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Does non-stationarity induced by multiyear drought invalidate the paired-catchment method?

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Abstract. Multiyear drought has been proved to cause non-stationary rainfall-runoff relationship. But whether this change can occur in catchments that have also experienced vegetation change and whether it invalidates the most widely used methods (the paired-catchment method (PCM), the time-trend method (TTM), and the sensitivity-based method (SBM)) for estimating impacts of vegetation change on runoff is still unknown and rarely discussed. In the Red Hill paired experimental catchments in Australia, which has experienced a 10-year drought (2000-2009) and afforestation, estimated inconsistent afforestation impacts were 32.8%, 93.5%, and 76.1% of total runoff changes by the PCM, TTM and SBM, respectively. In addition to afforestation, multiyear drought has also led to the non-stationary rainfall-runoff relationship of the paired catchments. For the TTM and SBM, traditional application did not further differentiate different drivers of non-stationary rainfall-runoff relationship, which led to significant overestimation of afforestation effects. A new framework was proposed to separate the effects of three factors on runoff changes including vegetation change, climate variability and multiyear drought caused non-stationarity. Based on the new framework, impacts of afforestation on runoff were 38.8% by the TTM and 21.4% by the SBM, agreeing well with that by the PCM (32.8%). Using paired-catchment observations, this study proved multiyear drought can induce non-stationary rainfall-runoff relationship and proposed a new framework to better separate the impact of vegetation changes on runoff under climate-induced non-stationary condition. More importantly, paired-catchment method is proven to be still the most reliable method even the control catchment experienced climate-induced shift in rainfall-runoff relationship.

1 Introduction

Vegetation change can exert significant impacts on catchment runoff (Farley et al., 2005; Filoso et al., 2017; Hallema et al., 2018). In addition to vegetation change, climate variability can also cause changes in catchment flow regimes and water yield (Kim et al., 2011; Ryberg et al., 2012). Understanding of the response of runoff to vegetation change was mainly gained through the use of paired catchment experiments over the past century (Wei et al., 2018). The paired catchment method (PCM), which is the standard approach for quantifying the effects of forest management on runoff, is based on paired catchment experiments and is still used today. However, separating the effects of vegetation change and climate variability on runoff remains a great challenge due to the complex interactions between climate variability and vegetation change (Bosch and Hewlett, 1982; Jones et al., 2006; Lee, 1980). Moreover, persistent hydroclimatic non-stationary changes observed during the past few decades have increased both temperatures and occurrences of extreme weather events (such as multiyear drought). These changes have led to non-stationary rainfall-runoff

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relationships in many catchments around the world (Li et al., 2018; Wang et al., 2013; Zhang et al., 2016). Therefore, the combined effect of these influencing factors will lead to greater uncertainty in estimating the impact of vegetation change on runoff using different methods. In particular, is the paired catchment method still valid under non-stationary rainfall-runoff relationships?

Hydroclimatic non-stationary changes such as multiyear drought-induced non-stationarity in rainfall-runoff relationships has been reported in some catchments around the world, such as with the 2014 California drought in the United States (Griffin and Anchukaitis, 2014) and with the 2010 drought in Amazonia (Lewis et al., 2011). It is widely known that Australia experienced multiyear drought (known as the Millennium Drought) between 1997 and 2009 (van Dijk et al., 2013). Some studies have also reported that stationary rainfall-runoff relationships in southeast regions of Australia were broken by the multiyear drought (Chiew et al., 2014; Petrone et al., 2010; Saft et al., 2016). Multiyear drought can lead to shift in catchment rainfall-runoff relationship (or non-stationarity) as vegetation change and thus pose great challenges to the basic idea of the PCM and how to separate the effects of vegetation change under multiyear drought conditions.

Three commonly used methods for separating the impacts of vegetation change on catchment water yield are the PCM, TTM, and SBM. The PCM requires a control and treated catchment located in close proximity and the primary role of the control catchment is to eliminate the impact of climate change on runoff. Essentially, observations from the control catchment can remove the effect of all factors that lead to change in rainfall-runoff relationship except the vegetation change between two paired catchments. This method has been applied in many paired catchments around the world to provide fundamental understanding and knowledge for water resource management under vegetation change (Brown et al., 2005; Lee, 1980). The time-trend method (TTM) assumes that rainfall-runoff relationship driven by climate variability during post-change period is stationary. Thus the impact of vegetation change on runoff is obtained as the difference between observed runoff during post-change period and estimated runoff based on the rainfall-runoff relationship obtained during the pre-change period (Lee, 1980; Zhang et al., 2019; Zhao et al., 2010). The sensitivity-based method (SBM) is a combination of the Budyko framework (Budyko, 1974) and the elastic response of runoff to rainfall and potential evapotranspiration developed by Zhang et al. (2001). The direct result from the SBM is runoff changes caused by climate variability, and the effect of vegetation change on runoff is derived by subtracting the effects of climate variability on runoff from total runoff changes. Generally, the PCM, TTM and SBM should provide consistent results for a specific catchment where non-stationary change in rainfall-runoff relationship is only affected by vegetation change. Zhang et al. (2011) applied the TTM and SBM to 15 catchments in Australia and demonstrated that this two methods yielded similar estimates with differences smaller than 25%.

However, the Red Hill catchment (treated catchment for afforestation), which is located in the southeast Australia, has experienced multiyear drought. Based on the data from 1990-2009 including the Millennium Drought period, Zhao et al. (2010) showed that estimated contributions of afforestation to the decrease in runoff between pre- and post-change periods using the PCM is only 27%, which was even smaller than ½ of estimated contributions derived using the other two widely used methods (71% for the time-trend method (TTM) and 57% for the sensitivity-based method (SBM)). In addition to vegetation change, multiyear drought may also cause non-stationary change in rainfall-runoff relationship, which may undermine prior assumptions of three widely used methods resulting inconsistency in their results. However, the issue about this hypothesis has not been explored and verified, and it is important for ecological engineering to examine whether non-stationarity induced by multiyear drought invalidate the PCM and the applicationablity of the three widely used methods under changing climate with frequent extremes in future. If this hypothesis is proved to be correct, it will require us to propose a new method to solve this problem. Red Hill paired experiments provides a very good case study to investigate this issue. The primary objectives of this study are: (1) to detect whether multiyear

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drought has induced non-stationarity in the rainfall-runoff relationship of the Red Hill paired experimental catchments; (2) to test whether multiyear drought undermine prior assumptions of three widely used methods and is the reason for inconsistency amongst three widely used methods; and (3) to develop a new framework for separating the effects of vegetation change and other influencing factors on runoff under non-stationary conditions.

2 Paired Catchments and Data

The Red Hill catchment (1.95 km^2) and the Kileys Run catchment (1.35 km^2) were paired catchments located northeast of Tumut in New South Wales, Australia (35.322ºS, 149.137ºE) (Fig. 1). The catchments are adjacent, and the soil types, topographic characteristics, and climatic conditions are similar. The main soil types are shallow red soils and red duplex (Major et al., 1998). The topography is rolling or undulating with mostly gentle slopes in Kileys Run. The climate of the two catchments is temperate with highly variable and winter-dominated rainfall. Red Hill was the treated catchment, which was converted from grassland into a *Pinus radiata* plantation in 1988 and 1989 (Bren et al., 2006). The neighboring catchment (Kileys Run) was the control catchment, which was kept as grassland over the entire observation period.

