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RESEARCH ARTICLE

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# Responses of water yield to changes in vegetation at a temporal scale

**Abstract** The effect of vegetation on the water recycling of a land ecological system is considerably significant. Understanding the relationship between vegetation and runoff changes will benefit regional eco-environmental and water resources management. Based on paired catchments and time trend studies, a number of studies had been undertaken to establish the relationship between vegetation cover and water yield. We obtained some results from paired watersheds by focusing on changes at various time scales. At the mean annual scale the runoff changes resulting from vegetation alteration can be predicted using Zhang's curves. The absolute change of runoff due to vegetation alteration in a humid area is larger than that in the dry region, while the relative change is reverse. At the annual scale, it takes 15–20 years or longer in the arid region for catchments to reach a new equilibrium after afforestation, and under natural restoration, it takes about a hundred years. The vegetation changes have a proportionally larger impact on low flow at the seasonal scale. For catchments in arid regions, relative changes in low flow sections of the flow duration curve will be much more significant compared with that in the high flow section, leading to increased number of zero-flow days. However, in humid regions, changes in runoff tend to be much more uniform.

**Keywords** temporal scale, changes in vegetation, stream flow response, flow duration curve, paired catchments studies

## 1 Introduction

Vegetation has a considerable effect on water recycling in an ecological land system (McCulloch and Robinson, 1993). Understanding the relationship between vegetation and runoff changes will benefit and improve regional eco-environmental and water resource management.

Paired catchments are widely built to study the relationship between water yield and changes in vegetation. Given this method, a number of studies have focused on the responses of stream flows to changes in land cover, such as clear cutting forests and other different management measures. With more and more studies, the congnition of stream flow responses to changes in vegetation has gradually shifted from qualitative to quantitative investigations (Hibbert, 1969; Bosch and Hewlett, 1982; Bruijnzeel, 1988; Stednick, 1996; Sahin and Hall, 1996). Studies of paired catchments in China started in the 1960 s (Li et al., 2001) and most results are in agreement with that increasing forest cover would decrease annual stream flows, especially in arid and semi-arid regions, such as the Loess Plateau in China (Liu and Zhong, 1978; Liu et al., 1996; Shi and Li, 2001).

Because paired catchments can provide basic data to discover the general rules of runoff responses to changes in vegetation at various temporal scales, they had been used in many regions. In fact, a particular temporal scale could also represent a special spatial scale. Zhang et al. (2001) had shown that space, illustrated in a model at a mean annual scale, is larger than that of Brown et al. (2005) at an annual scale. Some large-scale results are probably different from local investigations in a specific region. But to some extent, they reflect their maximum understanding of the rules in this field at different temporal scales. We combined their analysis and the research undertaken in China, to help to understand these rules of runoff responses to changes in vegetation. For many years, a large difference of opinion has dominated the argument whether or not vegetation changes alter precipitation. Generally, forest cover can effect precipitation by energy feedback between land and the atmosphere at a continental scale, but this concept is not supported at the level of a watershed (Calder, 1999). In our study, precipitation is regarded as independent of vegetation types.

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## 2 Regional evapotranspiration estimation at mean annual scale

The evapotranspiration from land surfaces is assumed to be mainly controlled by the availability of water, which can be approximated as precipitation and by atmospheric demand, which is often considered as potential evapotranspiration (Budyko, 1958). Under very dry conditions, all precipitation would be consumed in evapotranspiration processes where the evaporation coefficient is approximately 1 and the dryness index tends towards infinity. Under very wet conditions, water availability exceeds potential evapotranspiration and the actual evapotranspiration will asymptotically approach the potential evapotranspiration. Then, the dryness index approaches 0. The actual situation in an average area is between these two extremes. Based on this recognition, Zhang et al. (2001) used the Priestley-Taylor formula to estimate potential evapotranspiration to represent regional atmospheric demands and established the concept model to estimate regional evapotranspiration in consideration of the impacts of permanent vegetation changes. Furthermore, Zhang et al. (2001) applied the data from 257 paired-catchment and time-trend studies, conducted in 29 countries, tested and obtained corresponding values of the land surface parameter (*w*) representing the effects of different land surfaces. For forests, *w* is approximately 2.0, and for grass, *w* is 0.5. The curves in Fig. 1a illustrated the mean annual stream flow responses to the changes in vegetation using the precipitation gradient from the model by Zhang et al. (2001).

