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annual runoff
dynamics**

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Land-use changes reinforce the impacts of climate change on annual runoff dynamics in a southeast China coastal watershed

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Abstract

Study on runoff dynamics across different physiographic regions is fundamentally important to formulate the sound strategies for water resource management especially in the coastal watershed where peoples heavily concentrated and relied on water resources. The $L-R$ diagram, a conceptual model by which the land-changes evapotranspiration (ΔL) was estimated as the difference between actual and climate evapotranspiration to identify the specific impact of land-use changes on annual runoff changes (ΔR), was developed using the 53-year hydro-climatic data of Jiulong River Watershed, a typical medium-sized subtropical coastal watershed in China. This study found that land-use changes have reinforced the impact of climatic changes on runoff changes where nearly all points were scattered in II and IV quadrant. Deforestation and expansion of built up area has diminished the water retention capacity in a catchment as well as evapotranspiration thus produce extra runoff accounting for 12–183% of total runoff increase. In contrast, reforestation makes the significant contribution to decreasing annual runoff for about 21–82% of total runoff loss. This study revealed the river runoff has become more vulnerable to intensive anthropogenic disturbances under the context of climate changes in a coastal watershed.

1 Introduction

River runoff response to climate changes has been questioning recently especially in the developing coastal region where peoples heavily relied on river water. Changes in the hydrological cycle due to climate change may lead to diverse impacts and risks such as severe drought and flood in the future (Jiménez et al., 2014; Mudelsee et al., 2003). Using climate models, global runoff is projected to decrease in North Asia and Africa while it tends to increase in high-latitude region of America and Europe as well as in Southern Asia (Milly et al., 2005; Conway et al., 2009; Piao et al., 2010; Alkama et al., 2011; Zhang et al., 2011; Arnell and Gosling, 2013). However, changes in runoff cannot

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solely be attributed to climate changes because non-climatic factors such as land-use changes started showing significant impacts on the river runoff dynamic. For example, expansion of built-up area due to urbanization has commonly caused city flooding because of incapability of impervious area absorbing excess rainfall (O'Driscoll et al., 2010; Milly and Wetherald, 2002; Liu et al., 2012; Huang et al., 2014). Yet, the combined impacts of changes in climate and non-climate factor on river runoff are still less explored due to the difficulties to determine the specific impacts of non-climatic factors on river runoff. Therefore, research objective of this study is to identify the relative impacts of climate and land changes on annual runoff dynamic in a coastal watershed.

This study presented the L - R diagram, a conceptual model by which the land-changes evapotranspiration (ΔL) was estimated as the difference between actual and climate evapotranspiration to identify the specific impact of land-use changes on annual runoff changes (ΔR) in a developing coastal watershed, Jiulong River Watershed, southeast China. This agricultural watershed has experienced an increase in annual runoff along with increase in precipitation over the past five decades (Huang et al., 2013). In addition to climate changes, human pressure in the catchment is also intense and complex such as land-use changes, dam construction, and water intake. Large conversion of forest area into agricultural land was observed in early 1980s following the National Agricultural Policy. Built up area has expanded steadily over the past three decades (Huang et al., 2012; Zhou et al., 2014). Construction of more than 120 large scale dams occurred since 1992 to operate the hydropower plants (Huang et al., 2013). All of these issues may potentially disturb natural hydrological process in a catchment. However, in this study we just focus on the impact of land-use changes on runoff dynamic. For one thing, although large scale dams have been constructed within the catchment since 1992, but there is a strong consensus that dams only alter the intra-annual (seasonal) variation of runoff rather than annual runoff (Huang et al., 2013; Maingi and Marsh, 2002; Hu et al., 2008; Supit and Ohgushi, 2012; Zhang et al., 2012). For another, we ignored the effects of water intake on the river runoff due to the fact that large amount of water are taken in the downstream of two hydrological

stations. Finally, it is urgently necessary to investigate the specific impacts from such small disturbances on landscape pattern in a watershed on the runoff dynamic under the context of climate changes which is poorly understood in a developing coastal watershed. This study can provide us a better insight about how river runoff is responsive to the changes in climatic and non-climatic factors over decades, which could be fundamental input for water resources management.

