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LAND USE AND CLIMATE CHANGES AND THEIR IMPACTS ON RUNOFF IN THE YARLUNG ZANGBO RIVER BASIN, CHINA

Z. LIU, Z. YAO*, H. HUANG, S. WU AND G. LIU

State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 100101 Beijing, PR China

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ABSTRACT

Impacts of land use and climate change on runoff were investigated by studying the runoff in the Yarlung Zangbo River basin, China. Trends in precipitation, mean air temperature, and runoff were analysed by non-parametric Mann-Kendall tests. Land-use changes were examined with land-use transition matrix and geographic information system tools. Land-use and climate changes showed several characteristics, including increased reforestation, decreased grassland, retreat of glaciers and increased desertification. Human activity caused great impact, especially within densely populated regions and cities. Reforestation and degradation of grasslands were more frequent than deforestation and cultivation of grasslands. Annual mean air temperature, precipitation and runoff showed increasing trends between 1974 and 2000. The impacts of land use and climate change on runoff had different effects depending on region and season. In the season of freezing, climate change clearly affected runoff within regions that experienced precipitation. Altered evapotranspiration accounted for about 80 per cent of runoff changes, whereas land-use changes appear to have had greatest impact on runoff changes within regions that have inconsistent relationships between runoff and climate change. It was demonstrated that afforestation leads to increased runoff in dry seasons. It was estimated that glacier snow melt has caused annual runoff to increase at least 6·0 mm/10yr, 2·1 mm/10yr and 1·7 mm/10yr in Regions 1, 3 and 4, respectively, whereas evapotranspiration caused annual runoff to decrease at least 7·4 mm/10yr in Region 2. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS: land-use change; Yarlung Zangbo River; Mann-Kendall; land-use transition matrix; glaciers; PR China; runoff changes; climate change

INTRODUCTION

The effects of land use and climate change on hydrology have been an important area of research in recent decades, in particular, with respect to the generation of runoff. Land use directly impacts key aspects of hydrological processes, such as evapotranspiration, infiltration and runoff. Observational evidence indicates with high confidence that climate change effects hydrological systems (Rosenzweig *et al*., 2007). River discharge worldwide has noticeably increased since 1900, and studies suggest that land-use change may be directly responsible for as much as 50 per cent of this increase (Piao, *et al*., 2007).

Although there have been many studies on the impacts of land use on hydrology (see reviews by Bosch and Hewlett, 1982; Andréassian, 2004), the relationship between land use and hydrology is still unresolved. Forests generally have lower surface albedo, higher surface aerodynamic roughness, higher leaf surface area and deeper roots than other types of vegetation, with each characteristic tending to contribute towards an increase in evapotranspiration and a decrease in streamflow (Costa, *et al*., 2003; Farley, *et al*., 2005). Therefore, reduction of forest cover can increase runoff, and plantations have often been found to cause reductions of runoff (Hibbert, 1967; Calder, 2007). However, several studies have reported contradictory findings (Oudin, *et al*., 2008; Cao, *et al*., 1991; Wei, *et al*., 2008; Bevan, 2000; and others), which may be explained by variation in local climate, soil compaction and geology. There are several methods for evaluating the effects of land use on hydrological variables, including catchment experiments (Hibbert, 1967; Hewlett, *et al*., 1969; Bosch and Hewlett, 1982; Andréassian, 2004; and others), establishment of empirical relationships between hydrological variables and land-use types (Turner, 1991; Zhang, *et al*., 2001; Lu, *et al*., 2003; Oudin, *et al*., 2008; and others), the application of hydrological models (Onstad and Jamieson, 1970; Jain, *et al*., 1992; Hundecha and Bárdossy, 2004; and others) and geographic information system (GIS)-based tools (Calder, 2007; Jasrotia and Singh, 2006; and others). All of these methods have both advantages and disadvantages. For example, the scale of these experimental studies (generally less than 10 km^2) are too small to enable researchers to understand effects in large scale catchments (hundreds of km^2 or more). There are many uncertainties in the application of hydrological models (Nandakumar and Mein, 1997), which include model structure uncertainties, model

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*Correspondence to: Z. Yao, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 100101 Beijing, PR China. E-mail: yaozj@igsnrr.ac.cn

parameter uncertainties and model input uncertainties. Hydrological models have been used to assess the impact of both land use and climate change on hydrology in many studies (Tu, 2009; Barlage *et al.*, 2002; Hundecha and Bárdossy, 2004; Lørup *et al.*, 1998; Legesse *et al.*, 2003; Guo *et al.*, 2008; Li *et al.*, 2009; and others). But development of additional methods is required because of model uncertainties.

The Yarlung Zangbo River is the fifth longest river in China. The Yarlung Zangbo River basin (YZRB) is one of the highest river basins in the world with an average elevation of greater than 4600 m above sea-level. Because of its location in the Yarlung Zangbo Suture Zone, within which enormous transportation channels carry moisture from the Indian Ocean to the inner region of the Qinghai-Tibet Plateau, the YZRB plays an important role as a precipitation generation mechanism over the Qinghai-Tibet Plateau (Gao *et al.*, 1985; Yang *et al.*, 1989; Liu *et al.*, 2002; Zhou *et al.*, 2010). In addition, the YZRB has the greatest population density and the largest hydropower resources of the Qinghai-Tibet Plateau (Wang, 2009). As one of the largest ecologically sensitive regions on Earth, the YZRB has a unique and fragile environment vulnerable to climate and land-use changes (Wang *et al.*, 2008). Climate changes in the basin have been analysed by several studies (You *et al.*, 2007; Liu *et al.*, 2007; Shi *et al.*, in press). For example, You *et al.* (2007) detected trends in precipitation, air temperature and potential evapotranspiration within the basin between 1961–2005 based on linear regression analysis. Shi *et al.* (in press) investigated future climate changes over the basin in the twenty-first century based on a high-resolution regional climate model simulation. Liu *et al.* (2007) analysed characteristics of precipitation in the basin based on variation in $\delta^{18}O$ in precipitation.

However, there have been few studies of effects of climate change on water availability within the YZRB. In fact, runoff is very sensitive to land use and climate change in the basin. It shows obvious variability among land-use types within the upstream, midstream and downstream regions of the YZRB, which might affect runoff generation mechanisms within these regions. Several large-scale forest restoration programmes, which have been implemented since 1990, could have substantial influences on temporal and spatial distributions of runoff. Furthermore, the YZRB contains the largest number of glaciers (10 816 glaciers) of the exorheic basins in China (Yao *et al.*, 2010), this also plays an important role in the generation of runoff. Therefore, it is necessary to assess impacts of both climate and land-use change on runoff in the YZRB.