Daily rainfall and runoff from the two catchments were collected during the period of 1990–2015. Mean annual rainfall and mean annual runoff of the Red Hill catchment were 817 mm and 75 mm, respectively, during the study period. Mean annual rainfall and runoff were 817 mm and 161 mm, respectively, in the Kileys Run catchment over the same period. Monthly potential evapotranspiration records were obtained from the SILO Data (www.longpaddock.qld.gov.au/silo/point-data/). Figure 2 shows the Kileys Run rainfall anomaly that was calculated by the method proposed by Saft et al. (2015). It can be seen that Kileys Run experienced a multiyear drought that lasted 10 years from 2000 to 2009 and this coincided with the period of the Millennium Drought.

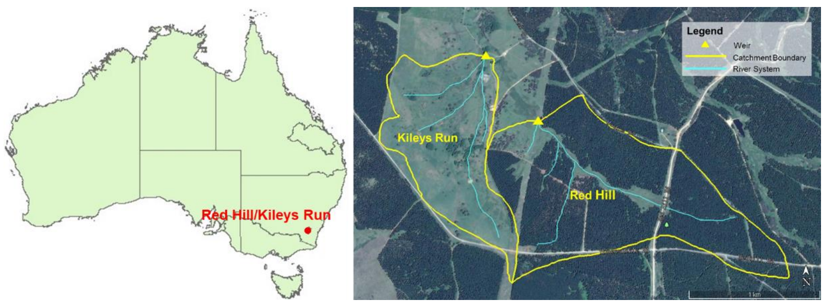

Figure 1: Location and satellite remote sensing image map of the Red Hill/Kileys Run catchment in New South Wales, Australia (© Google Earth).

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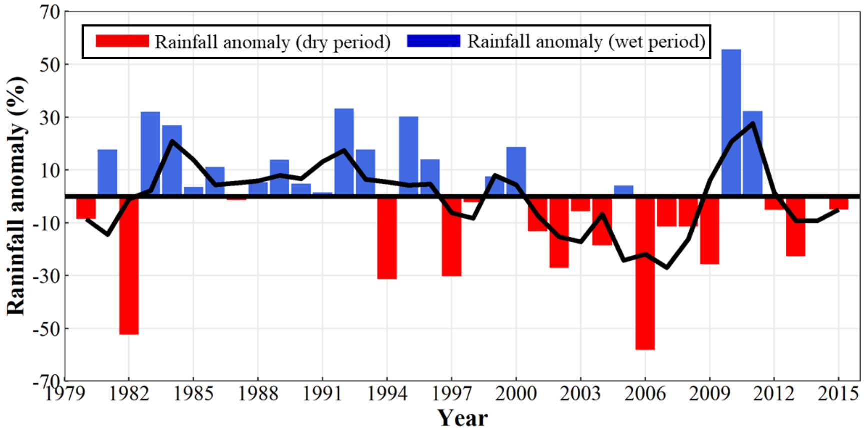

Figure 2: Rainfall anomaly as a percentage of the mean annual rainfall of the Kileys Run and Red Hill catchment, New South Wales, Australia. Red bars represent dry years and blue bars represent wet years. The black line represents the three-year moving average of the rainfall anomaly.

3 Methods

3.1 Detecting non-stationarity in the rainfall-runoff relationship

The Mann-Kendall test (Kendall, 1975; Mann, 1945) was used to detect the long-term trend in time series and the Sen's slope estimator was used to obtain the slope (Sen, 1968). Various studies reveal that Mann-Kendall is one of the most frequently used statistical methods for identification of monotonic trends in hydro-meteorological data such as water quality, runoff, temperature and precipitation (Peng et al., 2020). The Pettitt method (Pettitt, 1979) is a rank-based nonparametric statistical test method and has been used to detect a change point in time series data.

Double mass curve (DMC), flow duration curve (FDC), and rainfall-runoff linear regression curves were employed to detect changes in the rainfall-runoff relationship. A break in the slope of the DMC means that a change in the constant of proportionality between rainfall and runoff has occurred. The difference in the slope of the lines indicates the degree of change in the relation and the shift in rainfall-runoff relationship. The FDC represents the relationship between magnitude and frequency of runoff, providing thus an important synthesis of the relevant hydrological processes occurring at the catchment scale (Pumo et al., 2013) and apparent change in the shape of the FDC indicates the change in rainfall-runoff relationship. Moreover, the upward or downward changes in regressed annual rainfall-runoff relationship also can detect the non-stationary rainfall-runoff relationship.

3.2 Traditional methods for quantifying the effects of vegetation change on runoff

For a given catchment, the change in mean annual runoff between two periods can be estimated as:

$$\overline{\Delta Q_t^{total}} = \overline{Q_{t2}^{obs}} - \overline{Q_{t1}^{obs}} \tag{1}$$

where $\overline{\Delta Q_t^{total}}$ represents the total change in mean annual runoff, $\overline{Q_{t1}^{obs}}$ is the average annual runoff during the first period, and $\overline{Q_{t2}^{obs}}$ is the average annual runoff during the second period. In paired-catchment studies, the first period and the second period are usually defined as the calibration period (or pre-treatment period) and the prediction period (or post-treatment period), respectively.

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The total runoff change can be considered to result from vegetation change ($\overline{\Delta Q_t^{veg}}$), climate variability ($\overline{\Delta Q_t^{clim}}$), and hydroclimatic non-stationarity ($\overline{\Delta Q_t^{n}}$). Hydroclimatic non-stationarity can be caused by multiyear drought or other factors. Hence one can write:

$$\overline{\Delta Q_t^{total}} = \overline{\Delta Q_t^{veg}} + \overline{\Delta Q_t^{clim}} + \overline{\Delta Q_t^{n}} \quad (2)$$

Equation (2) has three unknowns and additional relationships are required to attribute the total runoff change to the respective three causes.

3.2.1 Paired-catchment method (PCM)

The PCM assumes that the correlation between runoff in two paired catchments will remain the same if the vegetation cover remains the same or changes in a similar fashion. This correlation is established by regression analysis during the calibration period, and then is used to predict the runoff for the treated catchment during the prediction period. The difference between the measured and predicted runoff of the treated catchment during the prediction period represents the impact of the vegetation treatment (e.g., afforestation, deforestation) on runoff (Bosch and Hewlett, 1982; Lee, 1980; Stoneman, 1993; Williamson et al., 1987):

During the calibration period:

$$Q_{t1}^{obs} = a_1 Q_{c1}^{obs} + b_1 \quad (3)$$

During the prediction period:

$$Q_{t2}^{sim} = a_1 Q_{c2}^{obs} + b_1 \quad (4)$$

$$\overline{\Delta Q_t^{veg1}} = \overline{Q_{t2}^{obs}} - \overline{Q_{t2}^{sim}} \quad (5)$$

where Q_t^{obs} and Q_c^{obs} represent measured runoff from the treated and control catchments, respectively; Q_{t2}^{sim} is the predicted runoff for the treated catchment; subscripts 1 and 2 represent the calibration period and the prediction period; and a_1 and b_1 are the fitted regression coefficients; $\overline{\Delta Q_t^{veg1}}$ is the change in mean annual runoff caused by vegetation change estimated by the PCM. The difference between total change ($\overline{\Delta Q_t^{total}}$) and $\overline{\Delta Q_t^{veg1}}$ of the treated catchment represents the combined effect of climate variability and hydroclimatic non-stationarity (i.e. $\overline{\Delta Q_t^{clim}} + \overline{\Delta Q_t^{n}}$).

