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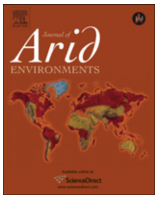

Runoff responses to long-term rainfall variability in a shrub-dominated catchment

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ABSTRACT

In this study we investigate how rainfall has changed between two nine year periods (1977–1985 and 2003–2011), and evaluate the effects of changes in rainfall on runoff from a shrub-dominated catchment in the southwestern USA. Analysis of rainfall characteristics shows that between these two periods there is an overall increase in annual rainfall, which corresponds with a long-term increase in rainfall in this region. Analysis of the frequency–magnitude distribution of rainfall events during these two periods indicates that there has not been a significant change in the return period of daily rainfall totals, whereas there has been a significant change in the return period of runoff-generating rainfall events. Between the two periods, there has been a large increase in the return period for a runoff event of a given magnitude. Although there has been an increase in rainfall between the two periods, results show that, contrary to what might be expected, an overall increase in rainfall has not resulted in an increase in runoff because of a change in the frequency–magnitude distribution of runoff-generating rainfall events. We anticipate that this reduction in runoff is due to a reduction in rainfall intensities between the two periods.

1. Introduction

Over the past century or more, there has been profound vegetation change in the southwestern USA, from native desert grassland to shrubland (Brown et al., 1997; Van Auken, 2000), which is associated with an increase in runoff and erosion (Parsons et al., 1996; Turnbull et al., 2010; Wainwright et al., 2000). This vegetation change is widely considered to be driven by changes in climate, overgrazing and changes in fire regimes (e.g. Buffington and Herbel, 1965; Brown and Archer, 1999; Gao and Reynolds, 2003; Neilson, 1986). At the Jornada Experimental Range in southern New Mexico, between 1914 and 2011 there has been a significant increase in annual rainfall at a rate of 0.7 mm a^{-1} ($p = 0.02$; Fig. 1). This increase in annual rainfall is manifest as an increase in summer rainfall at a rate of 0.58 mm a^{-1} ($p = 0.03$) and an increase in winter rainfall at a rate of 0.17 mm a^{-1} ($p = 0.17$).

Rainfall characteristics are important drivers of runoff dynamics in drylands, especially in terms of the frequency and magnitude of rainfall events. Larger, more extreme events are more likely to exceed the infiltration capacity of the soil and generate runoff, while the reverse will be true of less intense rainfall events. Therefore, changes in the frequency and magnitude of rainfall events that drive changes in the frequency and magnitude of runoff events will alter the characteristics of runoff, erosion and nutrient redistribution in drylands.

Increasingly, rainfall-manipulation experiments are being undertaken to uncover the effects of changes in rainfall characteristics on ecosystem processes (e.g. Reynolds et al., 2000; Sala and Lauenroth, 1982; Thomey et al., 2011; Wainwright et al., 2000). However, the direct effects of long-term changes in rainfall on runoff dynamics remain poorly understood. Projections of future climate change in the southwestern USA are for a decrease in annual rainfall due to the northward displacement of the subtropical anticyclone (Christensen et al., 2007: 888), and that the transition to a drier climate should already be underway (Seager et al., 2007). However, there is considerable uncertainty in these predictions for the southwestern USA, with some Atmospheric General Circulation Models predicting an increase in rainfall over this region (Christensen et al., 2007: 891). Several studies have used regional climate models to investigate the effects of predicted climate change on extreme events, with general consensus that the anticipated decrease in rainfall will lead to an increase in extreme events (Christensen et al., 2007). However, there is perhaps

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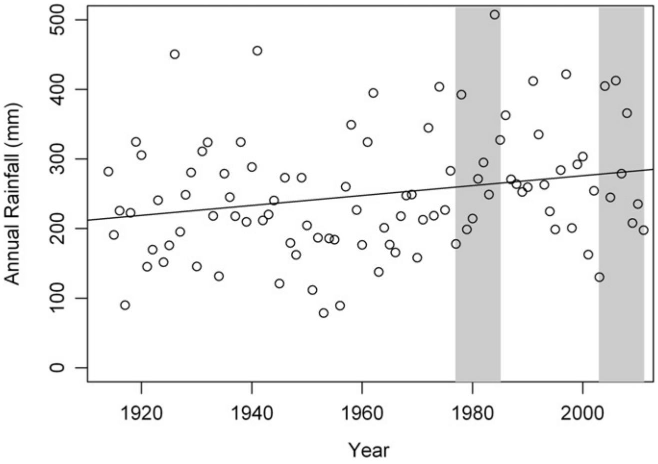