In this study, effects of both land use and climate changes on runoff within different regions of the YZRB were investigated on the basis of trends in hydrometeorological variables and the hydrologic budget, which might be an applicable method for related studies. The study area (YZRB) was restricted to the portion of Yarlung Zangbo–Brahmaputra River basin located in China. Firstly, land-use types and the land-use transition matrix for different regions within the basin were analysed using GIS tools. Then, monotonic trends of precipitation, mean air temperature (MAT) and runoff within different regions of the basin were assessed using non-parametric Mann-Kendall tests. Finally, impacts of land use and climate change on runoff for different regions of the basin were investigated, using the hydrologic budget in two periods, the frozen period (season) and the melting period (season).

MATERIALS AND METHODS

Study Area

The Yarlung Zangbo River in China originates from the Jiemayangzong Glacier in south-central Tibet and is roughly 2229 km long. The YZRB (Figure 1), which is located on the Qinghai-Tibet Plateau, is one of the highest major river basins in the world (lying approximately 4621·3 m above sea-level). The basin area is approximately $2{\cdot}4 \times 10^5$ km^2.

The YZRB is part of Indian Ocean water system. It exhibits obvious variation in its climate from upstream to downstream regions of the basin, which are caused by the location and the topographical features of the Qinghai-Tibet Plateau. The upstream region, which is located within a frigid zone with a mean annual precipitation of less than 300 mm, is mainly covered in alpine meadow. An alpine grassland lies within the midstream region and, has an annual precipitation of 300 mm to 600 mm. The downstream region, which is located in a subtropical humid zone has a mean annual precipitation of more than 2000 mm and is characterised as alpine forest. The Lhasa River basin, which is located in the middle region of the YZRB, is the largest sub-basin in the YZRB. It is covered by glaciers and discontinuous permafrost, with a glacier area of 690·53 km^2. The Lhasa River is one of the major water supplies of the YZRB.

The YZRB is sensitive to environmental change. Desertification in the YZRB, has been caused by both natural factors and human activity and has been a critical issue during the past few decades (Jin *et al.*, 1997; Dong *et al.*, 1999).

Data

Hydrological data: observed runoff at four hydrological stations (Figure 1), including monthly, seasonal and annual series from 1956 to 2000 (Tibet Hydroelectric Investigation, Designed Research Institute) were used in this study.

Meteorological data: observed precipitation and mean air temperature including monthly, seasonal and annual series were obtained from 15 National Meteorological Observatory stations in and around the YZRB, which included a

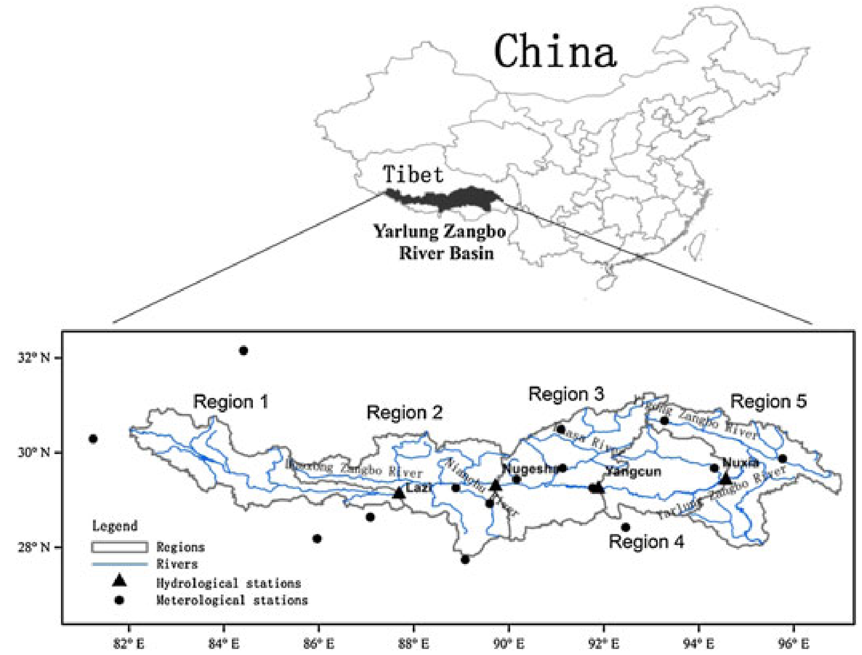

Figure 1. Location of the Yarlung Zangbo River basin in China and the hydrometeorological stations. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

comprehensive series of data between 1974 and 2010. All data used in the study had passed data quality control. The geographical locations and spatial distribution of these stations are shown in Figure 1.

Land-use data: Land-use data maps of the YZRB were collected from the Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences, which included 1980s and 2000 maps. These data maps were obtained from satellite imagery and field investigations. The scale of the 1980s data maps was recalculated to 1:250 000, in order to compare with the 2000 data map.

Methods

ArcGIS package

ArcGIS Spatial Analyst® provides powerful tools for comprehensive, raster-based spatial analysis. Land-use types within different regions of the YZRB were defined by the Resample command and the land-use transition matrix was calculated using the Tabulate Area command in ArcGIS Spatial Analyst® toolbox. The Tabulate Area command calculates cross-tabulated areas between two datasets and outputs a table. These two datasets represented identical spatial resolutions.

Mann-Kendall test

The rank-based non-parametric Mann-Kendall test has been commonly used to assess the significance of monotonic trends in hydrometeorological time series (e.g. Hirsch and Slack, 1984; Chiew and McMahon, 1993; Gan, 1998; Xu *et al*., 2007, 2010; Fu *et al*. 2009, and others). In the test, the standard normal statistic Z is estimated and compared with the standard normal deviate $Z_{\alpha/2}$. The test statistic Z is not statistically significant if $-Z_{\alpha/2} < Z < Z_{\alpha/2}$. Correspondingly, it shows a statistically significant trend if $Z < -Z_{\alpha/2}$ or $Z > Z_{\alpha/2}$ (Gan 1998). For the case that $n > 10$, the standard normal statistic Z is estimated by the following formula as (Hirsch *et al*., 1982; Gan, 1998):

$$Z = \begin{cases} (S-1)/\sqrt{\mathrm{Var}(S)} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ (S+1)/\sqrt{\mathrm{Var}(S)} & \text{if } S < 0 \end{cases} \tag{1}$$

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}\left(x_j - x_i\right) \tag{2}$$

$$\mathrm{sgn}(\theta) = \begin{cases} 1 \text{ if } \theta > 0 \\ 0 \text{ if } \theta = 0 \\ -1 \text{ if } \theta < 0 \end{cases} \tag{3}$$

$$\mathrm{Var}(S) = \left[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5) \right] / 18 \tag{4}$$

Where: t is the extent of any given tie.