3.2.2 Time-trend method (TTM)

The TTM can be applied to a single catchment that experienced vegetation change during two different periods. Runoff without vegetation change can be simulated by using the rainfall-runoff relationship that was developed over the calibration period (Lee, 1980):

During the calibration period:

$$Q_{t1}^{obs} = a_2 P_{t1}^{obs} + b_2 \quad (6)$$

During the prediction period:

$$Q_{t2}^{sim} = a_2 P_{t2}^{obs} + b_2 \quad (7)$$

where P is precipitation; a_2 and b_2 are the fitted regression coefficients.

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When the rainfall-runoff relationship of the treated catchment is not subject to hydroclimatic non-stationarity, the third term of Eq. (2) (i.e., $\overline{\Delta Q_t^n}$) can be ignored and hence the effect of vegetation change on runoff can be estimated as:

$$\overline{\Delta Q_t^{veg2}} = \overline{Q_{t2}^{obs}} - \overline{Q_{t2}^{sim}} \tag{8}$$

where $\overline{\Delta Q_t^{veg2}}$ is the change in mean annual runoff caused by vegetation change estimated by the TTM, Q_{t1}^{obs} and Q_{t2}^{sim} are the same as defined above.

3.2.3 Sensitivity-based method (SBM)

The SBM is widely used to directly estimate runoff change caused by climate variability. Runoff change caused by vegetation change can be estimated by subtracting the runoff change caused by climate variability from the total runoff changes. Runoff change caused by climate variability can be determined by changes in precipitation and potential evapotranspiration (Koster and Suarez, 1999; Milly and Dunne, 2002), expressed as:

$$\overline{\Delta Q_t^{clim}} = \beta \overline{\Delta P_t^{obs}} + \gamma \overline{\Delta PET_t^{obs}} \tag{9}$$

where $\overline{\Delta Q_t^{clim}}$is change in mean annual runoff caused by climate variability; ΔP, and ΔPET are changes in precipitation (P) and potential evapotranspiration (PET), respectively; β and γ are the sensitivity coefficients of runoff to precipitation and potential evapotranspiration, respectively, as estimated in Li et al. (2007) as:

$$\beta = \frac{1 + 2x + 3wx^2}{(1 + x + wx^2)^2} \tag{10}$$

$$\gamma = -\frac{1 + 2wx}{(1 + x + wx^2)^2} \tag{11}$$

where x is the mean annual dryness index (estimated as PET$/P$) and w is a fitted model parameter related to catchment conditions such as vegetation type, soil, and PET. w was set as 1.66 for the Red Hill catchment in this study according to Zhao et al. (2010).

When the rainfall-runoff relationship of the treated catchment is not subject to hydroclimatic non-stationarity, the third term of Eq. (2) can be ignored. Runoff change caused by vegetation change can be estimated by subtracting the runoff change caused by climate variability from the total runoff changes.

$$\overline{\Delta Q_t^{veg3}} = \overline{Q_t^{total}} - \overline{Q_t^{clim}} \tag{12}$$

where $\overline{\Delta Q_t^{veg3}}$ is the change in mean annual runoff caused by vegetation change estimated by the SBM, $\overline{Q_t^{total}}$ and $\overline{Q_t^{clim}}$ are the same as defined above.

The calibration and prediction periods for paired-catchment studies are usually defined by the vegetation change history. However, calibration period data were absent for the Red Hill and Kileys Run catchments because runoff observations started only about one year before the treatment. Therefore, the calibration period and the prediction period were taken as the pre-change period and post-change periods of runoff, respectively, as determined by the step change-point in the runoff of the treated catchment as previous studies on this site. This approximation will have little effect on the results as previous studies have shown that the establishment of the young pine tree plantation at Red Hill had very limited impacts on runoff in the first several years of establishment (Zhao et al., 2010).

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3.3 Proposed new framework for quantifying the effects of vegetation change on runoff under non-stationary conditions

The three methods have been successfully applied to paired-catchment studies to estimate the effect of vegetation change on runoff and there is little difference amongst $\overline{\Delta Q_t^{veg1}}$, $\overline{\Delta Q_t^{veg2}}$ and $\overline{\Delta Q_t^{veg3}}$ in catchments that did not experienced hydroclimatic non-stationarity (Zhao et al., 2010). However, when both catchments (i.e., control and treated catchments) experienced hydroclimatic non-stationarity, the use of the TTM becomes problematic as the rainfall-runoff relationship represented by Eq. (7) does not capture this non-stationarity effect because it is based on the assumption that the rainfall-runoff relationships are stationary with respect to hydroclimatic conditions. The SBM also has similar problems in quantifying the effect of vegetation change. In the case of non-stationarity induced by multiyear drought, the TTM and SBM will overestimate the effect of vegetation change on runoff and the results of this two methods are actually the combined effect of vegetation change and hydroclimatic non-stationarity (i.e. $\overline{\Delta Q_t^{veg}} + \overline{\Delta Q_t^{n}}$). The basic concept of the paired-catchment method is to compare the streamflow of two nearby catchments with similar physical characteristics, one being a control and the other being a treated catchment. The PCM assumes that the control and treated catchments would experience the same conditions or changes except the treatment implemented. To a first approximation, the PCM should provide accurate estimates of the effect of vegetation change even under hydroclimatic non-stationarity because the PCM assumes that the control and treated catchments would experience the same conditions or changes except the treatment of interest.

In previous studies on the Red Hill paired catchment site, the third term ($\overline{\Delta Q_t^{n}}$) in Eq. (2) was ignored, or the second term ($\overline{\Delta Q_t^{clim}}$) and the third term ($\overline{\Delta Q_t^{n}}$) in Eq. (2) were taken as a whole without being separated when the hydroclimatic non-stationarity happened. We proposed a new framework for quantifying the effects of vegetation change on runoff under non-stationary hydroclimatic conditions. The new framework considers three factors that affect runoff: vegetation change, climate variability and hydroclimatic non-stationarity, respectively. For a treated catchment, one can assume that the runoff reduction ($\overline{\Delta Q_t^{total}}$) is caused by vegetation change ($\overline{\Delta Q_t^{veg}}$), climate variability ($\overline{\Delta Q_t^{clim}}$); and hydroclimatic non-stationarity ($\overline{\Delta Q_t^{n}}$). (It is assumed that climate variability does not change the rainfall-runoff relationship. That is to say, climate variability does not alter runoff ratio (or slope between accumulated annual rainfall and accumulated annual runoff) and runoff sensitivity to *P* and PET. For the control catchment, the runoff reduction ($\overline{\Delta Q_c^{total}}$) is mainly caused by climate variability ($\overline{\Delta Q_c^{clim}}$) and multiyear drought ($\overline{\Delta Q_c^{n}}$). The principle of the new framework is shown in Fig. 3.