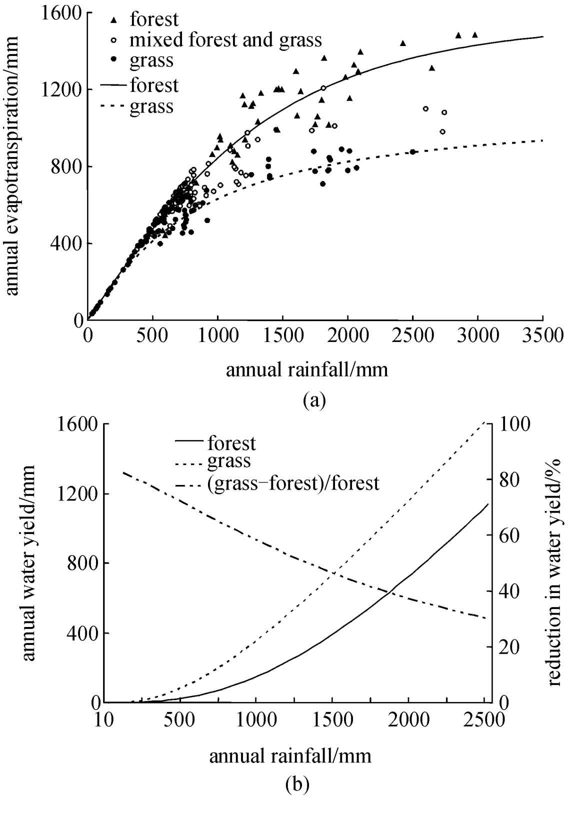


**Fig. 1** Change of hydrological cycle elements after permanent vegetation changes with precipitation gradient on mean annual scale. Source: Zhang et al. (2001). (a) Response curve of evapotranspiration, (b) response curve of water yield.

At a mean annual temporal scale, Zhang's curves not only describe the quantitative relation of stream flow responses to changes in vegetation in a specific precipitation area, but also implied the extent of stream flow changes due to vegetation conversion in regions with different precipitation. Figure 1b shows that the stream flow responses are very different from dry areas to wet conditions due to permanent vegetation changes. Quantitatively, the drier it becomes, the slighter the extent of vegetation changes on runoff. Conversely, the wetter is, the greater the extent. Qualitatively, the extent of the effect on runoff in dry areas from grass land to forest land is much more severe than in wet areas. This result has been validated by investigations in different regions. In the arid and semi-arid areas of the Loess Plateau, the accumulative runoff was reduced by 35%–70% after afforestation in a paired-catchment study (Wu and Zhao, 2001; Wang et al., 2004). While in humid areas like India, the runoff would be reduced by only 16%–25% (Samraj et al., 1988; Sharda et al., 1998).

## 3 Annual runoff response time to vegetation changes

The response time can be defined as the time taken for the annual catchment yield to reach a new equilibrium state after vegetation changes (Brown et al., 2005). It is very important to understand the annual water yield response time in vegetation management and water resource allocation. From investigations in different regions, the trend in annual water yield and response time can be summarized from forest cutting to afforestation and natural restoration.

### 3.1 Forest cutting experiment

Hornbeck et al. (1993) arrived at conclusions about the long-term effect of forest treatment on water yield in the USA under different climatic regions, using paired-catchment data (Fig. 2). Figure 2 shows that the initial increase occurred promptly after four different types of forest clearing, due to reduced interception and transpiration. The increase in stream flow diminished in about 10 years, due to the increased evapotranspiration of regrowth, compared to the old growth forest (M4). Reduction in stream flow occurred after about 15 years (HB2). Stream flow increases can be prolonged by controlling the regrowth. In the experiments, the F7 and LR2 types, both of which experienced different area management in different sections of the catchment area in different periods, the water yield returned to pre-disturbance levels after about 27 years.

## 3.2 Afforestation experiment

Using data from South African afforestation experiments, Scott and Smith (1997) developed a series of generalized curves to predict the impact of pine and eucalyptus afforestation on annual total and low flows as a function of plantation age, species planted and site suitability as shown in Fig. 3. Figure 3 shows that in these plantations, both total flows and low flows reached their new equilibrium levels after 15–20 years. On the other hand, the impact of afforestation on annual flow was more serious under optimal land conditions than under suboptimal land conditions. The extent of low flow responses to afforestation, regardless of planting type or land conditions, was more severe than that of total flow.