The magnitude of a trend was estimated by the slope estimator β (Hirsch *et al*., 1982). It was defined as

$$\beta = \mathrm{Median}\left(\frac{x_j - x_i}{j - i}\right) \quad \text{where } 1 < i < j < n \tag{5}$$

A positive value of β indicates an increasing trend, whereas a negative value of β indicates a decreasing trend (Xu *et al*., 2007).

Effects of land use and climate variables on runoff

In general, it has been found that vegetated areas generate more runoff than do barren areas (Nicolau *et al*., 1996). As for YZRB vegetated areas, runoff from forested land is greater than for other land-use types, including grasslands (Zhang *et al*., 2001; Andréassian, 2004; Calder, 2007). Water use by forested land is generally greater than other that of land-use types, leading to reduced flows from river basins and this is mainly caused by higher evapotranspiration. Although forests have obvious influences on flood events for small-scale catchments, effects of forests on floods are likely to be minimal for large scale catchments (Calder, 2007). In addition, effects of forests on dry season flows (low flows) remain unclear. The effects of land use on annual and monthly runoff were analysed in this study, whereas flood events and low flows were not considered.

Empirical relationships between runoff, precipitation and MAT indicated that runoff is positively related to precipitation but negatively related to MAT (Fu *et al*., 2007), especially during the frozen period. This implies that actual evaporation will increase under higher air temperature scenarios, which will lead to decreases in runoff. This relationship is more complex during the melting period in which runoff will increase under higher MAT because of increased generation of glacier and snow melt. Therefore, it is necessary to investigate impacts of climate and land-use change on runoff during the frozen period and the melting period separately.

In the hydrologic budget, soil water changes are negligible for long periods. Therefore, runoff changes are caused by changes in precipitation, glacier and snow melt and evapotranspiration within the basin. It can be described by the following formula:

$$\Delta R = \Delta R_p + \Delta R_g + \Delta R_e \tag{6}$$

Where: ΔR is total change in runoff, ΔR_p, ΔR_g, ΔR_e are runoff changes caused by precipitation, glacier and snow melt and evapotranspiration, respectively. Precipitation is a major climatic variable. Glacier-snow/ice cover is a land-use type and is also affected by climate. Land use influences changes in evapotranspiration through vegetation types (by evapotranspiration) and other land-use types (by evaporation). In general, changes in runoff are positively correlated with changes in precipitation and MAT (glacier and snow melt runoff) but are negatively correlated with changes in evapotranspiration.

In this study, the YZRB was divided into five regions with four hydrological stations (Figure 1) using digital elevation model data. In this division, each region was considered to be a sub-basin, in which runoff was measured by a hydrological station. In other words, runoff in each sub-basin would flow out via the corresponding hydrological station. For example, runoff in Region 1 was controlled by Lazi station; Runoff in Regions 2–4 corresponded to differences between Nugesha and Lazi, Yangcun and Nugesha, and Nuxia and Yangcun, respectively; Region 5 corresponded to the remainder of the YZRB in China. Land-use types and associated changes from 1980 to 2000 were estimated for each region based on land-use maps and the land-use transition matrix. Monotonic trends of climate variables (precipitation and MAT) and runoff were detected by the Mann-Kendall test. Because data from only four hydrological stations were obtained, runoff was only calculated for Regions 1–4. Areal precipitation and temperature within each region were averaged by station data based on weighted areas, which was obtained by the Thissen Polygon method. Finally, effects of land use and climate variables on runoff were investigated on the basis of relationships between land use, climate and runoff changes in the frozen period and the melting period.

RESULTS

Land-use Types and Changes within Each Region

Land use in the YZBR was categorised into seven types, including agricultural land, forest land, grassland, glacier and snow cover, waterbodies, built-up land, and barren land. More details for descriptions of land-use types can be found in Anderson *et al*. (1976). Land-use types and corresponding ratios of the basin are shown in Figure 2. The grassland showed the largest area, which covered 62·1 per cent of the basin area. Barren and forest lands were also major land-use types over the basin, which covered 17·9 per cent and 14·1 per cent of the basin area, respectively. Although the built-up land covered less than 0·5 per cent of the basin area, it increased greatly from 1980 to 2000 (Figure 3). Glacier and snow cover was estimated as approximately 7782 km^2 and covered 3·1 per cent the basin area.

Figure 2 illustrates spatial distributions of land-use types within each region of the YZRB. It shows obvious variability for land-use types from the upstream region to the downstream region of the basin. The grassland covered most of the basin area (more than 70 per cent) upstream of Yangcun station including Regions 1–3, where the ratio of the forest land was less than 3 per cent. Differences between the grassland and the forest land were not as obvious within the lower stream Region 4, which covered 39·6 per cent and 28·9 per cent of the basin area, respectively. In Region 5, forest land and grassland covered 44 per cent and 15 per cent of the basin area, respectively.