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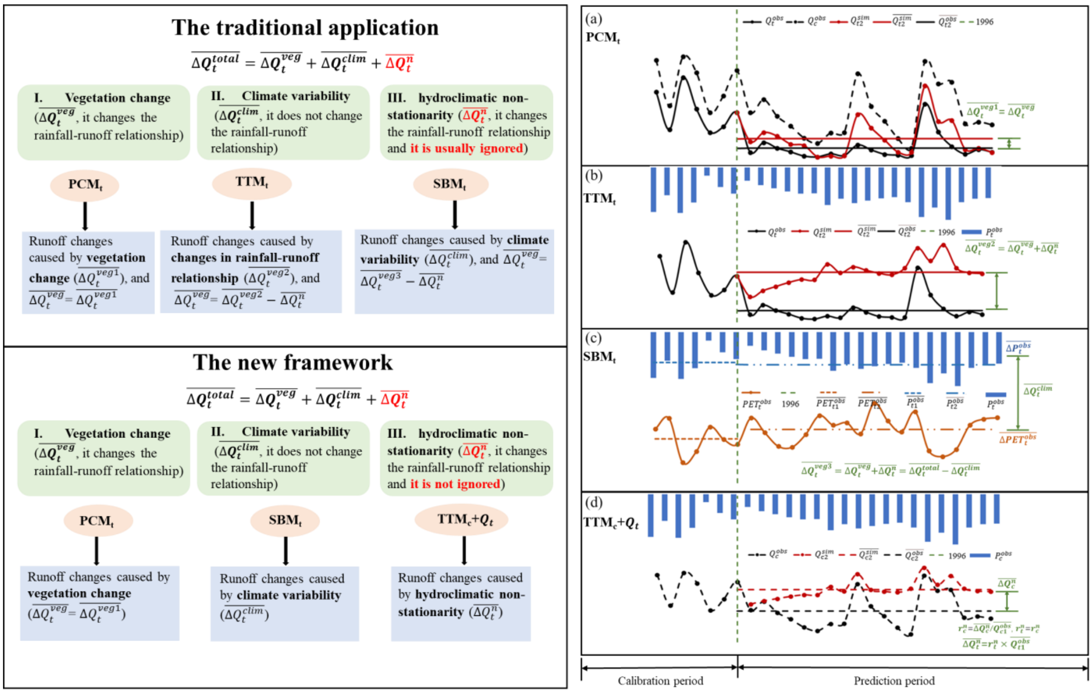

Figure 3: Schematic diagram showing principles of the traditional application and the new framework. PCM means paired-catchment method, TTM means time-trend method, SBM means sensitivity-based method, and subscripts *c* and *t* represent the control catchment and the treated catchment. (a) the PCM for estimating runoff change caused by vegetation change, (b) the TTM for estimating runoff change caused by vegetation change and hydroclimatic non-stationarity, (c) the SBM for estimating runoff change caused by climate variability and (d) the TTM used in the control catchment and runoff of the treated catchment for estimating runoff change caused by hydroclimatic non-stationarity.

3.3.1 Separating the effects of hydroclimatic non-stationarity on runoff

The control catchment is only affected by climate variability and hydroclimatic non-stationarity and the impact of hydroclimatic non-stationarity on runoff can be estimated by the TTM and the runoff and rainfall data. In view of the similarity of the attributes of the control and treated catchments, the impact of hydroclimatic non-stationarity on runoff of the treated catchment can be indirectly abtained by the control catchment and the runoff data.

$$Q_{c1}^{obs} = a_3 P_{c1}^{obs} + b_3 \tag{13}$$

where Q_{c1}^{obs} and P_{c1}^{obs} represent measured runoff and rainfall from the control catchment during the calibration period, respectively; a_3 and b_3 are the fitted regression coefficients.

The simulated runoff not affected by hydroclimatic non-stationarity during the prediction period can be obtained by Eq. (14), while the runoff change caused by hydroclimatic non-stationarity ($\overline{\Delta Q_c^n}$) can be obtained by Eq. (15).

$$Q_{c2}^{sim} = a_3 P_{c2}^{obs} + b_3 \tag{14}$$

$$\overline{\Delta Q_c^t} = \overline{Q_{c2}^{obs}} - \overline{Q_{c2}^{sim}} \tag{15}$$

where Q_{c2}^{obs} and P_{c2}^{obs} represent measured runoff and rainfall from the control catchment during the prediction period, respectively; Q_{c2}^{sim} is the predicted runoff for the control catchment.

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The percentage runoff reduction (r_c^n) caused by multiyear drought in the control catchment can be estimated as:

$$r_c^n = \overline{\Delta Q_c^n} / \overline{Q_{c1}^{obs}} \tag{16}$$

Assumed that the percentage of runoff reduction caused by hydroclimatic non-stationarity is the same for both control and treated catchments (i.e., $r_t^n = r_c^n$) because they have similar physical characteristics. Runoff reduction caused by hydroclimatic non-stationarity in the treated catchment ($\overline{\Delta Q_t^n}$):

$$\overline{\Delta Q_t^n} = r_t^n \times \overline{Q_{t1}^{obs}} \tag{17}$$

3.3.2 Separating the effects of vegetation change on runoff

For the PCM, the actual effects of vegetation change on runoff ($\overline{\Delta Q_t^{veg}}$) is equal to $\overline{\Delta Q_t^{veg1}}$. For the TTM, the actual effects of vegetation change on runoff ($\overline{\Delta Q_t^{veg}}$) is equal to $\overline{\Delta Q_t^{veg2}} - \overline{\Delta Q_t^n}$. For the SBM, the actual effects of vegetation change on runoff ($\overline{\Delta Q_t^{veg}}$) is equal to $\overline{\Delta Q_t^{veg3}} - \overline{\Delta Q_t^n}$. The difference amongst $\overline{\Delta Q_t^{veg1}}$, $\overline{\Delta Q_t^{veg2}} - \overline{\Delta Q_t^n}$ and $\overline{\Delta Q_t^{veg3}} - \overline{\Delta Q_t^n}$ should be small.

3.3.3 Separating the effects of climatic variability on runoff

For the PCM, the actual effects of climate variability on runoff ($\overline{\Delta Q_t^{clim}}$) is equal to $\overline{\Delta Q_t^{total}} - \overline{\Delta Q_t^{veg1}} - \overline{\Delta Q_t^n}$. For the TTM, the actual effects of climate variability on runoff ($\overline{\Delta Q_t^{clim}}$) is equal to $\overline{\Delta Q_t^{total}} - \overline{\Delta Q_t^{veg2}}$. For the SBM, the actual effects of climate variability on runoff ($\overline{\Delta Q_t^{clim}}$) is equal to the result of Eq. (9). The difference amongst $\overline{\Delta Q_t^{total}} - \overline{\Delta Q_t^{veg1}} - \overline{\Delta Q_t^n}$, $\overline{\Delta Q_t^{total}} - \overline{\Delta Q_t^{veg2}}$ and the result of Eq. (9) should be small.