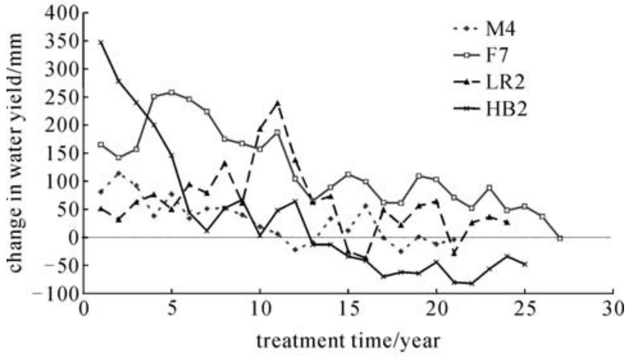


**Fig. 2** Changes in annual water yield from experiments in four catchment areas, with different treatments in the USA. Note: M4, 100% basal area cut; HB2, 100% clear felled then herbicide application on entire catchment; F7, upper half clear cut (year 0), herbicides on upper half (2–7), lower half cut (year 4), herbicide on entire catchment area (5–7); LR2, lower 24% clear cut (year 0), mid slope 27% clear cut (year 4–5), herbicide on lower and mid slope (year 7), 40% upper slope clear cut (year 8–9), herbicide application on entire catchment area (year 10) (Hornbeck et al., 1993).

In arid and semi-arid areas, it took more time for the response of stream flow to a new equilibrium level. In the paired-catchment study in the Loess Plateau, with a mean annual precipitation of 562 mm, it took more than 25 years for total flow to reach its new equilibrium level after afforestation (Fig. 4) (Huang et al., 2003).

## 3.3 Natural forest regeneration

The responses time to changes in vegetation is significantly different in natural forest regrowth from that in afforestation measures. Mountain ash forests, more than 200 years old and confined to the wetter parts of south-eastern Australia, are growing at elevations between 200 and 1000 m where mean annual rainfall exceeds 1200 mm and the mean annual water yield is 1195 mm. After bushfires, hundreds of seeds germinate per hectare and the intense competition

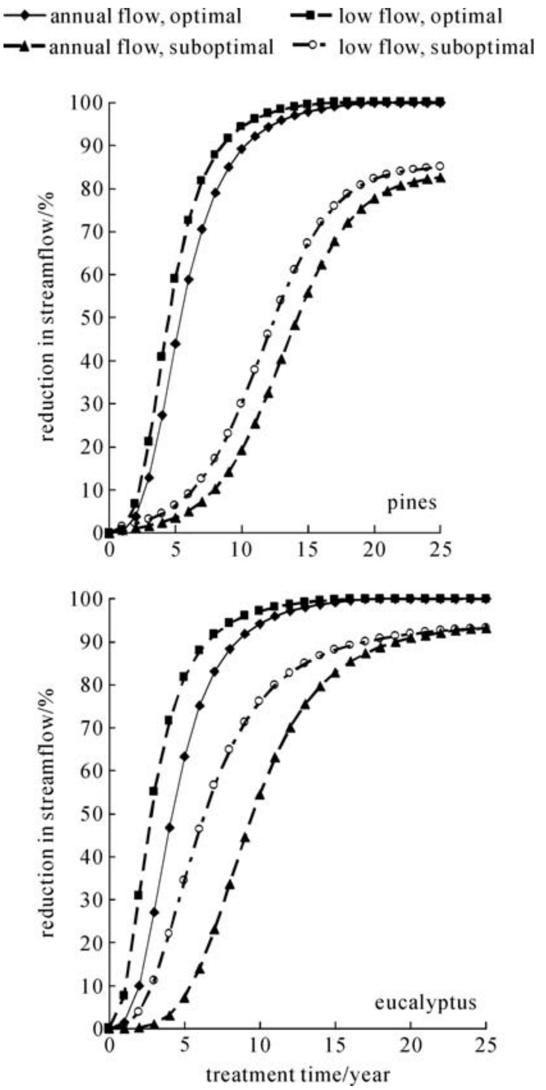


**Fig. 3** Generalized curves from estimating the percentage reduction in total and low flow after afforestation with pine and eucalypt in South Africa (Scott and Smith,1997)