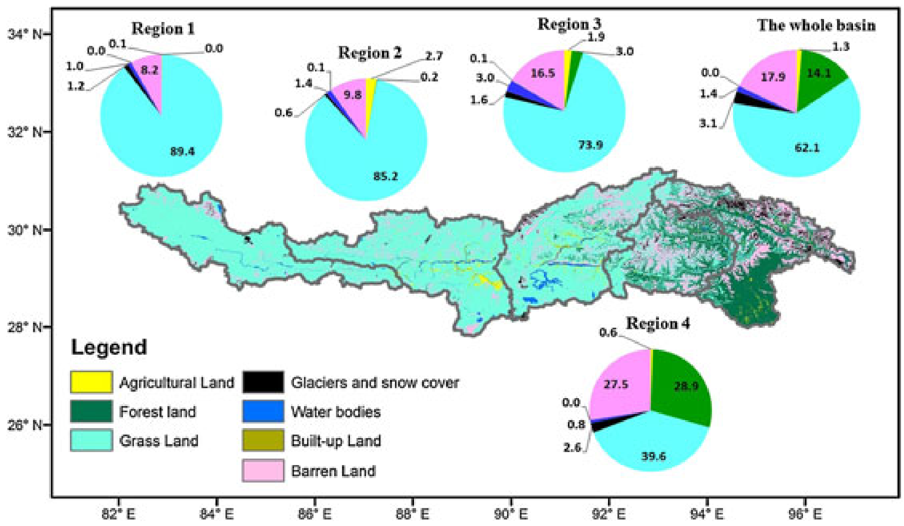

Figure 2. Land-use types (2000) and corresponding ratios of area at different regions of the Yarlung Zangbo River basin. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

Land-use changes between 1980 and 2000 within different regions of the YZRB are shown in Figure 3. There were two major characteristics of land-use changes in the YZRB. The forest land area increased substantially by more than 1·0 10^2 km^2, whereas the grassland area decreased by more than $0{\cdot}5 \times 10^2$ km^2. The increases in forest land were caused by forestation projects sponsored by the government. There were several factors leading to grassland degradation, which included overgrazing, consuming biomass energy (mainly within the grassland) for domestic energy, and damage caused by grassland rodents and insects (Chu *et al*., 2006; Cai *et al*., 1996). Results also showed variability for forest and grassland changes within different regions. The forests and grasslands noticeably changed within Regions 2 and 3, particularly in Region 3. They showed little changes within Regions 1 and 4. This may be explained by the fact that human populations and cities were mainly distributed in Regions 2 and 3, showed effects of human activity on forests and grasslands. Glacier and snow cover decreased nearly 40 km^2 within the basin. It is worth noting that this glacier recession was observed in all regions except Region 2. Glaciers retreated markedly within the YZRB; this was also found by Yao *et al*. (2010) and has affected runoff in the basin. Because of social and economic development, the built-up land has increased by about 20 per cent [Figure 3(b)], which is a much higher magnitude than other land-use type changes. The greatest increase of built-up land was in Region 3, which contained the largest numbers of cities and greatest human population of all the different regions. Barren land increased by 50 km^2 within the basin, which indicates severe desertification (Liu and Dong, 2003).

A transition matrix (Table I), in which rows and columns indicated land use in 1980 and 2000, respectively, described

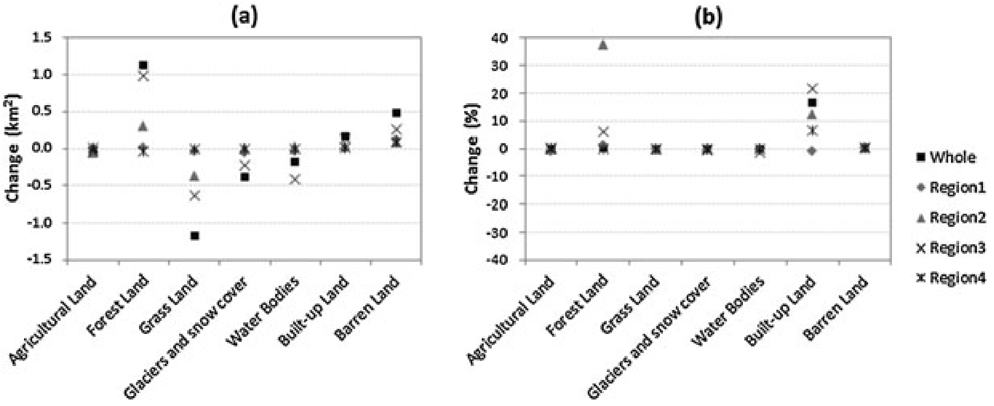

Figure 3. (a and b) Land-use changes from 1980 to 2000 in different regions of the Yarlung Zangbo River basin.

Table I. Land-use transition matrix from 1980 to 2000 for different regions of the Yarlung Zangbo River basin (unit: km^2)

		2000						
Regions	1980	Agri	Forest	Grass	Water	Glacier	Built	Barren
Entire	Agri	3020·7	81·4	272·0	0·0	32·2	11·7	8·3
	Forest	75·4	34 183·4	1206·6	11·7	108·0	1·1	379·8
	Grass	265·8	1193·3	153 586·7	68·8	158·6	8·4	2420·5
	Glacier	0·0	11·2	68·6	7290·8	0·4	0·0	411·3
	Water	33·0	49·2	161·8	0·1	3346·0	0·8	11·8
	Built	18·7	0·7	17·5	0·0	1·1	79·9	0·5
	Barren	10·4	340·4	2505·0	405·1	35·1	0·6	42 124·8
Region1	Agri	42·1	0·0	6·2	0·0	1·6	0·2	0·1
	Forest	0·1	22·1	1·3	0·0	0·0	0·0	0·1
	Grass	5·7	1·3	41 909·5	39·1	107·4	0·9	312·8
	Glacier	0·0	0·0	34·9	828·3	0·1	0·0	83·3
	Water	0·3	0·0	102·5	0·0	626·3	0·0	5·2
	Built	0·3	0·0	0·2	0·0	0·0	0·8	0·0
	Barren	0·3	0·0	312·7	72·5	19·4	0·0	3524·9
Region2	Agri	1414·7	3·9	151·7	0·0	19·2	6·1	5·6
	Forest	6·1	65·8	30·7	0·0	12·0	0·2	0·6
	Grass	148·9	8·4	48 945·2	22·0	69·6	3·3	778·8
	Glacier	0·0	0·0	23·3	540·7	0·0	0·0	7·6
	Water	20·5	3·5	70·7	0·0	1207·8	0·1	4·0
	Built	9·6	0·1	3·8	0·0	0·3	21·7	0·0
	Barren	4·1	0·3	789·2	7·3	5·4	0·1	4944·6
Region3	Agri	961·1	5·4	129·2	0·0	20·8	6·2	5·4
	Forest	10·1	1470·4	207·3	0·0	87·4	1·1	17·8
	Grass	125·5	169·7	41 529·8	18·0	71·5	4·7	749·0
	Glacier	0·0	0·0	19·1	1370·1	0·2	0·0	75·3
	Water	15·9	3·4	71·6	0·0	2652·9	1·0	5·1
	Built	10·2	0·5	15·0	0·0	1·3	49·1	0·5
	Barren	5·7	16·3	764·1	72·8	21·8	0·4	8688·9
Region4	Agri	179·2	8·1	26·7	0·0	3·6	0·2	0·6
	Forest	6·9	10 183·5	570·1	1·4	10·8	0·1	100·9
	Grass	27·4	590·9	13 702·6	9·4	46·3	0·4	528·8
	Glacier	0·0	1·5	9·5	1436·1	0·0	0·0	113·2
	Water	4·6	12·3	43·7	0·0	405·4	0·1	3·8
	Built	0·1	0·0	0·7	0·0	0·2	5·0	0·0
	Barren	0·6	87·1	550·3	122·5	4·2	0·0	9615·2