Fig. 1. Long-term rainfall record from the Jornada Experimental Range (1914–2011; Jornada Headquarters rain gauge) shows an overall increase in annual rainfall of 0.7 mm a^{-1} ($p = 0.02$). Highlighted segments show the two time periods that are investigated in this paper: period 1 (1977–1985) and period 2 (2003–2011).

even more uncertainty over these projections of changes in the frequency–magnitude distribution of rainfall events and the occurrence of extreme events, largely because much of the summer rainfall in this region is controlled by convective-scale rainfall events which are harder to simulate (Giorgi et al., 2001; Leung et al., 2003).

Changes in frequency–magnitude distributions of rainfall have long been recognized as important controls on geomorphic processes (Cooke and Reeves, 1976; Leopold, 1951). Analysis of long-term daily rainfall records from four sites across New Mexico showed a progressive increase in the frequency of small rainfall events (<12.5 mm) between 1850 and 1930 (Leopold, 1951). For example, in the semi-arid southwestern USA, there has been debate concerning impacts of extreme rainfall events on arroyo downcutting. Cooke and Reeves (1976) suggest that recent and historic episodes of arroyo downcutting have occurred as a result of unusually large rainfall events that cause particularly large flood events. Others argue that arroyo downcutting is driven by changes in vegetation cover and composition induced by factors such as drought which reduces vegetation cover, or by overgrazing (Antevs, 1952; Bull, 1997; Graf, 1983). The effects of changes in the