2 Methodology

2.1 Study area

The Jiulong River Watershed, a medium scale coastal watershed, located in south-east China (from 116°46'55" E to 118°02'17" E and from 24°23'53" N to 25°53'38" N) (Fig. 1). This watershed is considered as the second largest watershed in Fujian Province with total basin area of 14 700 km². Two major tributaries of North River and West River formed this watershed. Downstream of these two rivers meet in Zhangzhou and discharge about 12 billion m³ of annual runoff into Xiamen coastal water and eventually reaching Kinmen–Taiwan strait. The amount of water flowing through downstream of this river is considerably important to be concerned because it is the only sources of water for residents in Xiamen. Water is mainly taken from Jiangdong Reservoir in the downstream of North River.

Natural is the dominant land-cover type in the watershed accounting for 70–79%, followed by agriculture which accounts for 21–29%, and built accounts for 2–4% of the total area (Huang et al., 2012). Administratively, Jiulong River Watershed comprises of eight counties, including Zhangzhou, Xinlou, Zhangping, Hua'an, Changtai, Pinghe, Longhai, and Nanjing which rich of natural resources, including forest area, mineral deposit, and arable land. Nearly a quarter of Fujian Province's GDP (Gross Domestic Product) is contributed from the regions within watershed (Huang et al., 2012). Zhangzhou plain has been one of the most developed regions in China in term of agri-

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cultural production, with the main products of banana, longan, litchi, pomelo, citrus, and flowers. In 1994, Zhangzhou was approved as a National Export-oriented Agricultural Demonstration Zone. Chinese government encouraged agricultural production through National Agricultural Policy in 1980s, to meet the demand of national food security.

Anthropogenic disturbances have become unavoidable in watershed. Large conversion of forest area into agricultural land was detected during 1986–1996. Urbanization has also started appearing in watershed, where built up land has increased steadily over time (Huang et al., 2012; Zhou et al., 2014). The dynamic changes in land-use pattern were clearly described in Fig. 2.

2.2 Data

Hydrologic data: data of daily runoff ($\text{m}^3 \text{s}^{-1}$) recorded in Punan and Zhengdian hydrological stations (Fig. 1) were used in this study to investigate runoff dynamic in North River and West River during 1961–2013. These data of daily runoff were obtained from Hydrological Bureau of Fujian Province. Daily runoff data was aggregated annually to obtain annual runoff (m^3). Afterward, runoff (m^3) was divided with catchment area (km^2) toward runoff in mm. Catchment area of North River and West River is about 9560 and 3992 km^2 respectively.

Climatic data: this study used two main climatic parameters, namely precipitation (mm) and temperature ($^{\circ}\text{C}$). Data of daily precipitation and daily temperature (minimum, mean, and maximum) recorded in Longyan and Zhangzhou meteorological stations (Fig. 1) were collected to examine changes in climate variables in North River and West River during 1961–2013. These climate data were acquired from China Meteorological Administration website (<http://www.cma.gov.cn>). Similar to hydrologic data, data of daily precipitation were also aggregated annually to obtain annual precipitation (mm). For data of daily temperature, it was averaged to obtain mean annual temperature.

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2.3 Temporal trend of hydro-climatic variables

Regression analysis was used to examine the annual trend of hydro-climatic variability during 1961–2013. Increasing or decreasing tendency of hydro-climatic variability was identified from b value Eq. (1). Positive b value indicated hydro-climatic parameter has been increased over time. In contrast, negative b value demonstrated hydro-climatic has been decreased over time. The change is significant when p value < 0.05 (confidence level of 95 %).

$$Y = a + bX \quad (1)$$

Where: Y = annual hydro-climatic variables; a = intercept; X = year; b = coefficient regression.

2.4 Hydro-climatic model

Using water balance equation, precipitation lost in the environment through evapotranspiration, runoff, and storage (Eq. 2). Assuming the changes in storage capacity (ΔS) is small over time (Δt), runoff (R) therefore can be estimated as the difference between precipitation (P) and evapotranspiration (E) (Eq. 3). Schreiber (1904) discovered evapotranspiration as a function of aridity index (α) (Eq. 4). Aridity index itself refers to the ratio of potential evapotranspiration to precipitation (Arora, 2002) (Eq. 5). Simple model to estimate potential evapotranspiration was developed by Hargraeves (2003) based on temperature data (Eq. 6). Finally, runoff has positive linear relation with precipitation and negative exponential relation with aridity index (Eq. 7).