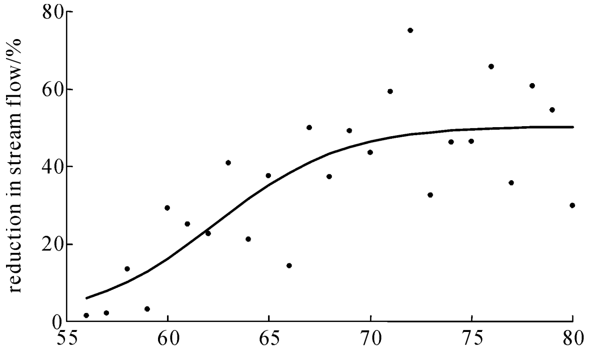


**Fig. 4** Reduction of annual runoff by afforestation in paired catchments experiments in the Loess Plateau (Huang et al., 2003)

between plants for light results in rapid tree growth and natural thinning of weaker trees. The "Kuczera curve", as shown in Fig. 5, describes the relationship between stand age and annual water yield (Kuczera, 1987; Vertessy et al., 2001). It is clear from Fig. 5 that after burning and full regeneration of mountain ash forests, the water yield is reduced to 580 mm at age 27. After 27 years, it takes about 150 years for the mean annual water yield to increase and return to pre-disturbance levels. There is significant evidence showing that the water yield volume from the catchment area is closely linked with stand age and its growth stage. The reduction intensity exerted by forest regeneration to water yield is much more severe when the trees become mature and approach the maximum primary productivity, than when the forest turns senescent (Wu and Zhao, 2001).

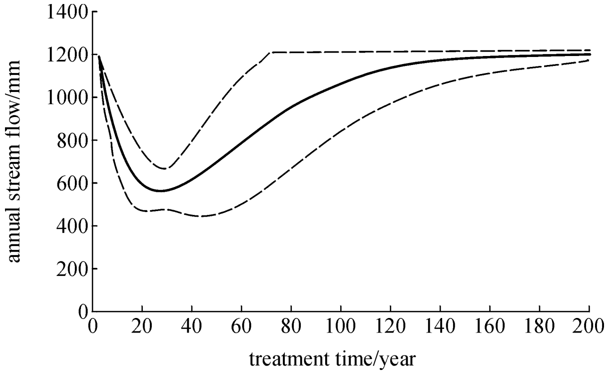


**Fig. 5** Empirical relationship between age of mountain ash forest and average annual water yield in Australia. (Note: Dashed lines indicates 95% confidence limits) (Vertessy et al., 2001)

### 3.4 Runoff responses to processes from forest cutting to afforestation

As a summary of these investigations, we can state that, after the original forests are disturbed with various treatments, water yield in a catchment would increase promptly and the response time for annual stream flow returning to pre-disturbance level varied largely due to the different types of treatment and their intensity. With clear-cut forest management, it may take about 10 years for the streamflow to return its previous level. With the treatment of cutting at different sections of the catchment area, it requires more time. With afforestation, it took about 15–20 years after full forest restoration. However, in arid and semi-arid areas, it needs more than 25 years. With natural regeneration, it requires about hundred years for the stream flow to reach a new equilibrium. Although the response time varies with changes in physical conditions, such as climate, landscape and soil types, the conceptual curve could be achieved as shown in Fig.6.

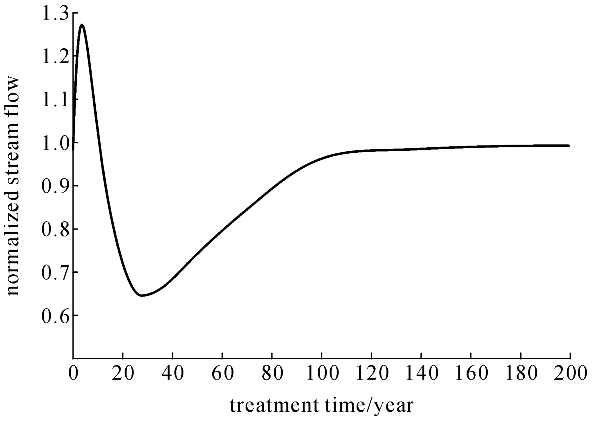


**Fig. 6** Empirical curve of annual water yield following cutting from original woodland, then afforestation or natural restoration