Note: Rows stand for land-use types in 1980, whereas columns mean that in 2000, each value in the transition matrix mean a land-use type in 1980 (columns) transformed into another land-use type in 2000 (rows). 'Agri', 'Forest', 'Grass', 'Glacier', 'Water', 'Built' and 'Barren' mean the agricultural land, the forest land, the grass land, glacier and snow cover, other water bodies, the built-up land and the barren land, respectively.

each land-use type in 1980 transformed into a different land-use type in 2000. Although the agricultural land area showed little change, the transition rate was greater than 10 per cent from agricultural land to other types of land use. There were two obvious land-use transitions within the basin, including a transition between grassland and forest land, and a transition between grassland and barren land (Table I). The area of deforestation into grassland was 1206·6 km^2, which was slightly greater than that of reforestation from grassland (1193·3 km^2). Cultivation of grassland from barren land, which was sponsored by the government, showed the greatest land-use transition with an area of up to 2505 km^2. It was greater than degradation of grassland to barren land (2420·5 km^2). The transition between grassland and other land-use types was obviously greater than other transitions, particularly compared to barren land. This indicated that grassland was of prime importance in the YZRB. This was not restricted to the basin, but was also found in sub-regions of the basin. It is worth noting that transitions between the grassland and agricultural land were also frequent in the basin. That might be due to increased population densities, which would lead to greater demand for agricultural land.

Trends in Climate Variables

Trends in precipitation

Results of the Mann-Kendall test for monthly and annual time-series of precipitation indicated that the climate of the

YZRB became wetter during the period of 1974–2000. Annual precipitation for the entire basin showed an increasing trend, but this was not statistically significant ($p > 0{\cdot}05$) (Figure 4). This result was consistent with results of You *et al.* (2007). The increasing trend of annual precipitation was mainly caused by an increased monthly precipitation from June through September, during which time more than 70 per cent of total annual precipitation falls. Annual precipitation for most regions showed increasing trends. The magnitude of trends varied from 19·4 mm/10yr to 35·0 mm/10yr, with the exception of Region 4, which showed a decreasing trend with a magnitude of approximately −10 mm/10yr. There were many months in which precipitation trends in different regions opposed each other, which implied that the trends in precipitation were spatially heterogeneous within different regions of the basin. It was interesting to note that August was the only month during which monthly precipitation showed increasing trends across all regions, with the magnitude of trends varying from 6·1 mm/10yr to 27·8 mm/10yr within Regions 1 and 2, respectively. The magnitude of most trends was greater within Region 2 than in other regions. All of these trends were not statistically significant ($p > 0{\cdot}05$), with the exception of April in Region 1.

Trends in mean air temperature

The results of the Mann-Kendall test showed that the climate of the YZRB warmed during the period of 1974–2000. Annual MAT of the entire basin showed a statistically significant ($p < 0{\cdot}05$) increasing trend. The magnitude of the trend was 0·27 °C/10a (Figure 5). This result was consistent with results of You *et al.* (2007). MAT of the basin in most months showed increasing trends, and the increasing trends in January, May, July and September were statistically significant ($p < 0{\cdot}05$). February was the only month during which temperature showed a slightly decreasing trend and its Z value was very small. An increasing trend for mean annual temperature was observed for all regions of the basin with the magnitude varying from 0·20 °C/10yr (Region 2) to 0·33 °C/10yr (Region 4). The increasing trends in Regions 3 and 4 were

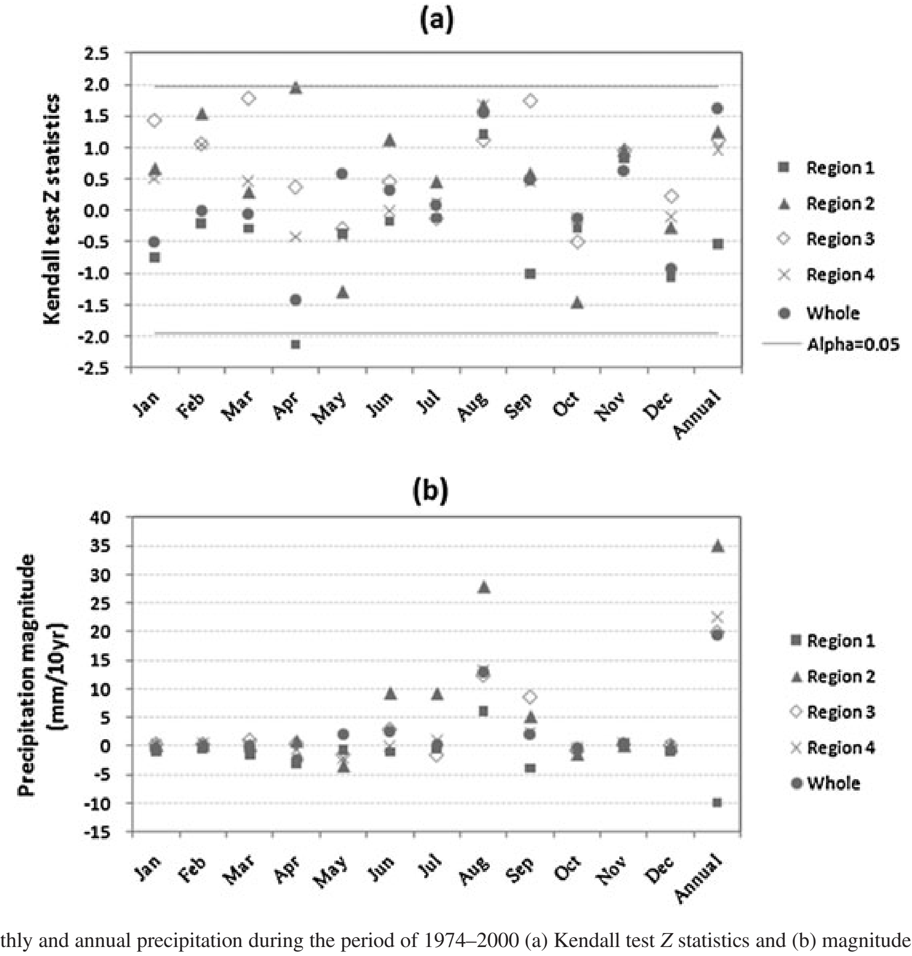

Figure 4. Trends of monthly and annual precipitation during the period of 1974–2000 (a) Kendall test Z statistics and (b) magnitudes of trend for the Yarlung Zangbo River basin.