$$P = E + R + \frac{\Delta S}{\Delta t} \quad (2)$$

$$R = P - E \quad (3)$$

$$\frac{E}{P} = 1 - e^{-\alpha} \quad (4)$$

$$\alpha = \frac{E_o}{P} \quad (5)$$

$$E_o = 0.0023 \cdot R_a \cdot (T_m + 17.8) \cdot \sqrt{T_{\max} - T_{\min}} \quad (6)$$

$$R = P e^{-\alpha} \quad (7)$$

Where: P = annual precipitation (mm); R = annual runoff (mm); $\Delta S/\Delta t$ = changes in storage capacity over time; E = annual evapotranspiration (mm); α = aridity index; E_o = annual potential evapotranspiration (mm); R_a = extraterrestrial radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$ – values can be converted to equivalent values in mm day^{-1} by dividing by $\text{Lambda} = 2.45$); T_m , T_{\max} , and T_{\min} = mean, maximum, and minimum temperature ($^{\circ}\text{C}$).

Relationship between runoff and climatic variability was compared during five periods from 1960s, 1970s, 1980s, 1990s, to 2000s in order to identify the influence of non-climatic factors on runoff dynamic.

2.5 Development of L - R diagram to identify relative impact of land changes on annual runoff dynamic

Changes in precipitation and evapotranspiration are the main factors contributing to runoff changes. For precipitation changes, it is certainly driven by climatic variability; while evapotranspiration changes are not merely affected by climatic variability, but also by vegetation type and land use. Vegetation loss may lead to decrease in evapotranspiration as well as diminish catchment storage capacity thus potentially increase the annual runoff. In contrast, reforestation is likely enhancing evapotranspiration and retarding the water in catchment which might decrease the annual runoff.

Changes in evapotranspiration due to land-use changes (ΔL) were estimated as the difference between the changes in actual evapotranspiration (E_a) and changes in climate evapotranspiration (E_c) (Eq. 8). Actual evapotranspiration (E_a) can be considered as the difference between precipitation (P) and runoff (R) based on aforementioned

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annual water balance equation (Eq. 9). For climate evapotranspiration (E_c), we used the model developed by Schreiber (1904) which considered evapotranspiration as the function of aridity index (α) (Eq. 10). Aridity index refers to the ratio of potential evapotranspiration to precipitation (Eq. 5). This study used Hargreaves equation to estimate potential evapotranspiration (E_o) (Eq. 6). Later, land use coefficient (ΔL) was plotted against annual runoff changes coefficient (ΔR) (Eq. 11), producing L - R diagram to identify the specific impact of land changes on runoff dynamics.

$$\Delta \frac{L}{P} = \Delta \frac{E_a}{P} - \Delta \frac{E_c}{P} \quad (8)$$

$$\frac{E_a}{P} = \frac{P - R}{P} \quad (9)$$

$$\frac{E_c}{P} = 1 - e^{-\alpha} \quad (10)$$

$$\Delta \frac{R}{P} = \frac{R_{t+1}}{P_{t+1}} - \frac{R_t}{P_t} \quad (11)$$

Where: E_a = actual annual evapotranspiration (mm); E_c = annual climate evapotranspiration (mm); P = annual precipitation (mm); R = annual runoff (mm); α = aridity index; R_{t+1} = annual runoff in year of $t + 1$ (mm); R_t = annual runoff in year t (mm); P_{t+1} = annual precipitation in year of $t + 1$ (mm); P_t = annual runoff in year t (mm).

2.6 Estimation the relative impact of changes in climate and land-use on runoff

Runoff changes were considerably determined as the changes due to changes in climatic variables and the changes due to land use (Eq. 12). For changes in runoff, we calculated changes in inter-annual runoff between dry year and wet year (Eq. 13). Runoff changes due to climate were estimated using Eq. (7). Changes in annual runoff due to land changes thereafter were denoted as the difference between changes in actual runoff and changes in climatic runoff (Eq. 14).

$$\Delta R = \Delta R_C + \Delta R_L \quad (12)$$

$$\Delta R = R_w - R_d \quad (13)$$

$$\Delta R_L = \Delta R - \Delta R_C \quad (14)$$

Where: ΔR = changes in annual runoff (mm); R_w = runoff in wet year (mm); R_d = runoff in dry year (mm); ΔR_C = changes in annual runoff due to changes in climatic variability (mm); ΔR_L = changes in annual runoff due to changes in land-use (mm).

