while LFFC shows the proportion of years when a flow is exceeded (Harris & Middleton 1993; Midgley *et al.* 1994).

In practice, the 7Q10 method has been used for selecting a particular low flow value (Telis 1992; Reilly & Kroll 2003). The 7Q10 method is an LFFC-based index and is defined as the lowest average flow that occurs for a consecutive 7-day period at the recurrence interval of ten years. A major limitation of the 7Q10 method for low flow selections is that in certain circumstances the low flows selected from this method could be near-zero, which would hinder its use for establishing criteria to prevent streams from significant harm to biological communities (Ouyang 2012).

To circumvent this obstacle, Ouyang (2012) developed a new approach for low flow selections based on the frequent low flow category that is used in the Minimum Flows and/or Levels Program in northern Florida, USA (Neubauer *et al.* 2008; SJRWMD 2010). This approach, referred to as the frequent-low (FL) approach, focuses on the 80th percentile flow derived from the FDC analysis. This FL threshold

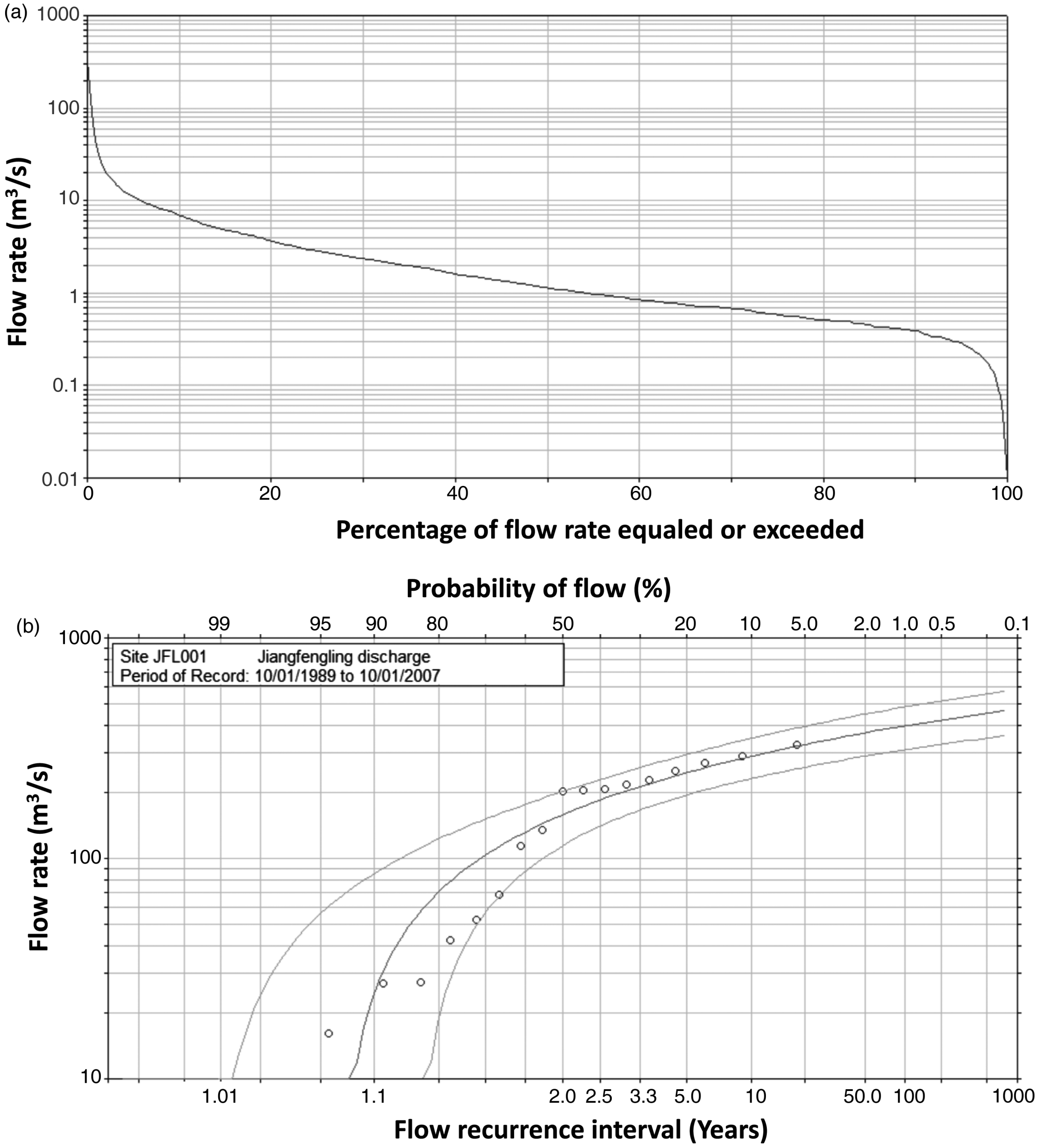

**Figure 2** | FDC (a) and low flow recurrence probabilities and recurrence intervals for a 60-day low flow duration (b).