## 4 Seasonal water yield response to vegetation change

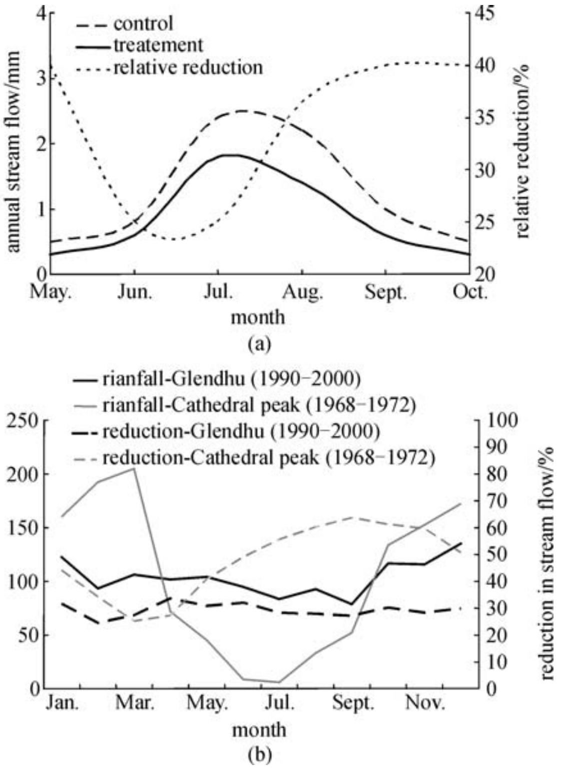
Due to the qualitative and graphical nature of many of the seasonal flow results reported in the literature, no generalizations have been made on the responses in seasonal water yield to changes in vegetation. Table 1, adapted from Brown et al. (2005), was used to summarize the observed seasonal changes in water yield. The absolute and proportional changes in water yield have important implications in water resources management. Absolute responses refer to the total volume change, while proportional response refers to the change with respect to the flow under the original vegetation type.

**Table 1** Seasonal responses in water yield to changes in vegetation (adapted from Brown et al. (2005))

| climate | absolute response | proportional response |
|---|---|---|
| tropical/summer dominant rainfall | larger changes in summer months, when rainfall is greater than monthly average | two types of responses observed: (1) similar changes in all months (2) larger changes in winter months, when rainfall is below monthly average |
| winter dominant rainfall | largest changes in winter months when rainfall in above monthly average | largest change in summer months when rainfall is below monthly average |
| uniform rainfall | uniform change across all seasons | with deciduous vegetation there is a larger change during the spring months. evergreen vegetation shows uniform change across all seasons. |
| snow affected catchment | largest changes in winter months when rainfall in above monthly average | largest change in summer months when rainfall is below monthly average |

Figure 7a is an example of the type of responses for climate to summer dominant rainfall. At the Loess Plateau, with a monsoon type of climate, the absolute reduction in stream flow was observed mainly in the summer from June to September, while in the winter months, the proportional reduction was larger (Huang et al., 2003). In regions with a winter dominant rainfall, the characteristics of stream flow responses to vegetation changes are similar to those in regions with a summer dominant rainfall, such as the Cathedral Peak catchment area in South Africa (Fig. 7b). In the region with a reasonably constant rainfall throughout the year, a constant reduction in stream flow was observed, as in the Glendhu catchments in New Zealand in Fig. 7b.

In summer dominant rainfall catchments, the maximum potential evapotranspiration results from the highest interception and evapotranspiration in the vegetation growing season occurs during the period of highest rainfall and leads to a large, absolute stream flow reduction. In the winter with low rainfall, the greater interception and soil moisture stores from forest stands that were previously grassland, probably leads to a proportionally larger reduction in stream flow. In a rainfall uniform distribution area, evergreen land cover results in uniform interception and evapotranspiration throughout the year and uniform changes in stream flow were observed over a number of years. However, the various combinations of forest types and establishment, soil type and depth, precipitation features can result in other stream flow response characteristics. For example in summer dominant rainfall catchments in India with high precipitation, both the absolute and proportional stream flow reductions were observed uniformly across the entire year (Sharda et al., 1998).