3 Results and discussion

3.1 Hydro-climatic variability in North River and West River

Annual runoff showed an increasing trend ($b = 1.93$) in West River and decreasing trend ($b = -0.25$) in North River over the past 53 years (1961–2013), even though these trend were not significant ($\rho = 0.904$; 0.430 , $\rho > 0.05$). Runoff and precipitation are naturally fluctuated such as an oscillation, consist of dry, normal, and wet year (Fig. 3). Annual runoff varied from 421 to 1763 mm and annual precipitation ranged from 960 to 2478 mm in dry year and wet year respectively. Indistinct trend in annual runoff were also found in other river basins following the unclear trend on precipitation, indicating the climate variability strongly control the runoff dynamic (Kling et al., 2012). We found annual runoff (R) is the function of annual precipitation (P) and aridity index (α) (Eq. 15), which was consistent with the earliest hydrological model developed by Schreiber (1904).

$$R = P^a e^{-b\alpha}; \quad R^2 = 0.9995 \quad (15)$$

where: α = aridity index ($\alpha = E_o/P$); E_o = potential evapotranspiration (mm) is calculated using Hargreaves equation (2003); P = precipitation (mm); R = runoff (mm); a = precipitation coefficient; b = aridity coefficient.

From Fig. 3, we could see variation in a and b value in hydro-climatic model in North River and West River over the past five periods. a is coefficient of precipitation and

b is aridity index coefficient. Both a and b coefficient can be used to describe runoff response to precipitation and evapotranspiration respectively. Low a and b value indicated that evapotranspiration was low thus runoff response to precipitation were also low as observed in 1980s and 1990s. In contrast, high a and b value might represent that evapotranspiration was high thus runoff response to precipitation were getting higher.

In general, smaller catchment of West River (3772 km²) has higher a value of 0.98 than that in the larger catchment of North River (9560 km²) which is 0.96. This mean river runoff in the smaller catchment of West River is more responsive to changes in precipitation. Larger catchment will allow water to be exposed for a longer duration to infiltration and evaporation before it reaches the downstream (Critchley and Siegert, 1991). Therefore, the b value was higher in the North River. Surprisingly, the lowest a and b value were found in West River in 1990s (Fig. 3). Low value of a and b were also observed in North River in the two periods of 1980s and 1990s. There should be sharp decreases in evapotranspiration during these periods in which was closely related to the blooming of socioeconomic development since 1980s due to open-door policy (Koo and Lou, 1997) and national agricultural policy in China (Huang et al., 2012). In the last periods of 2000s, a and b value is much higher, indicating the evapotranspiration increased.

3.2 Land changes reinforces the impact of climate changes on runoff dynamic

The specific impact of land changes on runoff dynamic can be identified using $L-R$ diagram (Fig. 4). The $L-R$ diagram consists of four quadrants. First quadrant described the increase in evapotranspiration due to reforestation has diminished the impact of climate changes on increasing annual runoff. Second quadrant illustrated decrease in evapotranspiration due to deforestation has reinforced the impact of climate changes on increasing annual runoff. Third quadrant represents the decrease in evapotranspiration due to deforestation has diminished the impact of climate changes on decreasing

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annual runoff. Fourth quadrant explained increase in evapotranspiration due to reforestation has reinforced the impact of climate changes on decreasing annual runoff.

Annual runoff dynamic in the North River and West River were strongly reinforced by land use changes over the past 53 year as most of the points were scattered on the II and IV quadrant (Fig. 4). This means deforestation contributed positively to increasing annual river runoff, while reforestation led to the decrease in runoff. The results of *L-R* diagram were supported by quantitative estimation of the relative impact of land-use changes on annual runoff dynamic between dry year and wet year over the past five period observations (Fig. 5).

As shown in Fig. 5, changes in runoff were mainly driven by changes in climatic variability and land-use changes reinforced the impact of climate changes on runoff dynamic. Unexpected result was observed in the 1960s and 1970s where increase in runoff was influenced by land-use changes. Land runoff contributed about 12–85 % of the total runoff increase during 1967–1970 and 1971–1975. It was largely expected due to the China Cultural Revolution which occurred during 1967–1976. Devastation of forest area in Fujian Province was induced by this big political event. Forest Department lost their power to control the unsupervised cutting of timber trees (illegal logging) (Primack, 1988).