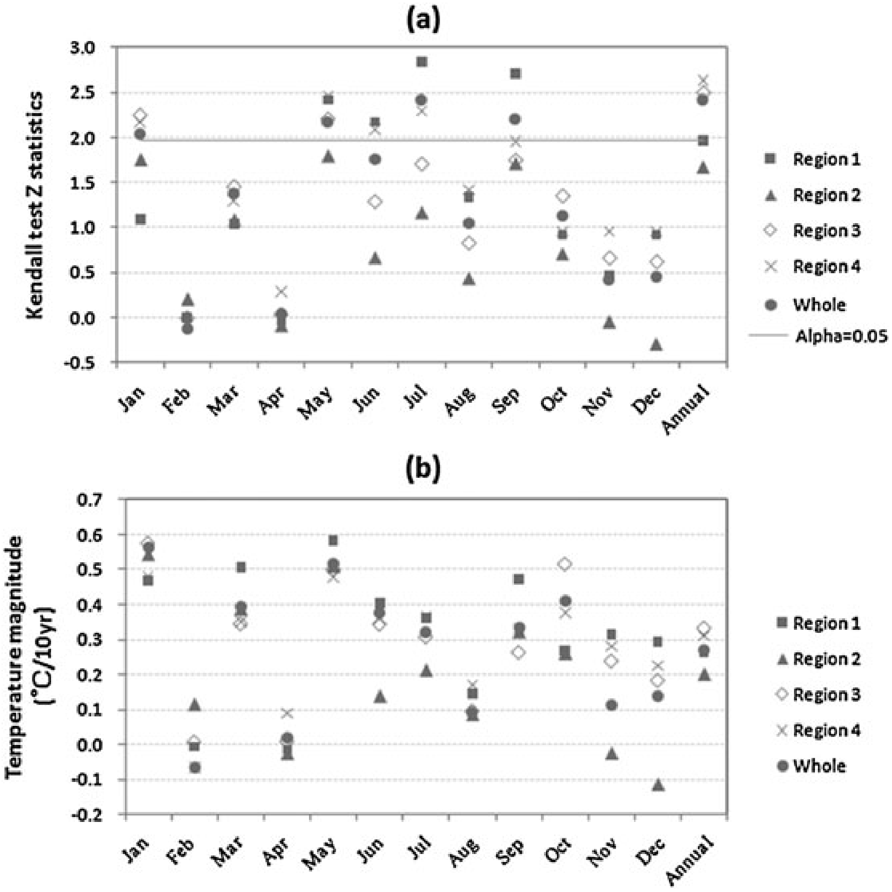

Figure 5. Trends of monthly and annual mean air temperature during the period of 1974–2000 (a) Kendall test *Z* statistics and (b) magnitudes of trend for the Yarlung Zangbo River basin.

more obviously than those in Regions 1 and 2. The trends of both annual and monthly temperatures in Region 2 were not statistically significant ($p > 0{\cdot}05$). Furthermore, the magnitude of trends was low for Region 2 relative to other regions. Although annual temperatures showed statistically significant increasing trends, the trends in most months were not great, particularly for February, March, April, October, November, and December during which times the trends were not statistically significant within the basin and within regions. The magnitude of those trends was the largest in January and May with values of approximately 0·5 °C/10yr or more, whereas magnitude was lowest in February and April with values close to zero.

Trends of Runoff and Impacts of Climate and Land-use Changes on Runoff

Annual variations in streamflow, precipitation, and MAT during the period from 1974 to 2000 for the basin are shown in Figure 6. Annual runoff depth exhibited increasing trends in all regions of the basin, while those trends were not statistically significant ($p > 0{\cdot}05$) (Figure 7). This indicated that runoff in the YZRB increased during the period of 1974 to 2000. More great increasing trends were observed in Regions 3 and 4 than in Regions 1 and 2, which was consistent with trends in mean annual temperature. The largest increase was in Region 3, in which the magnitude of the trend was about 14 mm/10yr. The magnitude of trends was lowest in Region 1 with a value of only about 2 mm/10yr. Trends in monthly runoff depth were also not obviously for all regions except Region 3. Monthly runoff depth in Region 3 showed increasing trends in most months except June, with statistically significant increases from November to May of the next year. Monthly runoff depth in Region 4 also showed increasing trends in most months except January and February. Monthly runoff amounts in Regions 1 and 2 only showed increasing trends from June to November, while showing decreasing trends in other months.

The period from November to April of the following year was the frozen period in the YZRB, in which impacts of glacier and snow melt on runoff could be ignored. Monthly runoff in this period exhibited statistically significant