(a)

(b)

**Fig. 7** Seasonal impact of revegetation on streamflow in different climate regions. (a) dominant summer rainfall (Huang et al., 2003); (b) dominant winter rainfall and uniform rainfall across year (Brown et al., 2005).

## 5 Flow duration curves

The impact of vegetation changes on flow regimes can be depicted by the flow duration curve (FDC) of a catchment. The FDC for a catchment provides a graphical summary of the stream flow variability at a given location. The shape of FDC is determined by rainfall patterns, catchment size and the physiographic characteristics of the catchment and is also affected by water resource development and changes in land use/cover.

Figure 8a depicts the change in flow regime with daily data for the paired-catchments in the Loess Plateau (Huang et al., 2003). After afforestation, the FDC in the high flow section was reduced by 20% and an even greater reduction occurred in the low flow section leading to increased numbers of zero-flow days. Figure 8b describes the FDC graphics for the Red Hill catchment in southeastern Australia, which was planted with pines on what was previously grassland (Vertessy, 2000). FDCs in the first year with precipitation of 887 mm and the 8th year with 879 mm, indicates that there was approximately a 50% reduction in high flow sections, while there was a 100% reduction in low flow sections.

Figure 8c shows the changes in FDC in the Glendhu catchments in New Zealand where the rainfall is uniform across the year (Brown et al., 2005). The control and treated catchments have a mean annual rainfall of 1310 and 1290 mm, respectively. Unlike the paired-catchments in the Loess Plateau and Red Hill, the control and treated FDC are similar for all sections with an approximate 30% reduction in both low and high flows as a result of vegetation change.

## 6 Conclusions and discussion

### 6.1 Conclusions

We have summarized the generalization of stream flow responses to permanent vegetation changes at different temporal scales from paired-catchment studies.

At a mean annual scale, the model by Zhang et al. (2001) represents the trend of change of evapotranspiration and stream flow at a precipitation gradient due to changes in vegetation. When grassland changes to permanent forests, the absolute reduction in mean annual water yield in a high rainfall region is much greater than that in a low rainfall region, while the proportional reduction is reversed.

At an annual scale, the stream flow needs a period of time to reach a new equilibrium for both afforestation and