River runoff is sensitive to the land-use changes in a watershed. Deforestation strongly stimulated the increasing trend of runoff during 1980s to early 2000s. It contributed about 41–183 % of the total runoff increase. Decrease in forest area as well as the expansion of agricultural land was occurred in JRW during 1986–1996 (Fig. 2) which was following the national agricultural policy (Huang et al., 2012). Deforestation might accelerate the surface flow either by lowering water infiltration to the soil or by reducing the storage capacity (Critchley and Siegert, 1991). Deep-rooted plants (i.e. trees) generally have larger storage capacity than shallow-rooted plants (i.e. crops) (Zhang et al., 2001). The root system as well as organic matter in the soil also increases the soil porosity thus allowing more water to infiltrate.

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Vegetation loss and increase on impervious area has consistently produced extra runoff from 2004 to 2006. Built-up area has been expanded exponentially over the past thirty years in Jiulong River Watershed. Even though it account for less than 5 % of the total area of catchment, however this increase in impervious area might diminish evapotranspiration as well as storage capacity in a watershed, as the excess precipitation will generate overflow runoff. There was also decrease in forest area during 2002–2007, but the forest was converted into agricultural land rather than built up area (Zhou et al., 2014). Although the changes on land-use pattern were relatively small and in fact watershed was still dominated by natural landscape, however urban sprawl may potentially affect the river runoff. This study confirmed our understanding that vegetation loss may potentially bring the negative impact on the watershed by increasing the river runoff which is related to flooding hazard.

In opposite, reforestation played an important role on shrinking of river runoff. Just after the chaos of the Cultural Revolution in 1976, Forest Department reasserted its control over forest management through implementing the planting trees policy vigorously. Outcome of this policy was quite successful as the highest percentage of natural area in Jiulong River Watershed was observed in 1986. This increase in forest area was associated to the decrease in river runoff during 1975–1980 in the North River and West River. Loss of runoff due to reforestation was about 21–51 % of the total runoff loss. Since 1996 the agricultural land has been shrunk constantly, coincidence with the increased in forest area in 2002. Farmers were likely to start planting the woody plant and fruit trees rather than paddy because they might earn more benefit (Lin and Ho, 2005; Ni et al., 2003; Ye and Huang, 2009). Changes in vegetation type from crops into forest area led to increase in evapotranspiration contributing to the large decrease in runoff during 2001–2004.

Although decreasing trend of runoff was similar to that in precipitation, however river runoff was declined sharper. Shortage in runoff due to reforestation accounted for 72–82 % of the total runoff loss in a catchment. Reforestation would lead to large and spatially extensive decreases of long-term average runoff (Trabucco et al., 2008) by

increasing the evapotranspiration (Zhang et al., 2001). Dense vegetations also tend to retard the water flow in a catchment (Critchley and Siegert, 1991).

Although the specific impact of land use changes on river runoff dynamic has been clearly investigated, but we need to always keep in mind that the major driver of the runoff dynamic is climatic variability. Sharp decrease on annual rainfall will lead to the decrease in annual runoff. Similarly, the increase in annual rainfall may generate more runoff. Non-climatic factor only trigger the impacts from climate changes on river runoff. We found that river runoff is responsive to the changes in watershed area. As the anthropogenic disturbances tend to increase in the future due to rapid economic development and population growth, thus the demand on land, water, and food may also be escalated. Based on the past 53-year observations, the runoff and precipitation showed the fluctuation trend such as an oscillation. Appropriate strategy to mitigate the risk of flooding and drought should be concerned seriously in a developing coastal watershed especially in the smaller catchment such as in the West River during the extreme hydrological years.

4 Conclusion

Analyzing the temporal trend of annual runoff relative to annual climatic variability was one of the great interests related to the impact of climate changes on freshwater system. In the case study of Jiulong River Watershed, river runoff was strongly controlled by climatic variability through precipitation and evapotranspiration. However, this study discovered that land changes reinforced the impact of climate changes on annual runoff dynamic. Deforestation played significant role in generating overflow runoff in a watershed during heavy precipitation. In contrast, reforestation enabled watershed to store more water in a catchment during dry years. This study inferred that severe drought and flood in the future cannot be fully addressed as an impact of climate changes, but it might also be related to the intensified anthropogenic disturbances within the catchment, such as urban sprawl in coastal cities.