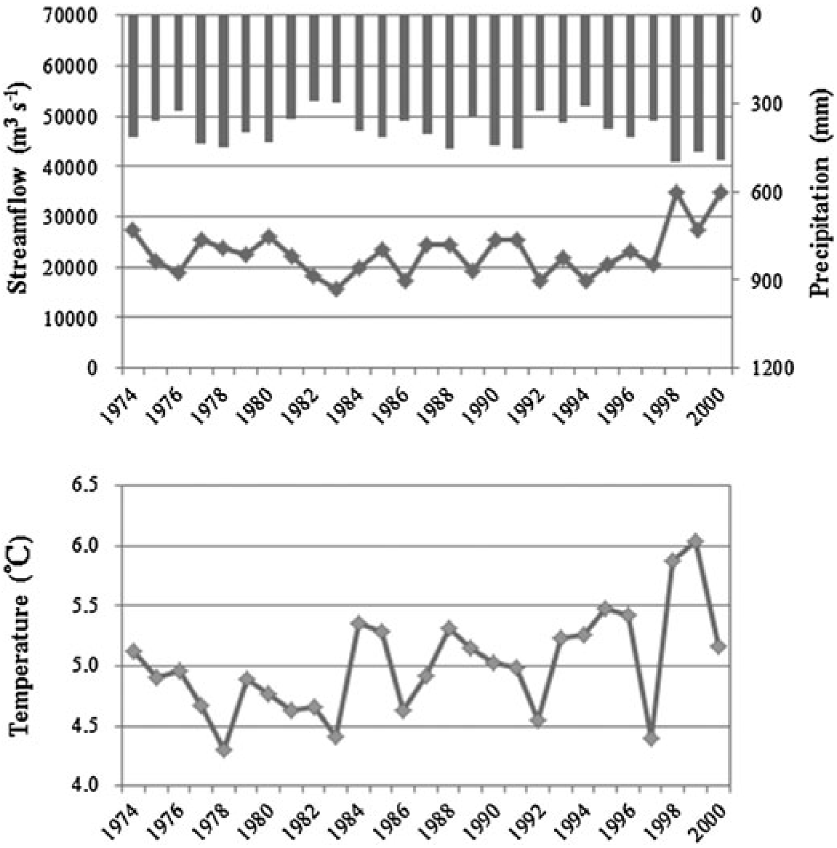

Figure 6. Annual variations of streamflow, precipitation and air temperature for the Yarlung Zangbo River basin (In the upper figure, linear and columnar graphs describe streamflow and precipitation, respectively).

increasing trends in Region 3. Those trends were greater than in other regions and their corresponding magnitudes were substantially larger. During this period, due to changes in precipitation and temperature, relevant trends and their corresponding magnitudes did not show obvious differences between Region 3 and other regions; land-use changes may have been the main factor affecting runoff changes. The most obvious land-use change was that forest land increased by more than $1{\cdot}0 \times 10^2\,\mathrm{km}^2$ in Region 3. This indicated that increases in forest land may have been the main factor leading to markedly increasing trends in runoff during this period. This is because forest land experiences higher infiltration rates and increased water conservation, which induces greater groundwater recharge and positive increases in dry season runoff (Calder, 2007). As for Regions 1 and 2, the trends in monthly runoff were consistent with estimates of monthly precipitation during this period, in which both runoff and precipitation showed increasing trends during November and exhibited decreasing trends during December through April. This indicated that climate (precipitation) changes played an important role in affecting runoff changes in Regions 1 and 2 for this period. In addition, the increasing trends of temperature which would increase evaporation might partly explain decreasing trends in runoff during the frozen months (Fu *et al*., 2007). It was concluded that impacts of land use and climate changes on runoff within the YZRB during the frozen period exerted different effects depending on region: climate changes played an important role in affecting runoff in Regions 1 and 2 based on the fact that runoff was positively and negatively related to precipitation and MAT respectively, while the increase in runoff within Region 3 may have been caused by increased forestlands which induced more runoff during the dry seasons, and the increased MAT which induced more glacier and snow melt runoff.

Because there is an extensive area covered by glaciers in the YZRB, the contribution of glacier and snow melt to runoff might play an important role during the melting period. This was confirmed by the results for trends in MAT, glaciers, and runoff. Runoff and MAT in all regions showed increasing trends during the period of July through October, while precipitation exhibited decreasing trends in some regions. This implied that the contribution of glacier and snow melt to runoff might be more important than changes in precipitation. In fact, glacial area decreased within all regions between 1980 and 2000, especially

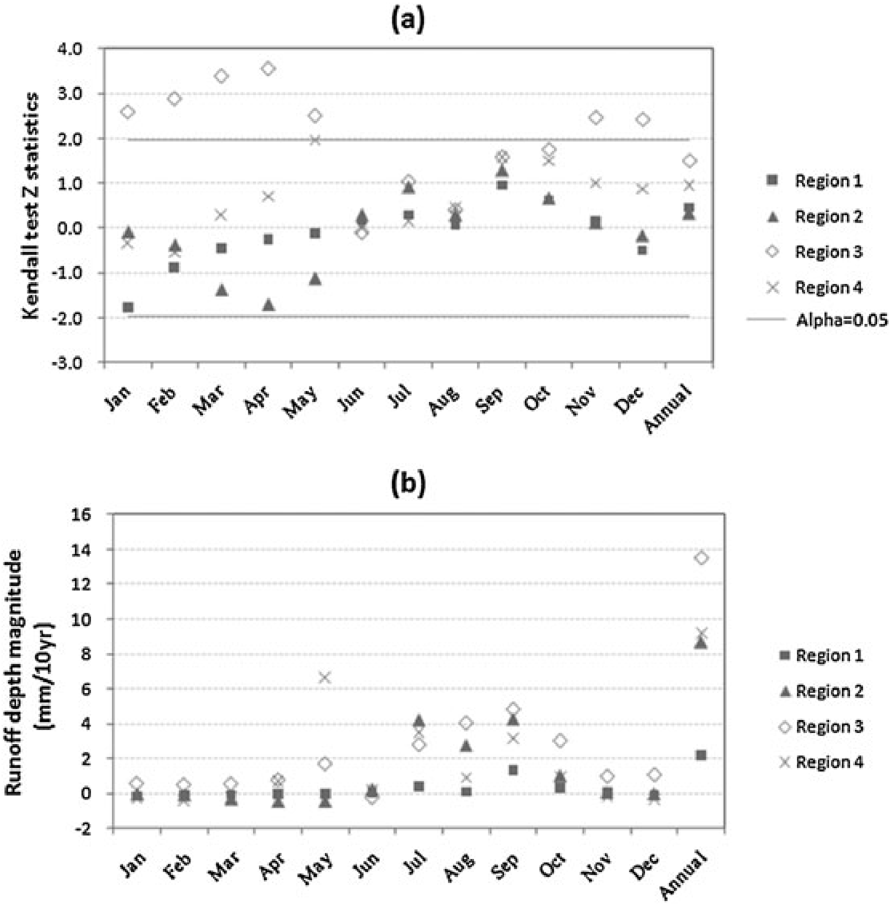

Figure 7. Monthly and annual runoff depth trends (a) Kendall test *Z* statistics and (b) magnitudes for the Yarlung Zangbo River basin.

within Region 3 where it diminished by more than 0·5 $10^2\,km^2$. The decreasing glacial area would positively increase runoff during the melting period. Although the magnitude of increasing trends for precipitation within Region 3 was lower than that for other regions during August and also even showed decreasing trends in July and October, Region 3 exhibited the largest magnitude of increasing trends for runoff during these months, where the decreasing glacial area was much greater relative to other regions. Therefore, it was concluded that the impacts of decreasing glacial area on runoff during the melting period, mainly because of air temperature changes, were of greater impact than changes in precipitation in the YZRB, especially for Region 3, which contained the largest glacial area and exhibited the greatest decrease in glacial area.