3.3.4 The contribution of climate variability, vegetation change and hydroclimatic non-stationarity to runoff reduction

The percentage contribution of vegetation change, climate variability and hydroclimatic non-stationarity to total runoff reduction can be estimated as:

$$p_t^{veg} = \overline{\Delta Q_t^{veg}} / \overline{\Delta Q_t^{total}} \tag{18}$$

$$p_t^{clim} = \overline{\Delta Q_t^{clim}} / \overline{\Delta Q_t^{total}} \tag{19}$$

$$p_t^n = \overline{\Delta Q_t^n} / \overline{\Delta Q_t^{total}} \tag{20}$$

4 Results

4.1 Detecting non-stationarity in the rainfall-runoff relationships of control and treated catchments

The double mass curve (DMC) of monthly rainfall and runoff of the two paired catchments is shown in Fig. 4 (a) and Fig. 4 (b). The cumulative rainfall-runoff relationship of the two catchments changed significantly twice as seen in the slope changes of the regressions applied to the double mass curve data. Two change points occurred in December 1996 and January 2010 in the Red Hill catchment, and in October 2001 and May 2010 in the Kileys Run catchment. Thus, the entire study period can be divided into three periods in the two catchments, i.e. the first period (January 1990 to December 1996 in the Red Hill catchment and January 1990 to October 2001 in the Kileys Run catchment), the second period (January 1997 to December 2009 in the Red Hill catchment and November 2001 to May 2010 in the Kileys Run catchment), and the third period (January 2010 to December 2015 in the Red Hill catchment and June 2010 to December 2015 in the Kileys Run catchment).

Figure 4 (a) and Figure 4 (b) shows that the slopes and intercepts of the DMC regressions of the two catchments in the different periods were quite different. The slopes of the linear regression lines in the first, second, and third periods were 0.27, 0.11, and 0.19 in the Kileys Run catchment, respectively. And the slopes were 0.21, 0.02, and 0.06 in the Red Hill catchment, respectively. Runoff of the two catchments both experienced a large reduction during the second period (i.e., the period of multiyear drought) and then slightly increased during the third period (i.e., the post-drought period), but still well below the runoff of the first period. And the decrease of runoff or the change of rainfall-runoff relationship in the second period of the Red Hill catchment is much higher than that of the Kileys Run catchment, suggesting that the Red Hill catchment was affected by both vegetation change and the multiyear drought, while the Kileys Run was only affected by the multiyear drought. It showed that the rainfall-runoff relationships of the two catchments became non-stationary during and after the multiyear drought.

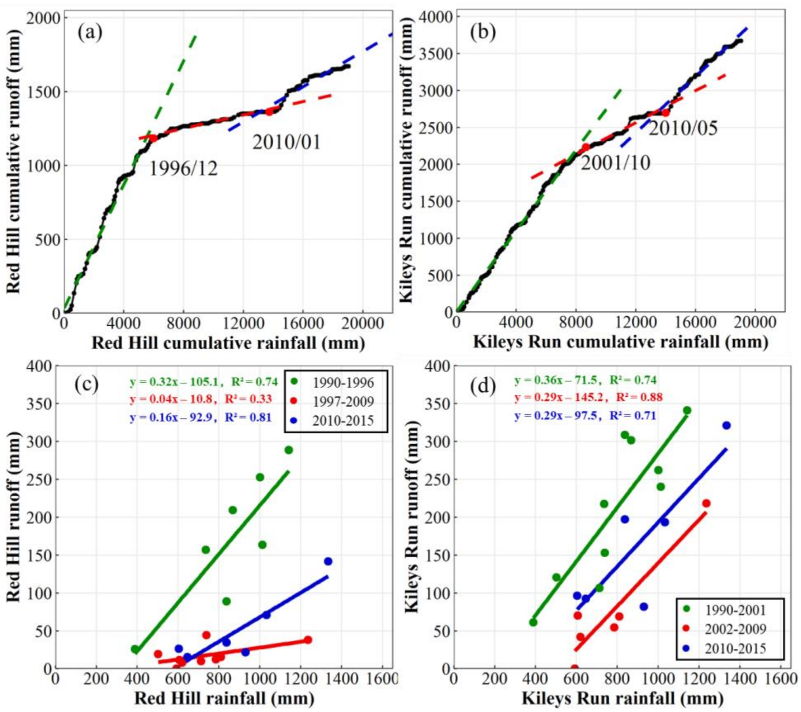

Figure 4: (a) Double mass curve of monthly rainfall and runoff of the Red Hill catchment (treated catchment), (b) Double mass curve of monthly rainfall and runoff of the Kileys Run catchment (control catchment), (c) Relationships between annual rainfall and runoff of the Red Hill catchment (treated catchment), and (d) Relationships between annual rainfall and runoff of the Kileys Run catchment (control catchment), New South Wales, Australia, during the period of 1990–2015. The dashed lines in (a) and (b) represent the linear regression lines between cumulative rainfall and cumulative runoff during three different periods (January 1990 to December 1996 (green), January 1997 to January 2010 (red), and February 2010 to December 2015 (blue) in Red Hill; January 1990 to October 2001 (green), November 2001 to May 2010 (red), and June 2010 to December 2015 (blue) in Kileys Run). The green, red, and blue lines in (c) and (d) represent the linear regression lines for three different periods (1990-1996, 1997–2009, and 2010–2015 in Red Hill; 1990-2001, 2002–2009, and 2010–2015 in Kileys Run).

The linear regression lines defining the relationship between annual rainfall and runoff for the periods of 1990–1996, 1997–2009, and 2010–2015 in the Red Hill catchment and the periods of 1990–2001, 2002–2010, and 2011–2015 in the Kileys Run catchment are shown in Fig.4 (c) and Fig. 4 (d). The differences in the slope and intercept of the Red Hill catchment were −0.28 and 94.3

mm, respectively, between the second and first period, indicating a significant reduction in runoff and a great change in the rainfall-runoff relationship because of afforestation and the multiyear drought during the second period. Runoff of the Red Hill catchment partially recovered during the third period, as shown in Fig. 4 (c). The intercept and slope of the Kileys Run catchment have similar changes, as shown in Fig. 4 (d). These results suggest that the rainfall-runoff relationship of the two catchments experienced considerable change during and after the multiyear drought in the second period.