was established to minimize biological and ecological impacts and the low flows selected from this approach are unlikely to be near-zero. In general, the first step in low flow selection with the FL method is to obtain long-term discharge data and then to construct the FDC. Once an FDC is constructed, a low flow can be obtained from the FDC at the 80th percentile. A complete description of the FL method can be found in Ouyang (2012). In this study, the FL method was employed to estimate the impacts of climate change upon low flow in Tainchi watershed from JFL.

Analysis of FDC and low flow recurrence probabilities and intervals were accomplished with the HYDSTRA Model (Version 10.3.2, Kisters, Inc.). HYDSTRA is a commercial software package that has the capabilities to analyze hydrologic characteristics (e.g., river discharge and stage, groundwater flow and level, baseflow separation, and precipitation), water quality, and other ecological and environmental factors that have time-series data, to perform duration curve and frequency distribution analysis on hydrology and water quality data, to identify recurrent intervals in response to climate change, and to perform data acquisition, data importing and exporting, data management, data analysis, modeling and simulation, and automated task scheduling.

## RESULTS AND DISCUSSION

The FDC for the stream discharge data from 1990 to 2007 at the secondary forest watershed from JFL are shown in Figure 2(a). Based on this FDC and the low flow selection method developed by Ouyang (2012), the low flow with a 60-day duration for the entire 18-year period (1990–2007) was 0.52 $m^3/s$. At this low flow rate, its recurrence probability and interval were, respectively, 1.01 year and 99%, which can be inferred from Figure 2(b). In other words, the recurrence probability for the low flow at 0.52 $m^3/s$ was 99%, which could occur every 1.01 years. It should be noted that low flow estimation can be performed using either annual or partial series analysis. The annual series analysis uses daily flows and analyzes short low flow duration (generally less than 183 days), whereas the partial series analysis uses monthly flows and is suitable for long low flow duration (12 months or more) (McMahon & Mein 1986). In this study, the annual series analysis was employed with daily discharge data. The selection of 60-day low flow duration in this study reflected the minimum frequent low flow category, which is one of five categories in the Minimum Flow and Levels Program used in a Florida Water Supply Study Program (Neubauer *et al.* 2008; SJRWMD 2010). This category represents a chronically low flow that generally occurs only during periods (typically 60–90 days) of reduced rainfall that can result in dewatered wetlands and forest lands. Use of this low flow is intended to prevent deleterious effects on the composition and structure of floodplain soils, the species composition and structure of floodplain and in-stream biotic communities, and the linkage of aquatic and floodplain food webs (Neubauer *et al.* 2008; SJRWMD 2010).

It should be noted that low flow varies with locations and with time periods used for its estimation. The latter feature provides an opportunity to analyze how the climate change affects the stream low flow as time elapses. To scrutinize the impacts of past climate change on low flow at the secondary rainforest watershed from JFL, we further divided the period of data records into three-year increments. These increments allowed us to examine how past climate change affected the low flows and their recurrent intervals and probabilities over time. The three-year increment was chosen for analysis because the air temperature in this watershed increased successively and significantly every three years based on our field measurements. Low flows and their corresponding recurrence intervals and probabilities for each three-year increment are given in Table 1 and Figure 3. In general, low flow decreased linearly ($R^2 = 0.62$) as the time

**Table 1** | Variations of recurrence probability and recurrence interval of low flows for a 60-day duration with a three-year increment at the primitive forest watershed from JFLM, Hainan Island, China

| Year interval | Low flow ($m^3/s$) | Probability (%) | Recurrent interval (year) | Average air temperature (°C) |
|---|---|---|---|---|
| 1990–1992 | 0.58 | 49 | 2 | 24.93 |
| 1993–1995 | 0.48 | 71 | 1.3 | 24.95 |
| 1996–1998 | 0.5 | 53 | 1.8 | 25.17 |
| 1999–2001 | 0.54 | 70 | 1.5 | 24.92 |
| 2002–2004 | 0.46 | 81 | 1.3 | 24.95 |
| 2005–2007 | 0.38 | 79 | 1.2 | 25.51 |