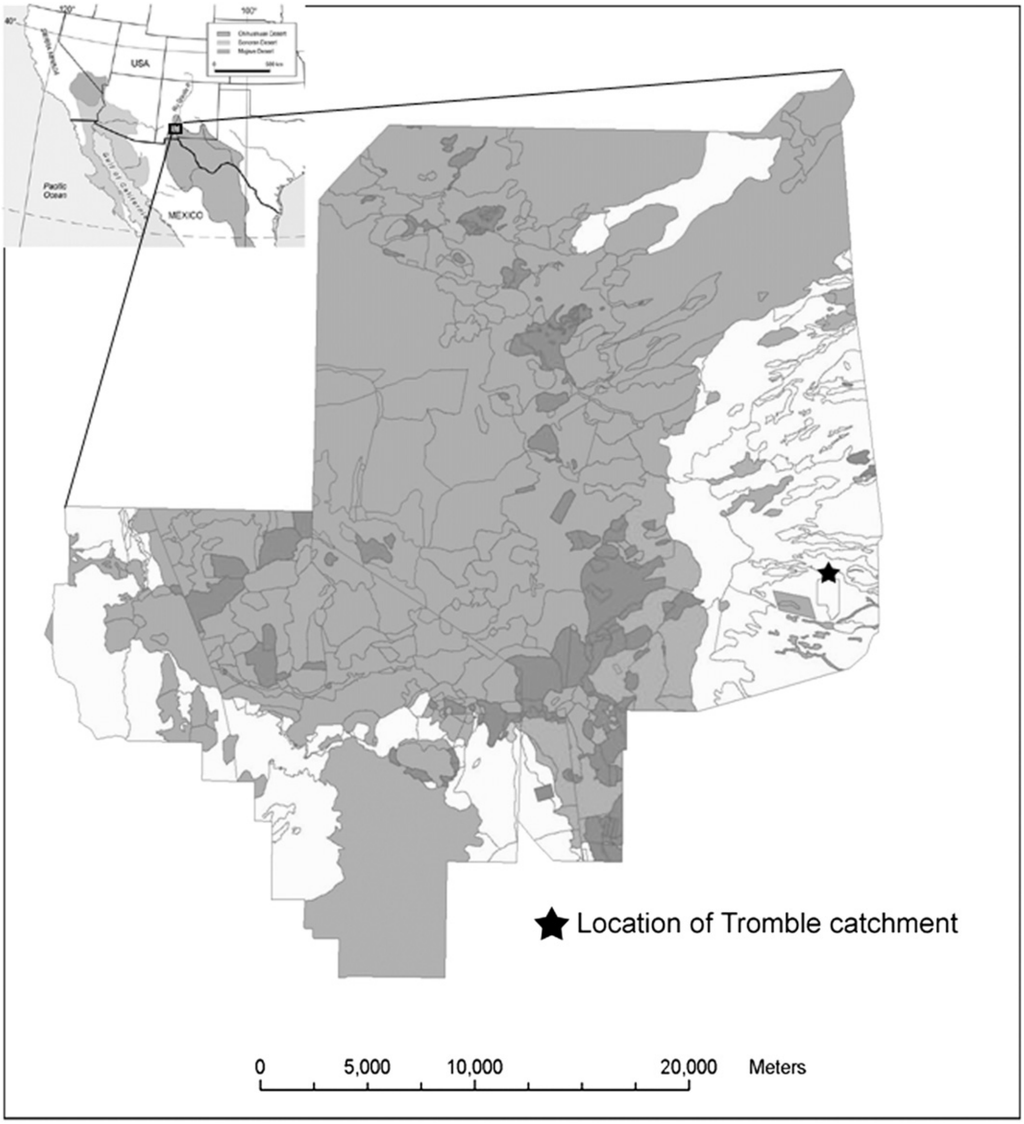

Fig. 2. Location of the Tromble catchment in the Jornada Experimental Range, New Mexico, USA. Within the Jornada Experimental Range (larger map), areas shaded in dark gray are dominated by grasses, areas shaded in light gray are dominated by mesquite and tarbush and areas in white are dominated by creosotebush (adapted from Gibbens et al., 2005).

Fig. 3. The 2.8 $m^3\ s^{-1}$ Santa Rita flume where runoff from the catchment is measured (looking downstream).

frequency–magnitude distribution of rainfall on runoff dynamics and arroyo downcutting remain contested. This debate has received considerable attention in the past and is set to receive more attention in the future, given the projections that future climate change will comprise changes in the frequency and magnitude of rainfall events.

To date, there have been very few studies that have sought to understand the effects of changes in the frequency–magnitude distribution of rainfall on the frequency and magnitude of runoff events in dryland regions, in isolation from the effects of vegetation change. The objective of this paper is to determine the effects of changes in rainfall on the frequency–magnitude distribution of runoff in a dryland catchment.

2. Methods

2.1. Study catchment and pre-treatment of data sets

In 1977 John M. Tromble instrumented a 4.7 ha (delineated using a 1-m digital elevation model; Templeton, 2011), shrub-dominated catchment on the eastern bajada of the Jornada Experimental Range, New Mexico, USA (Fig. 2). Historic vegetation