The daily flow duration curves (FDCs) of the two catchments in three different periods (same periods defined by DMC) are shown in Fig. 5. Zero flows were not observed during the first period (before the drought period), but they were observed in 14% and 8% of the times during the second and third periods (i.e., the multiyear drought period and the post-drought period), respectively in the Kileys Run catchment. But in the Red Hill catchment, zero flows were observed in 3%, 70% and 59% of the times during the three periods, respectively. The FDCs during the first period (green line) were flatter and smoother than the lines for the other two periods, indicating that runoff changes before the multiyear drought period or runoff reached a new equilibrium state were relatively stable and had a stationary relationship with rainfall. However, for most percentages of the FDC during the second period (red line), runoff decreased by more than 50%. Especially low flow decreased most rapidly, and there were 14% and 70% no-flow days. Runoff during the third period (blue line) increased compared with the second period. Especially in the high flow region, daily flow recovered to more than 50% of the runoff that occurred before the multiyear drought, but the low flow increased relatively less, and there were also 8% and 59% no-flow days. In summary, the shape and percentage of the zero flows of FDCs in Fig. 5 further proves that the relationship between rainfall and runoff of the two catchments changed significantly over the three periods, especially for the Red Hill catchment suffered from both the multiyear drought and afforestation.

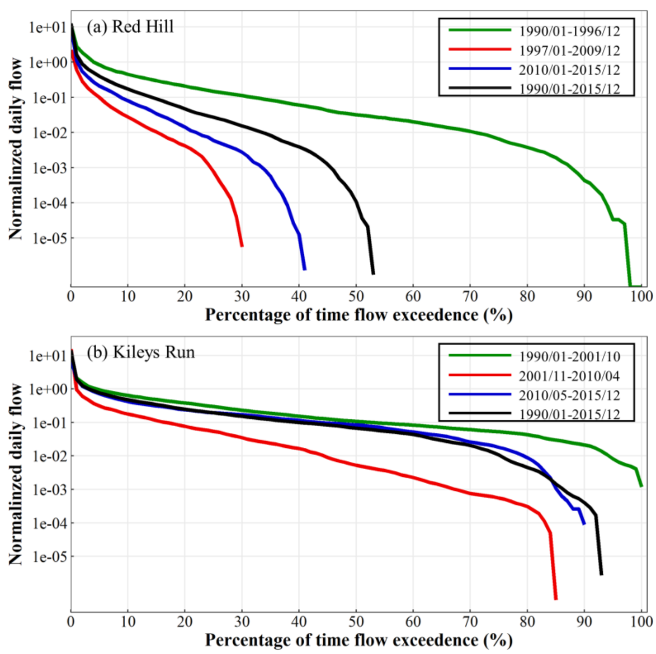

Figure 5: Daily flow duration curves of (a) Red Hill catchment (treated catchment) and (b) Kileys Run catchment (control catchment), New South Wales, Australia, over three different periods.

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4.2 Separated effects of vegetation change using three traditional methods

The statistical information of the trends and change points in annual runoff, rainfall, and PET of both catchments based on observed data from 1990 to 2015 are shown in Table 1. The change point in annual runoff at Red Hill occurred in 1996 and annual runoff decreased significantly after 1996 (β=−5.3, p<0.05). Annual runoff at Kileys Run also decreased, but the reduction was not significant (β = − 8.1, 0.05<p≤0.1). Annual rainfall and PET of two catchments decreased and increased respectively (β=−3.4, β=3.5, p>0.1). Thus, the calibration period was set as 1990–1996 and the prediction period was set as 1997–2015.

Table 1: Estimated trends and abrupt change points in annual runoff (*Q*), precipitation (*P*), and potential evapotranspiration (PET) of the Red Hill and Kileys Run catchments, New South Wales, Australia, during the period of 1990–2015.

Catchment	*Q*			*P*			PET		
	Z	β (mm yr^{-1})	Year[a]	*Z*	β (mm yr^{-1})	Year[a]	*Z*	β (mm yr^{-1})	Year[a]
Kileys Run	−1.9	−8.1*	1996	−0.3	−3.4	1993	1.1	3.5	2001
Red Hill	−2.4	−5.3**	1996*	−0.3	−3.4	1993	1.1	3.5	2001

Note. *** represents *p-value*≤0.01，** represents 0.01<*p-value*≤0.05，* represents 0.05<*p-value*≤0.1. [a]the change point year.

The R^2 values of the monthly runoff-runoff relationship and the monthly rainfall-runoff relationship were 0.82 and 0.52, respectively. The linear relationships were Q_{RH}=0.87× Q_{KR} −3.9 (where Q_{RH} is monthly runoff of Red Hill, Q_{KR} is monthly runoff of Kileys Run), and Q_{RH}=0.28× P_{RH} −6.0 (where P_{RH} is monthly rainfall of Red Hill). These results indicate a good relationship between monthly runoff at these two catchments during the calibration period. Therefore, the relationships can be used to predict runoff of Red Hill during the prediction period and to estimate runoff change caused by vegetation change.

Table 2: Runoff reduction caused by vegetation change, climate variability and hydroclimatic non-stationarity ($\overline{\Delta Q_t^{veg}}$, $\overline{\Delta Q_t^{clim}}$, $\overline{\Delta Q_t^{n}}$) of the Red Hill catchment, New South Wales, Australia, estimated using the traditional methods and the new framework. The bold red numbers represent results that can be calculated directly from the observation data. The bold blue numbers are final results that further calculated by the red bold numbers.

(mm)		Paired catchment method	Time-trend method	Sensitivity-based method
$\overline{\Delta Q_t^{total}}$		138.1	138.1	138.1
A. Traditional methods	$\overline{\Delta Q_t^{veg}}$	**45.3**	**129.1**	138.1-33.0=**105.1**
	$\overline{\Delta Q_t^{clim}}$	138.1-45.3=**92.8**	138.1-129.1=**9**	**33.0**
B. New framework	$\overline{\Delta Q_t^{veg}}$	**45.3**	129.1-75.5=**53.6**	138.1-33.0-75.5=**29.6**
	$\overline{\Delta Q_t^{clim}}$	138.1-45.3-75.5=**17.3**	138.1-129.1=**9.0**	**33.0**
	$\overline{\Delta Q_t^{n}}$	**75.5**	**75.5**	**75.5**
	$\overline{\Delta Q_t^{veg}}+\overline{\Delta Q_t^{n}}$	45.3+75.5=**120.8**	**129.1**	138.1-33.0=**105.1**

Estimated runoff change caused by vegetation change in the Red Hill catchment using the traditional three methods with 26 years of data are shown in Table 2. The total runoff change was −138.1 mm between the prediction and calibration period. By using the PCM, TTM, and SBM, the estimated runoff changes due to vegetation change were −45.3 mm, −129.1 mm, and −105.1 mm, respectively, percentage change of 32.8%, 93.5%, and 76.1%. Clearly, the contribution of vegetation change to the changes in total runoff estimated by the three methods were still quite different. The decrease in runoff caused by the vegetation change estimated

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by the PCM was much lower than that calculated by the other two methods. This inconstancy amongst the three methods is the same as described by Zhao et al. (2010) although a much longer observation period was used in this study.