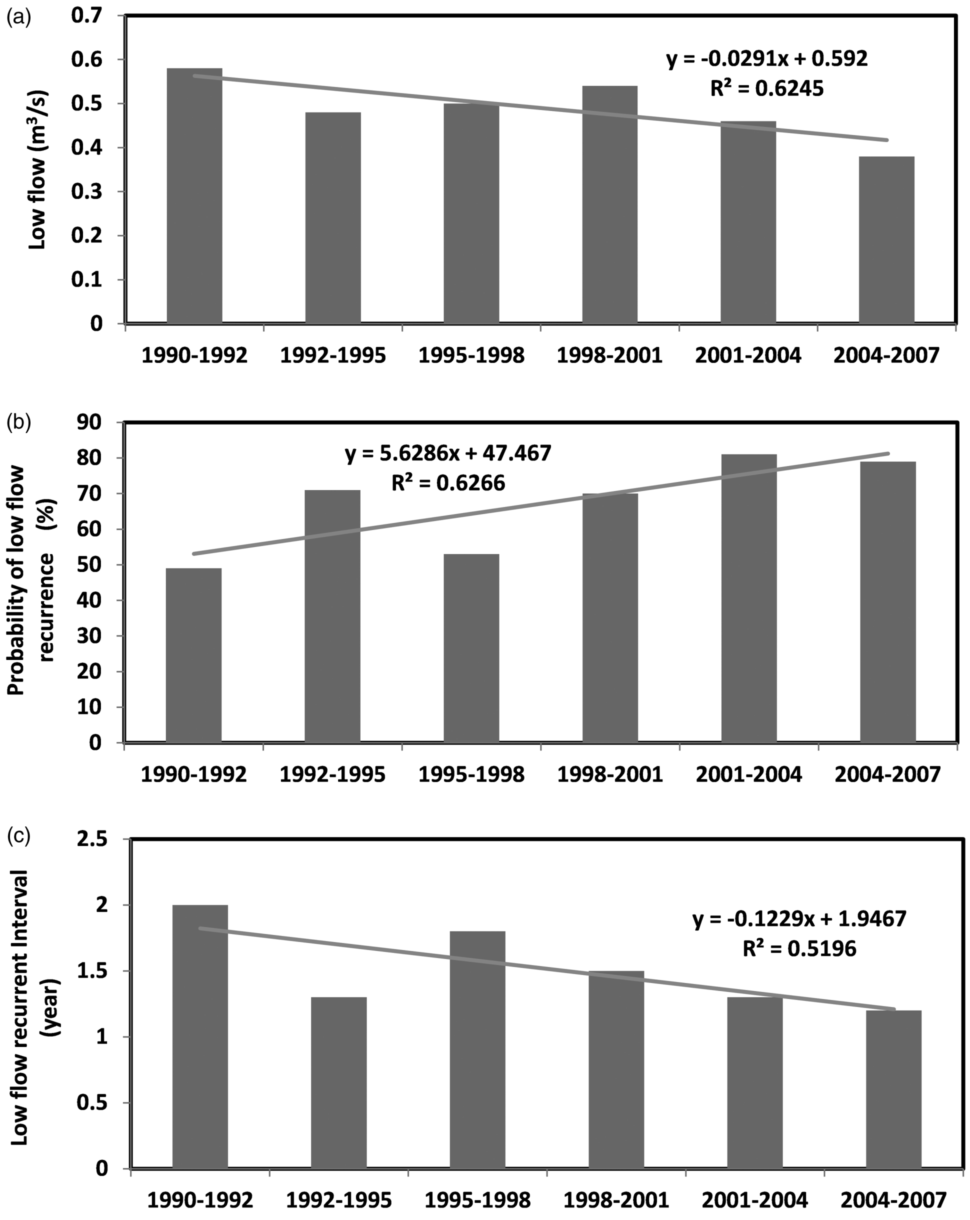

**Figure 3** | Low flow (a), recurrence probability of low flow (b), and recurrence interval of low flow (c) for the 60-day low flow duration in a three-year increment.