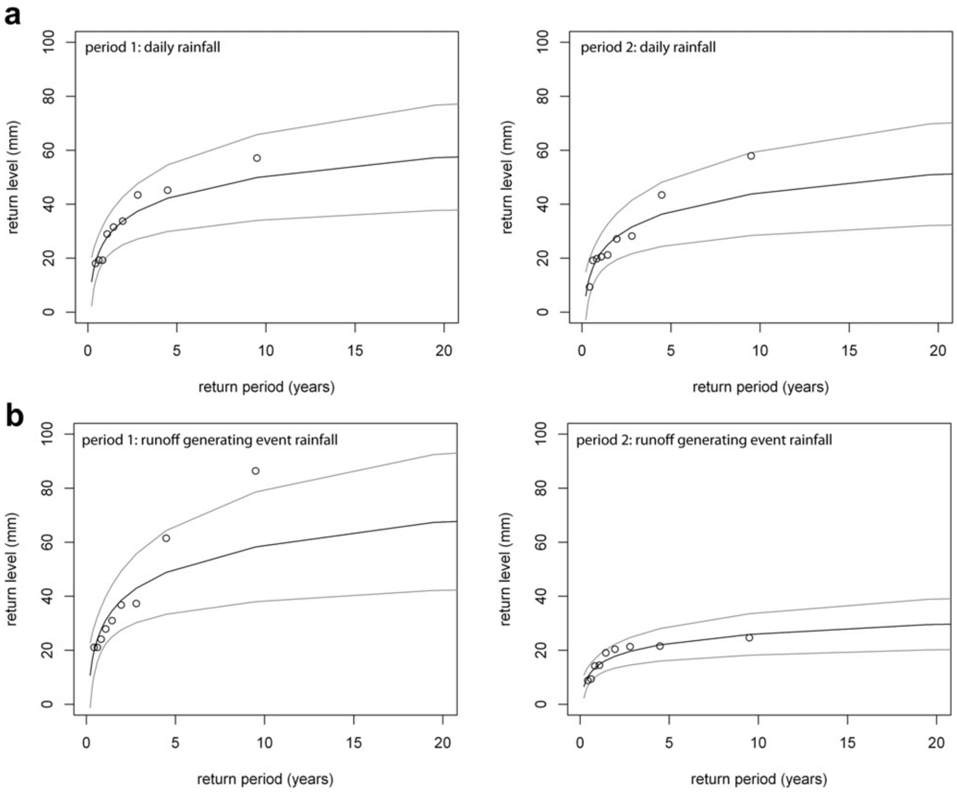

Fig. 4. (a) Return periods of daily rainfall and (b) return period of runoff generating rainfall events for period 1 (1977–1985) and period 2 (2003–2011). Gray lines show the 95% confidence limit of the return periods.

maps indicate that this catchment was dominated by upland grasses in 1858, but by 1919–20, these upland grasses had been replaced by creosotebush, tarbush, mesquite and mariola which still dominate (Gibbens et al., 2005; Templeton, 2011). Grazing has not been excluded from this catchment, but low animal densities during the period investigated are likely to have had negligible effects, not least because the vegetation is unpalatable (Havstad et al., 2006).

The catchment outlet was instrumented with a 2.8 $m^3 s^{-1}$ Santa Rita supercritical flume (Fig. 3) and flow depth in the flume was recorded using a paper chart recorder. Runoff data were collected from January 1977 until December 1985 at the catchment outlet. For this time period, rainfall data used in the subsequent analysis were collected at the Watershed rain gauge which was located 260 m from the catchment outlet. In 2003 the site was reactivated, and data collection was converted to a digital format. The paper chart was replaced with a Druck pressure transducer in the stilling well. A rain gauge was installed at the catchment outlet and rainfall data from this gauge were used in analysis for the period commencing 2003. Using these data, we analyze the rainfall–runoff response for two periods of observations: period 1 from 1977 to 1985 and period 2 from March 2003 to September 2011.

Measured flow depth was converted to discharge (Q, $m^3 s^{-1}$) based on depth discharge calibration equations for this size of Santa Rita supercritical flume (Smith et al., 1981), where:

$$Q = 0.081d + 4.307d^2 \tag{1}$$

For period 2, an *in situ* calibration between pressure-transducer output (p, in mV) and flow depth (d, in m) was carried out, yielding the relationship:

$$d = 0.306p - 0.307 \tag{2}$$

During period 1, the sensitivity of the equipment meant that flow was only recorded once it reached 0.003 m. Therefore, to ensure data from both periods were comparable, a runoff event was defined as the period during which flow was greater than 0.003 m, until a break in flow of more than 1 h was reached, marking the end of an event. Similarly, event rainfall was defined as rainfall that lasted until a break in rainfall of more than 1 h was reached. Screening of runoff data was undertaken to remove events where the measured flow depth did not return to zero, since a reliable estimate of event discharge could not be determined.

2.2. Data analysis

All data analyses were carried out in R version 2.15.1 (R Development Core Team, 2011). For each period a standard maximum likelihood estimate was used to fit a Gumbel distribution to rainfall and runoff data (e.g. Castillo, 1988). Confidence intervals indicate how well the data fit the distributions. A cumulative distribution function was used to estimate the return periods of rainfall and runoff. Because of variability in underlying controlling variables (such as differences in within-event rainfall characteristics and antecedent soil-moisture conditions), the amount of runoff for a given amount of rainfall is variable, thus giving rise to independent distribution functions for both rainfall and runoff. To compare the difference in the probability distribution functions between periods, a two-sample Kolmogorov–Smirnov test was carried out. Quantile regression was carried out using the R package, Quantreg (Koenker, 2011), to explore further the conditional distribution of runoff response variables (total discharge and maximum discharge) to rainfall. The application of quantile regression is particularly well suited since it is more robust to outliers in the response variable than least-squares regression.

3. Results

There is an increase in the amount of rainfall from period 1 to period 2, from an average of 293 mm per year (S.D. = 105 mm) to 306 mm per year (S.D. = 80 mm; for years of 2004–2010 during period 2 – the years for which annual rainfall data were available [January to December]). This increase is consistent with the significant increase in rainfall over the last century at the nearby Jornada Headquarters rain gauge between 1914 and 2009 (0.8 mm per year, $p = 0.012$, Fig. 1). However, in spite of this increase in rainfall between the two periods, there are no apparent changes in the return period of daily rainfall totals (Fig. 4a). However, return periods of runoff-generating event rainfall between the two periods are markedly different with an increase in the return period of a runoff-generating rainfall event of a given size (Fig. 4b). For runoff, there is a large increase in the return period for a runoff event of a given magnitude between periods 1 and 2 (Fig. 5).