4.3 Separated effects of vegetation change using the new framework

The results presented in section 4.2 demonstrated that the rainfall-runoff relationship of the control catchment (Kileys Run) was altered by the multiyear drought and the rainfall-runoff relationship of the treated catchment (Red Hill) was altered by both the multiyear drought and afforestation. Based on the new framework, impacts of vegetation change on runoff of the Red Hill catchment were re-estimated using the three methods again, and the results are listed in Table 2. The percentage runoff reduction induced by multiyear drought (r_t^n) is −45%. Runoff changes in rainfall-runoff relationship induced by vegetation change ($\overline{\Delta Q_t^{veg}}$) and multiyear drought ($\overline{\Delta Q_t^{n}}$) are −45.3 mm and −75.5 mm, respectively. Runoff change caused by climate variability ($\overline{\Delta Q_t^{clim}}$) calculated by the SBM is −33.0 mm. The sum of the three terms $\overline{\Delta Q_t^{veg}}$, $\overline{\Delta Q_t^{n}}$ and $\overline{\Delta Q_t^{clim}}$ is −153.8 mm, which is close to the total runoff changes (−138.1 mm). Figure 6 shows the contribution percentage of vegetation change to the total runoff changes estimated using the traditional methods and the new framework. By considering the effects of multiyear drought on the runoff of the treated catchment, apparent large differences amongst the three methods no longer existed by using the new framework. Estimated impacts of afforestation on runoff decreased greatly from 93.5% to 38.8% calculated by the TTM and decreased greatly from 76.1% to 21.4% by the SBM. It shows that new framework can better separate the impact of three factors on runoff.

Based on the above analysis, we found that multiyear drought changed the rainfall-runoff relationships of the control catchment (Kileys Run) and the treated catchment (Red Hill). And differences among the three methods at the Red Hill experimental site were still existed although a much longer observation period was used. The reason for the big difference is that the non-stationary rainfall-runoff relationship of the treated catchment caused by the multiyear drought that was neglected in the TTM and the SBM.

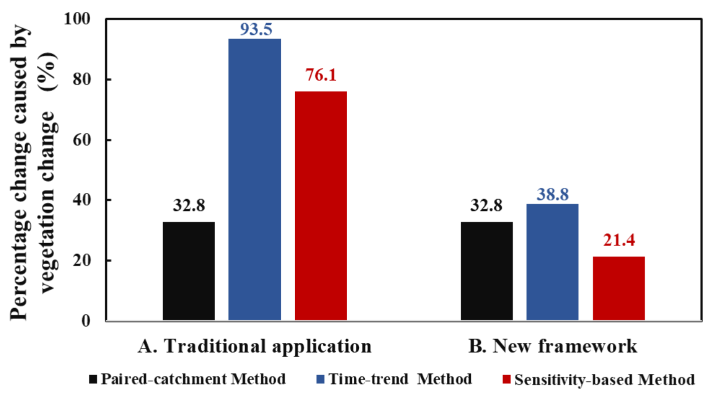

Figure 6: The contribution percentage of vegetation change to the total runoff changes of the Red Hill catchment, New South Wales, Australia, estimated using this three methods under the traditional application and the new framework.

5 Discussion

5.1 Differences in estimated impacts of vegetation change on runoff using three traditional methods

Comparing the results of the traditional application with the result of the new framework, it is found that the TTM and the SBM significantly overestimate the impact of vegetation change on runoff (higher than 100.0 mm). The main reason for this difference is that the runoff change estimated by the TTM and the SBM is caused by the total non-stationary change, and the non-stationary changes are caused by both vegetation change and multiyear drought in Red Hill catchment. That is to say, both TTM and SBM significant overestimate the impact of vegetation change on mean annual runoff as both afforestation and multiyear drought induced runoff decrease.

The response of runoff to vegetation change estimated by the PCM (45.3 mm) is relatively accurate in this study, but the PCM is difficult to further separate the effects of climate variability and multiyear drought on runoff because the total runoff change minus runoff changes directly obtained by PCM is the sum of runoff changes caused by climate variability and multiyear drought. The TTM eliminates the influence of the stationary variation of rainfall-runoff relationship by establishing rainfall-runoff relationship in Red Hill (i.e. treated) catchment. The result of the TTM, which is 2.8 times greater than the result of the PCM (see Table 2), are essentially runoff changes caused by the non-stationary change in the rainfall-runoff relationship induced by vegetation change and multiyear drought. Significant overestimation by the TTM is actually the effect of multiyear drought on runoff. For the SBM, the changes of *P* and PET under the Budyko framework do not cause non-stationary change, so it can directly get runoff change caused by climate variability, and residual runoff changes, which is close to the result of TTM (see Table 2) and is about 2.3 times greater than the result of the PCM, are not only caused by vegetation change, but also by non-stationary changes caused by multiyear drought.

5.2 Multiyear drought induced changes in the rainfall-runoff relationship

According to the results in session 4.2, multiyear drought has led to shift in rainfall-runoff relationship. Specific reasons may be likely the reduction in inter-annual rainfall variability, the changed rainfall seasonality, and the decreased groundwater level (Potter et al., 2010). Inter-annual rainfall variability decreased and high rainfall years were missing during the drought period that may lead to a reduction in rainfall and continuous runoff during the drought period (Fig. 2). Rainfall seasonality during three periods were different (Fig. 7). In Kileys Run and Red Hill catchment, less rainfall in autumn resulted in lower antecedent soil moisture, which means more precipitation were used to replenish the soil water deficit in winter. As a result, the decrease of runoff began to increase in winter and the decrease of rainfall in spring further affected the runoff generation during the drought period, finally resulting in runoff reduction. It is consistent with less runoff during the second period under the same rainfall in Fig. 4. The decline in groundwater levels may also be the reason for runoff reduction. Decline in precipitation usually results in a decline in groundwater levels (Peters et al., 2003), and may cause the connection between groundwater and surface water to be disrupted (Kinal and Stoneman, 2012).

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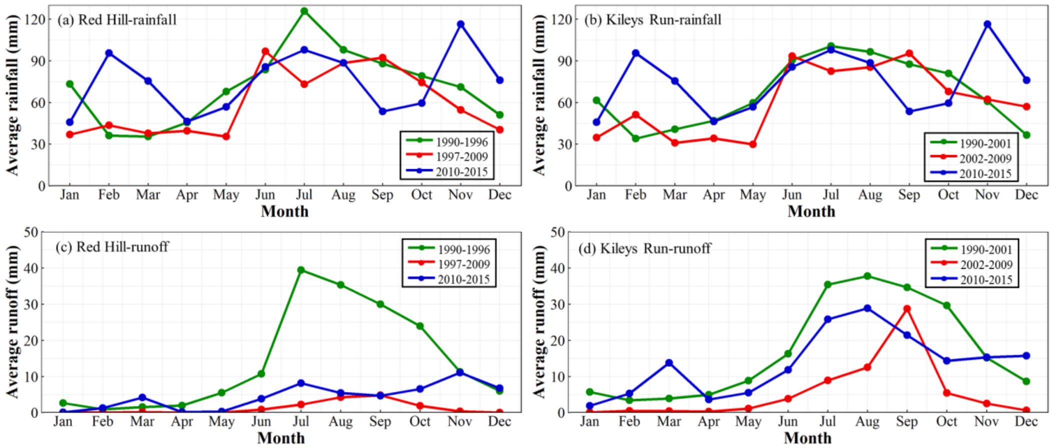

Figure 7: Seasonal changes in (a) monthly rainfall and (c) monthly runoff of Red Hill catchment (treated catchment), (b) monthly rainfall and (d) monthly runoff of Kileys Run catchment (control catchment), New South Wales, Australia, during the three different periods (1990-1996, 1997–2009, and 2010–2015 in Red Hill; 1990-2001, 2002–2009, and 2010–2015 in Kileys Run).