increment elapsed (Figure 3(a)). For example, the rate of low flow was 0.58 $m^3$/s during 1990 to 1992, but was 0.38 $m^3$/s during 2005–2007. The latter was 1.5-fold lower than the former over a 15-year period. This occurred primarily due to the warmer air temperature as time elapsed during this period (Figure 4(a)) since there was little to no anthropogenic activities in this watershed. The warmer air temperature from climate change resulted in a warmer soil temperature (Figure 4(b)), both of which were the driving forces for a higher watershed evapotranspiration and thus causing the drier streams and lower low flows. Figure 4(a) and 4(b) further revealed that the three-year average annual air and soil temperatures were 19.67 and 22.51 °C, respectively, during 1990–1992, but were 20.29 and 23.60 °C, respectively, during 2005–2007. The three-year average annual air and soil temperatures had increased 0.6 and 1.1 °C, respectively, over a 15-year period. Such increases in air and soil temperatures resulted in a 1.5-fold decrease in low flow, apparent evidence for climate change affecting stream low flow. A similar finding was reported by Du *et al.* (2015). They estimated the return period and risk analysis of nonstationary low flow series under climate change in the Wei River, China. They found that low flow decreases as the annual average air temperature increases.

Using the data given in Table 1, Figure 5(a) showed a negatively linear correlation between the low flow and the air temperature, which further confirmed that the warmer air temperature due to climate change decreased the low flow as time elapsed. This was also true for soil temperature, i.e., a negatively linear correlation existed between the low flow and the soil temperature (Figure 5(b)). In general, a 1.0 °C increase in air and soil temperature could decrease the low flow by 0.46 and 0.13 $m^3/s$, respectively, at this watershed as can be deduced from Figure 5(a) and 5(b).