These differences are mirrored in the probability distribution functions of runoff-generating event rainfall and event runoff for the two periods which are significantly different (Fig. 6; Table 1). However, the probability distribution functions of daily rainfall for the two periods are not significantly different (Table 1). For period 1, the peak of the runoff probability distribution function corresponds to total event runoff of 346 m^3 and for period 2 a total event

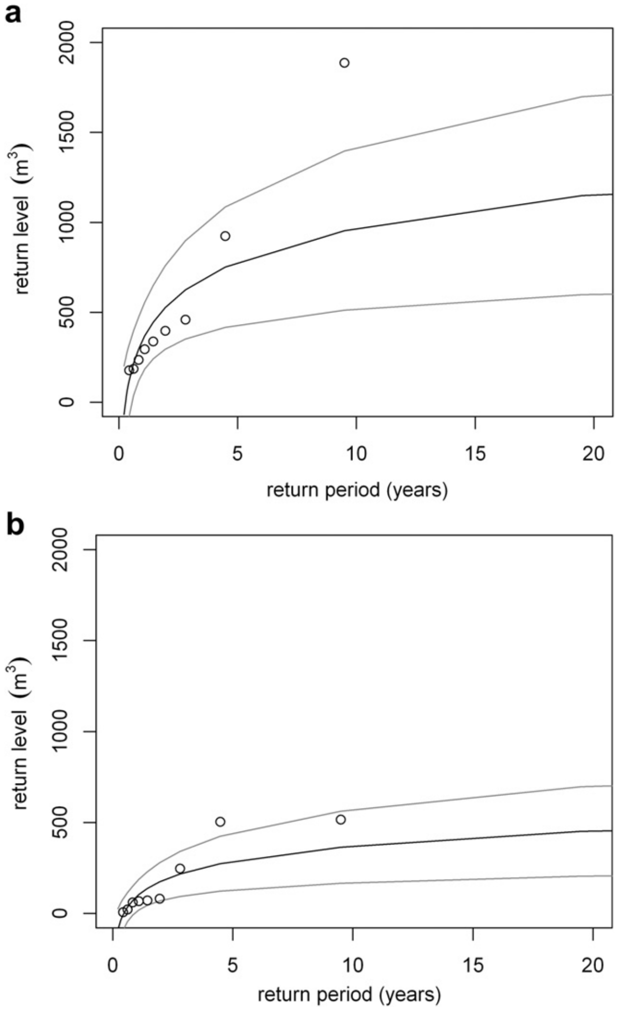

Fig. 5. Return periods of runoff events for (a) period 1 (1977–1985) and (b) period 2 (2003–2011). Gray lines show the 95% confidence limit of the return periods.