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Author contributions. A. Ervinia designed the concept of the paper, developed the model of *L-R* diagram, performed data analysis, and prepared the manuscript. Z. Zhang contributed in data acquisition including data of hydro-climatic parameters and land-use pattern in the watershed. J. Huang provided the intellectual input and constructive comments on the development of model as well as revised the paper.

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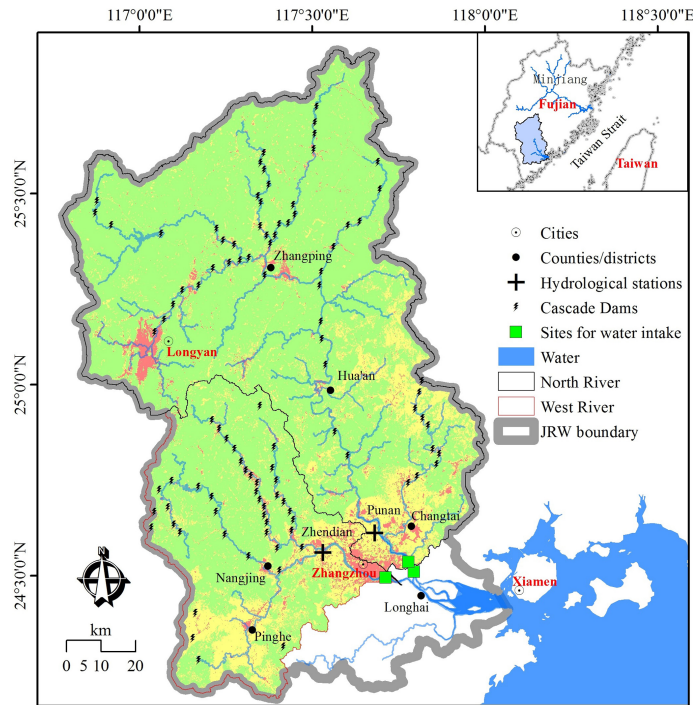


Figure 1. Study area of Jiulong River Watershed.

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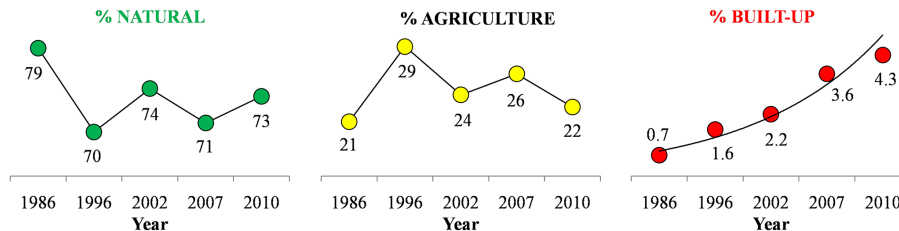


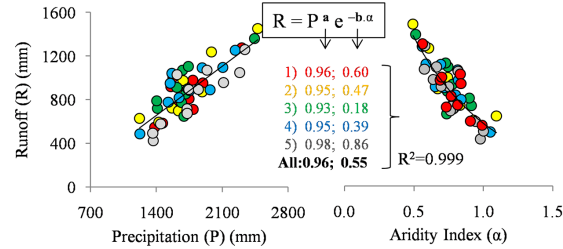
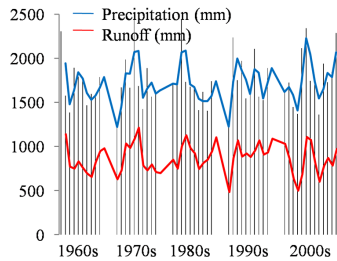
Figure 2. Land use pattern in Jiulong River Watershed during 1986–2010. Data of land use pattern were obtained from Huang et al. (2012) and Zhou et al. (2014).