On an annual scale, runoff showed an increasing trend in Region 1 with a magnitude greater than 2·0 mm/10yr, but precipitation exhibited the opposite trend with a magnitude of about −10 mm/10yr. Therefore, it was demonstrated that the increased annual runoff within the region was mainly caused by decreasing glacial area which generated more glacier and snow melt runoff within this region. Although annual runoff and annual precipitation exhibited increasing trends in Regions 2–4, the magnitudes of these trends were not consistent. The lowest change in precipitation trends was in Region 3, which was slightly low relative to Region 4, and precipitation showed the greatest increasing trend in Region 2. Magnitude of runoff showed the lowest and highest trends in Regions 2 and 3, respectively. This implied that precipitation changes were not the sole factor inducing runoff changes, MAT and land-use changes also played important roles in these regions. This was confirmed by differences between actual runoff and potential runoff estimated by the product of precipitation and runoff coefficients (runoff coefficient is the ratio of mean annual runoff to mean annual precipitation, so potential runoff does not include glacier and snow melt runoff) at different regions. Actual runoff and potential runoff increased by 8·5 mm and 16·1 mm in Region 2, whereas they increased by 14 mm and 11·4 mm in Region 3, respectively. It was concluded that effects of evaporation and glacier and snow melt played important roles in runoff

Table II. Trends magnitude of runoff depth at different regions of the Yarlung Zangbo River basin (Unit: mm/10yr)

	Frozen period			Melting period			Annual		
Regions	ΔR	ΔR_P	$\Delta R-\Delta R_P$	ΔR	ΔR_P	$\Delta R-\Delta R_P$	ΔR	ΔR_P	$\Delta R-\Delta R_P$
Region 1	−1·3	−1·0	−0·3	2·7	−2·0	4·7	2·2	−3·8	6·0
Region 2	−0·6	0·3	−1·0	9·5	11·2	−1·7	8·7	16·1	−7·4
Region 3	−4·6	1·2	−5·8	20·0	10·2	9·8	13·5	11·4	2·1
Region 4	−3·4	−0·3	−3·1	12·6	10·5	2·1	9·2	7·4	1·7

Note: 'ΔR' is trends magnitude of actual runoff depth. 'ΔR_P' is trends magnitude of runoff depth, which induced by precipitation. It is calculated by the product of precipitation magnitude and runoff coefficients. '$\Delta R-\Delta R_P$' means the difference between ΔR and ΔR_P. It includes runoff changes caused by glaciers-snow melting and evapotranspiration according to the equation (6).

within Regions 2 and 3, respectively. The magnitude of actual runoff was obviously lower than that of potential runoff, which might be caused by increased evaporation in Region 2. The magnitude of actual runoff was greater than that of potential runoff, which implied that the increase in actual runoff was affected by additional glacier and snow melt runoff in Region 3.

Trends in magnitude of runoff depth within different regions of the basin are shown in Table II. Because glacier and snow melt and evapotranspiration have positive and negative effects on runoff changes, it was concluded that glacier and snow melt induced increases in runoff of at least 6·0 mm/10yr, 2·1 mm/10yr and 1·7 mm/10yr in Regions 1, 3 and 4, respectively. Evapotranspiration caused runoff decreases of at least 7·4 mm/10yr in Region 2. During the melting period, glacier and snow melt induced the highest and the lowest runoff increases in Regions 3 and 4, respectively. This was consistent with the magnitude of glacial recession within corresponding regions. There was little glacier and snow melt during the frozen period, so changes in runoff were caused by precipitation and evapotranspiration. Precipitation played an important role in affecting runoff changes in Region 1, accounting for 77 per cent of change. Evapotranspiration explained more than 80 per cent of runoff changes in Regions 2–4.

CONCLUSIONS

This study detected monotonic trends of precipitation, MAT and runoff within different regions of the YZRB using nonparametric Mann-Kendall tests. Land-use changes were estimated for each region based on the land-use transition matrix and GIS tools. Impacts of land-use and climate changes on runoff were investigated by the hydrologic budget for runoff, land use and climate changes. Results showed that land use and climate changes had different effects on runoff depending on region and period. The following conclusions were made as follows:

The increased forestlands and decreased grasslands were the most obvious land-use changes from 1980 to 2000 within the YZRB, which changed by $1{\cdot}0 \times 10^2\,\mathrm{km}^2$ and $-0{\cdot}5 \times 10^2\,\mathrm{km}^2$, respectively. The increased forest lands were caused by forestation projects sponsored by the government. The grassland degradation might be due to overgrazing, consuming biomass energy for domestic energy, and damage by grassland rodents and insects. It is worth noting that the most obvious land-use changes were within Region 3, where dense populations and cities lead to more human activity. In addition, glacial retreat and desertification within the basin are of concern.

Annual MAT, precipitation and runoff experienced increasing trends within the YZRB between 1974 and 2000. The increasing trend of annual precipitation was mainly caused by increasing precipitation from June to September, in which precipitation accounted for more than 70 per cent of annual runoff. The largest increasing trend for runoff was within Region 3, with a magnitude of runoff depth of approximately 14 mm/10yr.

During the frozen period, climate change played an important role in influencing runoff changes within Region 1, accounting for 77 Per cent. Evapotranspiration, which combined effects of increased forestland and air temperature, explained more than 80 per cent of runoff changes in Regions 2–4. Because the empirical relationships between runoff and climate changes were not consistent within Region 3, land-use changes, which mainly exhibited as the increased forests, might be the main factor affecting the increase of runoff. This demonstrated that forestation could lead to increased runoff in dry seasons. Although impacts of land use and climate changes on runoff were very difficult to evaluate exactly, it was estimated that glacier and snow melt increased annual runoff by at least 6·0 mm/10yr, 2·1 mm/10yr and 1·7 mm/10yr in Regions 1, 3 and 4, respectively, whereas evapotranspiration caused annual runoff to decrease at least 7·4 mm/10yr in Region 2.

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