5.3 Application and suitability of the new framework under changing environments

The traditional application of the three methods in catchments experienced multiyear drought may lead to large error because only two factors including non-stationary change (or vegetation change) and stationary change (or climate variability) are considered to affect runoff, which is the essence of the limitations of traditional application. In this study, a new framework is proposed by applying the TTM to the control catchment to quantify runoff changes caused by changes in rainfall-runoff relationship induced by multiyear drought. Compared with the traditional application, the new framework further divides the nonstationary change into two parts driven by vegetation change and multiyear drought separately. Thus runoff changes caused by vegetation change, multiyear drought and climate variability can be partitioned and quantified (Fig. 6 and Table 2). This new framework also confirmed the fact that multiyear drought altered the rainfall-runoff relationship in Red Hill catchment, and multiyear drought weakens the impact of vegetation change on runoff (see Table 2), which is important for us to adopt ecological engineering for sustainable water resources management.

In the new framework, control catchment plays an irreplaceable role in estimating the impact of vegetation change and multiyear drought on runoff. Because control catchment can eliminate the impact of climate variability and multiyear drought on runoff when the PCM is used to quantify runoff change caused by vegetation change, and the impact of multiyear drought on treated catchment is transferred from control catchment. The former must use the runoff data of control catchment, and the latter needs both the rainfall and runoff data of the control catchment.

One of the hypothesizes of the new framework is that the percentage of runoff reduction caused by multiyear drought of control catchment (r_c^n) and treated catchment (r_t^n) is same, and it might need further investigation in the future. The different response mechanism of runoff to multiyear drought in catchments with different properties is complex, it is closely related to climatic conditions, soil moisture, soil condition, groundwater levels, vegetation structure, etc. (Descroix et al., 2009; Stuart-Haëntjens et al., 2018; Yang et al., 2016). Most of the studies are qualitative description of the differences of runoff response in different catchments without quantitative analysis, such as, Jiao et al. (2020) and Liu et al. (2016) found cultivated lands and grasslands showed higher sensitivity to drought than natural biomes and forests exhibited the lowest sensitivity. However, it is difficult to quantify the difference in response to multiyear drought between control catchment and treated catchment, especially when afforestation and multiyear drought occur at the same time. Compared with the runoff change caused by multiyear drought in a single catchment, bias caused by different responses of vegetation cover of paired catchments to multiyear drought should be much smaller than non-stationary changes caused by multiyear drought. Because Saft et al. (2016) found that the percentage of woody cover was not an important factor in predicting shifts in rainfall-runoff partitioning during multiyear drought in south-eastern Australia. Therefore, the hypothesis can be considered reasonable.

5.4 The importance of the paired catchment experiments for estimating the effects of vegetation change on runoff under non-stationary conditions

According to the results of this study, the non-stationary change of rainfall-runoff relationships in this two paired catchments caused by multiyear drought does not invalidate the paired-catchment method. The similar hydrological behavior of the control and the treated catchments in terms of geomorphological, soil properties and climatic conditions determines that these two catchments have a relatively similar response process to multiyear drought and climate variability, which can be seen from the close occurrence time of the second abrupt change point in Fig. 4 (a) and (b). Therefore, the most significant difference between control and treated catchments between pre- and post-change periods is the change of vegetation cover type (control catchment was kept as grassland unchanged and treated catchment was covered by *pine* trees). And the control catchment can eliminate the impact of multiyear drought and climate variability on the treated catchment by establishing the runoff-runoff relationship between this two catchments, so that the PCM can get true runoff change caused by vegetation change. Therefore, the PCM is still a valid and fundamental method estimating the impact of vegetation change on runoff.

The length of data used in this study is extended from 16 years (used in Zhao et al. (2010) study) to 26 years. The difference between the contribution of vegetation change to the changes in total runoff estimated by this study and Zhao et al. (2010) is only 5.8%, which is far less than the difference of the TTM and SBM. It indicates that the PCM not only has good applicability non-stationary conditions, but also has good robustness for different data lengths. And it also shows that the data length has little effect on the estimation of runoff change caused by vegetation change after runoff of catchment experiencing vegetation change reaches a new stable equilibrium state. However, it should be noted that the time required for runoff in different catchments to reach a new equilibrium state is different. For example, Red Hill catchment takes seven years, Australia and New Zealand have suggested that three to 10 years, or even more (18 years for an afforested catchment in Biesievlei, South Africa (Brown et al., 2005)), are required for the treated catchment to reach a reasonably stable rainfall-runoff relationship after vegetation change (Zhao et al., 2010).

6 Conclusions

Through the study of the typical paired-catchment experimental site – Red Hill, we found that multiyear drought during 2000–2009 had altered the stationary rainfall-runoff relationship of both the treated and control catchment. The PCM is not invalidated by the non-stationarity induced by multiyear drought because of the role of the control catchment. However, the essence of the TTM and SBM is to separate runoff changes caused by non-stationary (vegetation change) and stationary (climate variability) changes in rainfall-runoff relationship, which makes the TTM and SBM significantly overestimate the impact of vegetation change on runoff. On this basis, we propose a new framework by applying the TTM to the control catchment to quantify runoff changes caused by changes in rainfall-runoff relationship induced by multiyear drought. The contribution percentage of vegetation change to runoff reduction using the three methods under the new framework become consistent. We proved that the PCM is still a valid and fundamental method estimating the impact of vegetation change on runoff even the control catchment experienced

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hydroclimatic non-stationarity in rainfall-runoff relationship under changing environments. This study provides a new way to more accurately quantify the impacts of vegetation change, climate variability and factors causing non-stationarity except vegetation change on runoff. The findings in this study not only makes up the shortcomings of the application of traditional methods, but also can provide assistance in developing strategies and management practices to ecological engineering under changing climate with frequent extremes in future.

Code and data availability

The daily rainfall and runoff data are provided by Forests NSW (https://www.forestrycorporation.com.au/) and CSIRO (https://www.csiro.au/) in Australia. The monthly potential evapotranspiration data can be obtained from the SILO Data (www.longpaddock.qld.gov.au/silo/point-data/). All analyses were carried out with the open-source software R (https://www.r-project.org/). Code used in this manuscript are available from the corresponding author upon a reasonable request.

Author contributions

YZ conceived the study, performed the analyses and prepared the manuscript. LC contributed to the study design and interpretation of the results. LZ provided data of rainfall and runoff. All the authors reviewed and edited the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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