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(a) North River



(b) West River

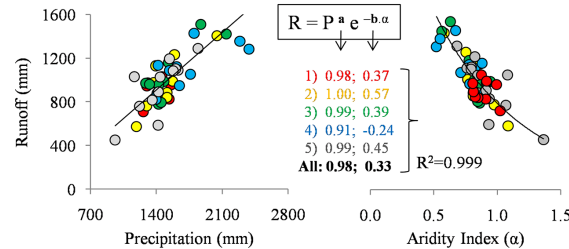
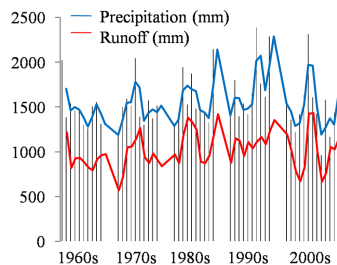


Figure 3. Observed annual runoff (mm) and annual precipitation (mm); hydro-climatic model in North River **(a)** and West River **(b)** over the past five periods (1 = 1960s; 2 = 1970s; 3 = 1980s; 4 = 1990s; and 5 = 2000s).

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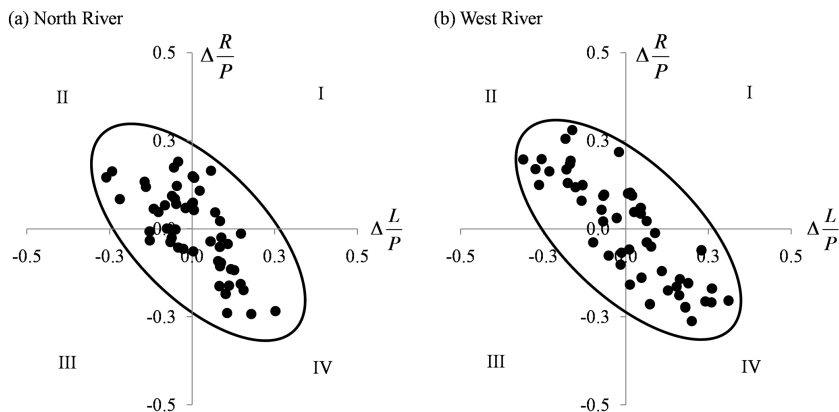


Figure 4. *L-R* diagram to identify the specific impact of land-use changes on runoff dynamic in North River **(a)** and West River **(b)**.

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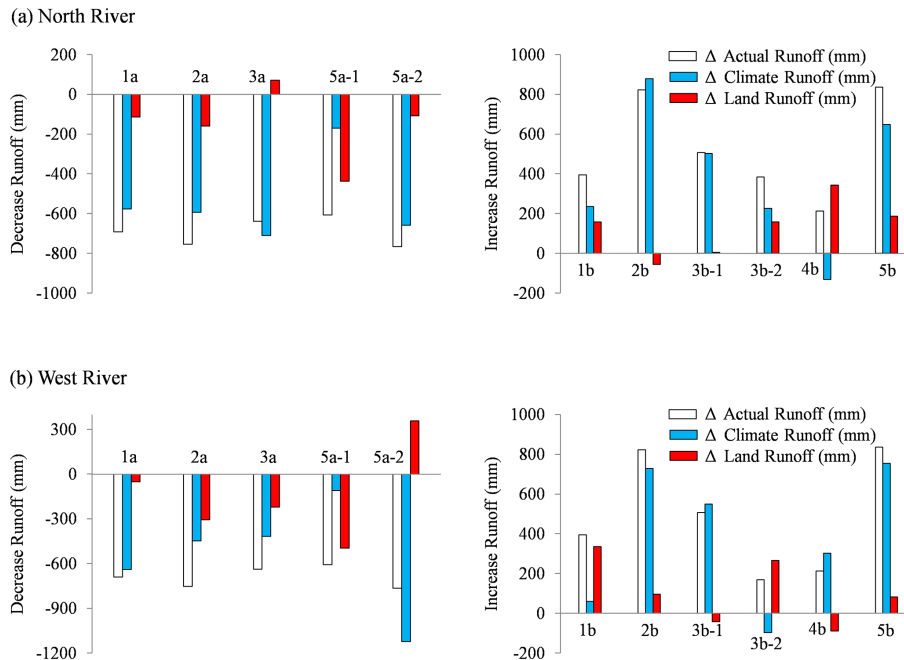


Figure 5. Runoff changes in North River and West River between dry year and wet year in the five periods. Downward trend (1a = 1961–1967; 2a = 1975–1980; 3a = 1983–1987; 5a-1 = 2001–2004; 5a-2 = 2006–2009) and upward trend (1b = 1967–1970; 2b = 1971–1975; 3b-1 = 1981–1983; 3b-2 = 1987–1990; 4b = 1993–1998; 5b = 2004–2006).

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