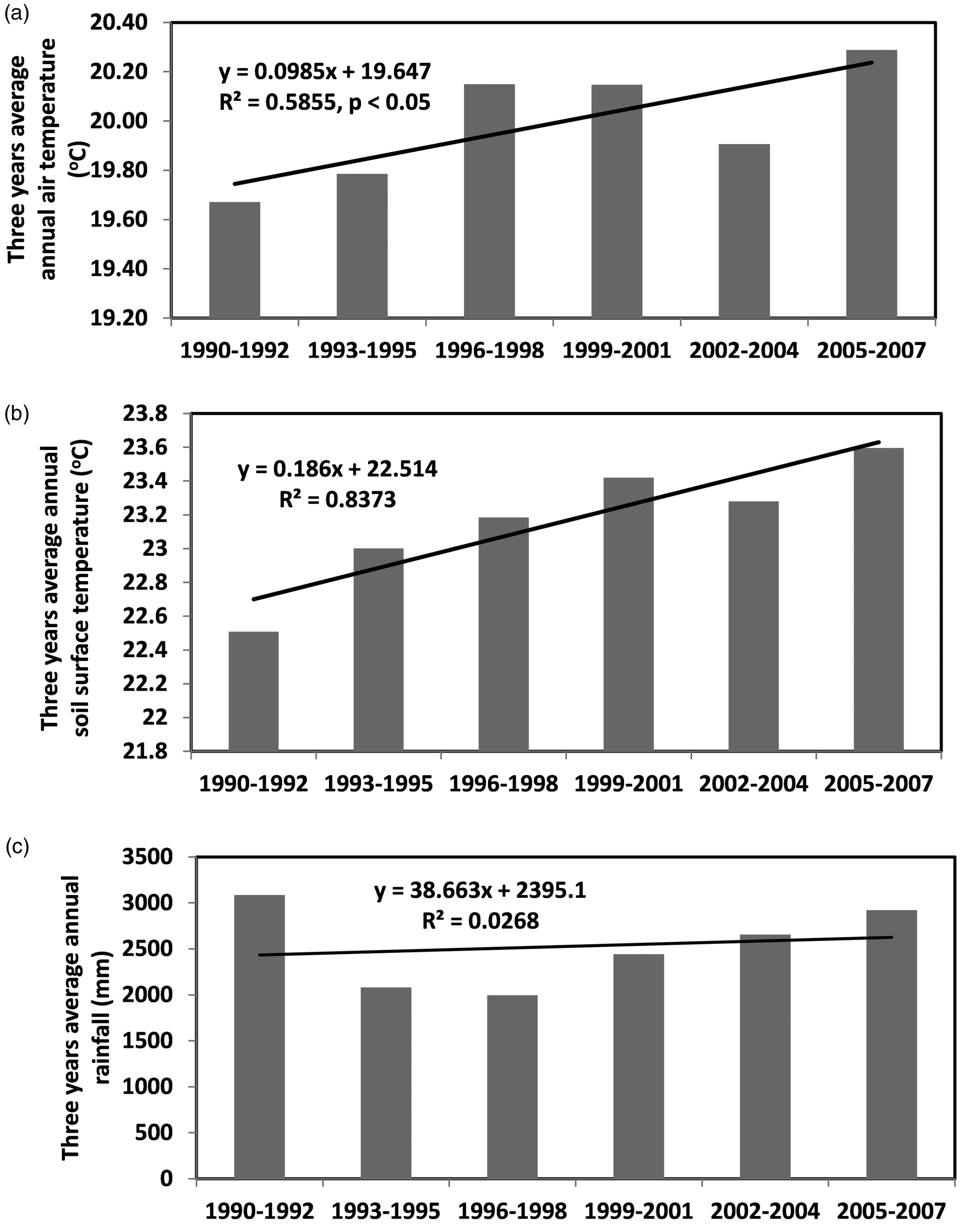

**Figure 4** | Relationships of three-year annual mean air temperature (a), soil temperature (b), and rainfall (c) to the elapsed time.