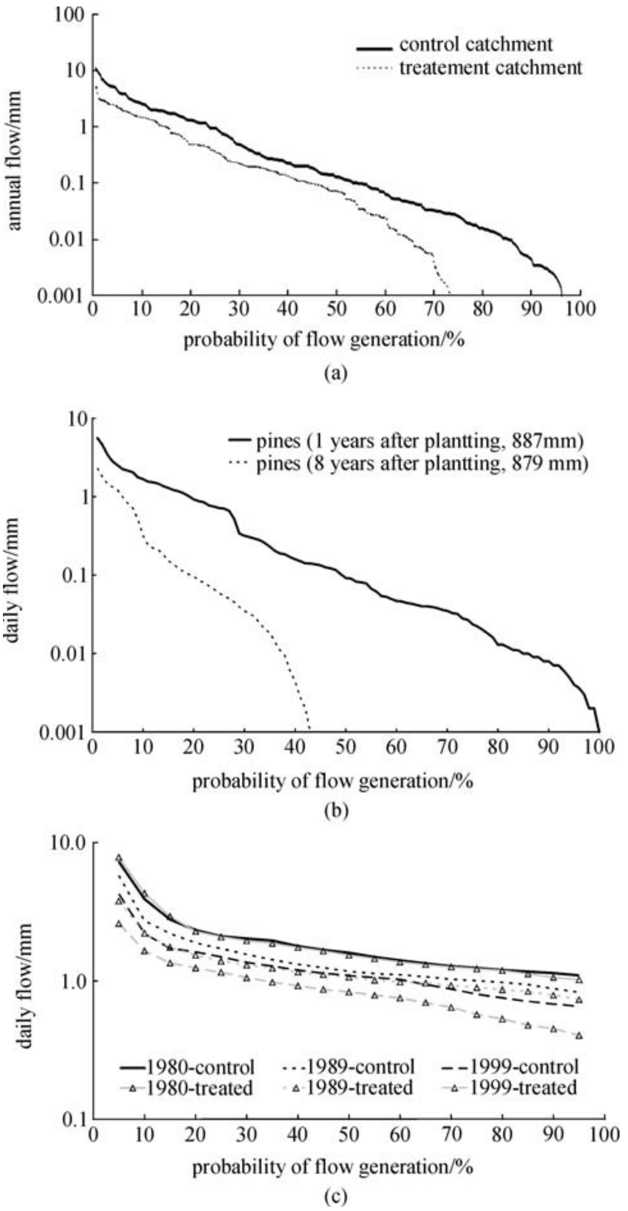


**Fig. 8** Impact of revegetation on flow duration curves in different climate regions. (a) dominant summer rainfall (Huang et al., 2003), (b) dominant winter rainfall (Vertessy, 2000), (c) uniform rainfall across the year (Brown et al., 2005).

deforestation, while the response time is longer for afforestation measures. Generally, deforestation causes stream flow to increase promptly and it takes about 10 years for stream flow to reach a new equilibrium with forest regrowth. With afforestation, it takes about 15–20 years or longer in arid regions for stream flow to reach a new equilibrium. Under natural restoration, it takes about a hundred years.

The types of seasonal stream flow responses vary with afforestation due to different conditions of precipitation, soil type and landscape. Generally, in the region with monsoon effects, an absolute stream flow reduction is observed during the growing season, while the proportional reduction is reversed. In a region with uniform rainfall across years, the stream flow reduction is uniform across the years. FDCs show that the relative changes in low flow section in arid and semi-arid areas are of much greater importance compared with that in high flow sections, leading to an increased number of zero-flow days. However, in humid regions, changes in runoff tend to be much more uniform.

## 6.2 Discussion

### 6.2.1 Application of paired catchment study results

Paired-catchment studies include the use of two catchments which are located adjacent to or in close proximity to each other and with similar characteristics in terms of slope, aspect, soils, area, climate and vegetation. As an effective study method, the advantage of paired-catchment studies is that climate variability can be accounted for in the analysis. The changes in water yield can then be attributed to changes in land use/cover, such as changes in vegetation. However, scaling the results to larger catchments is still a major problem for these studies because areas subject to vegetation change are likely to be patchy and relatively small compared to the overall catchment size. However, given a reasonable hypothesis, generalizations from small catchment experiments are possible for use on a regional scale. For example, Scott et al. (1998) used the generalized curves of Scott and Smith (1997) (Fig. 3) for annual reduction in water yield, to determine the likely change in water yield on total runoff and low flows at a regional scale as a result of afforestation in South Africa. Adapting the Holmes and Sinclair curves (1986) to establish the relations between water yield and precipitation under different vegetation and land cover conditions, Vertessy et al. (1999) estimated the likely changes in mean annual water yield in the Murrumbidgee catchment in Australia, due to afforestation in the middle reaches. Mundy et al. (2001) developed a model using results from paired-catchment studies of the Red Hill and Karuah to simulate the temporal changes in stream flow associated with afforestation of existing grassland and the subsequent management of the forest for timber harvesting for the Adjungbilly catchment (389 km$^2$) in Australia.

### 6.2.2 Application of mean annual water balance model by Zhang et al. (2001)

The model by Zhang et al. (2001) depicts the responses of stream flow to permanent changes in vegetation at a mean annual scale and provides a useful method to estimate the changes in water resources at a regional level. The curves of Zhang et al. (2001) are obtained from the results of paired-catchments studies in regions with different rainfall and the parameter representing land cover effects indicates this responses at a macro spatial and temporal scale. For one specific catchment, the effects of landscape and soil characteristics would be much more important for water yield. The parameter indicating land cover properties must be calibrated using local condition to obtain locally suitable curves.

### 6.2.3 Annual stream flow response time and FDC

The stream flow response time is closely linked to the growing stage of vegetation. So, understanding the response time for changes in stream flow from the original forest to undertaking cutting and regeneration is helpful and useful to understand the complex inter-processes of eco-hydrology and the sustainability of ecological establishments in China. FDC studies provide a tool to estimate the flow regime changes. FDCs can be constructed using multiple temporal scales of stream flow data: annual, monthly or daily flows. Comparisons between FDCs make the stream flow responses due to changes in vegetation much clearer.

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