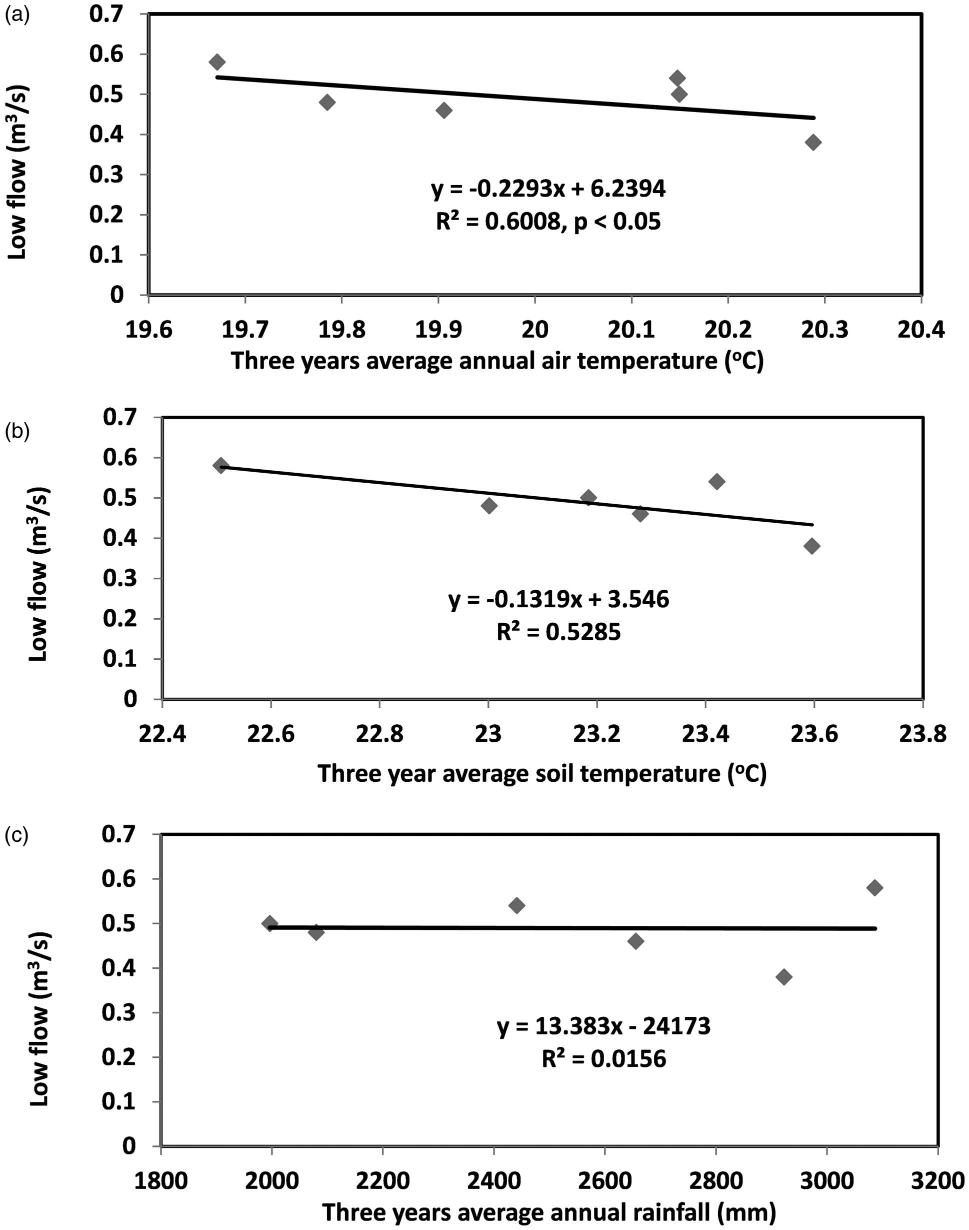

**Figure 5** | Relationships of low flow to the three-year annual average air temperature (a), soil temperature (b), and rainfall (c).

Results demonstrated that an increase in air temperature resulted in a much lower low flow than in soil temperature. This occurred because a warmer air temperature caused a higher leaf transpiration rate than a warmer soil temperature. Leaf transpiration is a major water loss mechanism in forest land due to evapotranspiration.

Changes in three-year annual mean rainfall over the period from 1990 to 2007 was statistically not significant for this watershed (Figure 4(c)). In other words, no significant increase in a three-year average annual rainfall was observed during this period, indicating the impact of climate change on rainfall over this period at this watershed was trivial. Using the data given in Table 1, a plot of mean annual rainfall against low flow demonstrated that no correlation existed between annual rainfall and low flow (Figure 5(c)). Therefore, rainfall was not a factor influencing stream low flow in this gradually warming forest watershed although the exact reasons for this phenomenon remain to be investigated.

Figure 3(b) showed that the probability of low flow recurrence increased as time elapsed from 1990 to 2007, whereas Figure 3(c) revealed that the interval of low flow recurrence, in general, decreased as time elapsed during the same period. In other words, the low flow occurred with an increasing frequency and a decreasing time interval from 1990 to 2007. As this is a forest watershed with little human disturbance, we concluded that a warming climate had increased the recurrence probability and decreased the recurrence interval of low flow in this watershed.

## CONCLUSION

In this study, we evaluated the magnitude, recurrence interval, and recurrence probability of low flow in a secondary rainforest watershed within the JFL Mountain area, Hainan Island, China, using the low flow selection method developed by Ouyang (2012) and the frequency and probability analysis technique from the HYDSTRA model. Results indicated that low flows had occurred with a decreasing value and an increasing frequency over the historical period of record due to warming air temperature. To scrutinize the impacts of past climate change upon low flows, we further divided the period of data records into six time increments, each of three years (i.e., 1990–1992, 1993–1995, 1996–1998, 1999–2001, 2002–2004, and 2005–2007). These increments allowed us to examine how past climate change, namely the air temperature rise, affected the low flows and their recurrence intervals and probabilities over time. Results demonstrated that low flow rate decreased linearly both as time increment elapsed and as air temperature rose, whereas the recurrence interval of low flow was shorter (or occurred more frequently) as the time increment elapsed. Our results further revealed that an increase in 1 °C of air temperature resulted in 1.76-fold lower low flow than an increase in 1 °C of soil temperature. This occurred because air temperature is a major driving force for leaf transpiration, which is a major water loss from evapotranspiration in a forest watershed. In light of these findings in low flow, and considering the implications for the entire JFL, conserving water and stream system protection will become vitally important for keeping minimum stream flows required to prevent significant harm to water resources and stream ecosystems. Management practices that help to reduce evapotranspiration and enhance infiltration and groundwater discharge to streams may become important tools in mitigating future climate impacts on low flows. We also believe that our findings from this study provide a useful reference to other similar regions around the world when characterizing impacts of climate change on hydrological processes. Further study is also warranted to investigating the impact of soil water storage along the steams within the watershed to determine the correlation between low flow and soil water content during the time when low flow occurs.

## ACKNOWLEDGEMENTS

This work was supported by the Special Research Program for Public-Welfare Forestry (No. 201404201) and the Lecture and Study Program for Outstanding Scholars from Home and Abroad (CAFYBB2011007).

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First received 20 October 2015; accepted in revised form 2 October 2016. Available online 27 October 2016