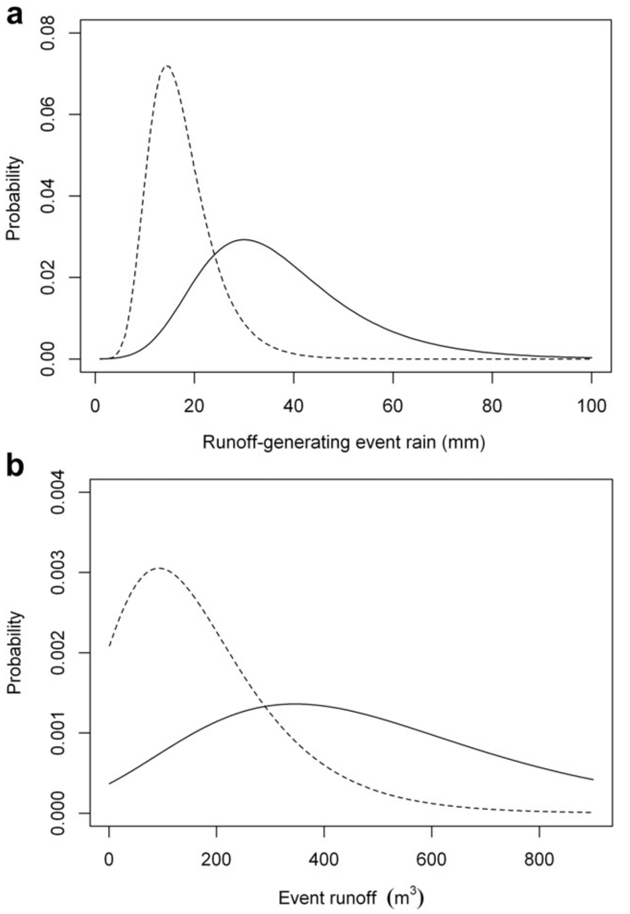

Fig. 6. Probability distribution functions for (a) runoff-generating event rainfall and (b) runoff for period 1 (1977–1985; solid black line) and 2 (2003–2011; dashed black line).

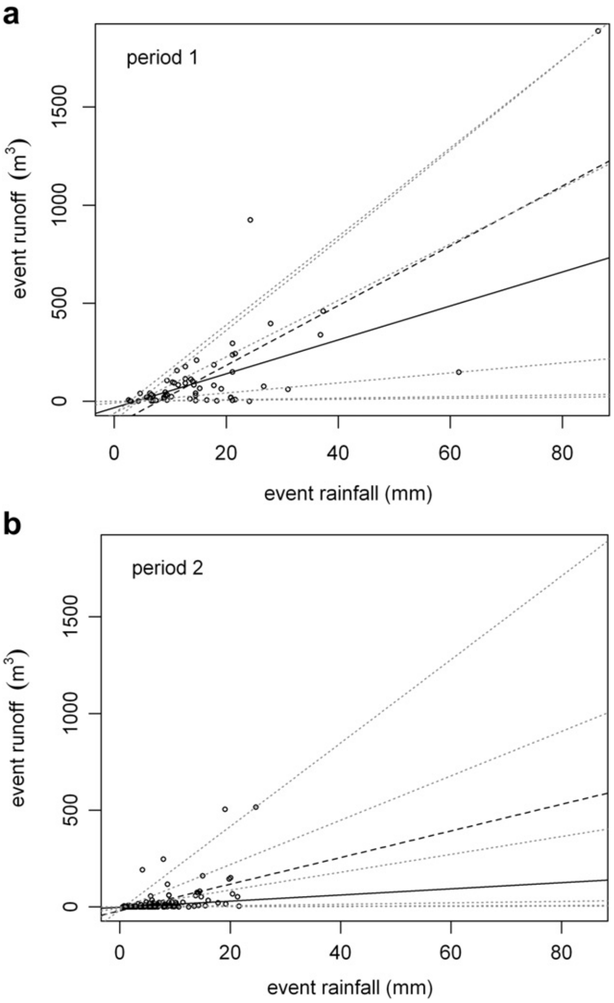

Fig. 7. Quantile regression demonstrating the relationship between event rainfall and event runoff for (a) period 1 (1977–1985) and (b) period 2 (2003–2011). In both of the graphs the solid black line is the ordinary least squares regression, the dashed black line is the regression on the median of the data and the dashed gray lines are the regressions on the 0.05, 0.10, 0.25, 0.75, 0.90 and 0.95 quartiles.

runoff of 73 m^3, and there is much higher probability of events occurring at this magnitude during period 2. While there is not a significant difference in the distribution of total daily rainfall between the two periods, there is a significant difference in the distribution function of runoff response, and similarly in the distribution of runoff-generating rainfall events which indicates that factors other than event size control the runoff response.

To explore the rainfall–runoff relationship for both periods further, quantile regression was used (Koenker, 2011). In period 1, higher event runoff occurs for relatively small rainfall events, whereas in period 2, the event runoff tended to be lower for the same amount of rainfall (Fig. 7). Although high-magnitude runoff events are more characteristic of period 1, the similar slope of the regressions on the 0.90 and 0.95 quantiles for period 1 and period 2 indicate that high-magnitude events are not totally exclusive to period 1. The difference in the relationship between rainfall and runoff between both periods indicates a difference in the runoff coefficient, which, in dryland systems is controlled largely by rainfall intensity and the clustering of wet and dry periods which affect soil-moisture content (see Wainwright, 2005, for a discussion of persistence of rainfall in the Jornada Basin and Turnbull et al., 2010, for the implications of the timing of rainfall events on soil moisture and thus runoff generation at a nearby site). Rainfall intensity data are only available for period 2, so it is not possible to evaluate the extent to which intra-event characteristics of rainfall differed between the two periods, potentially affecting the runoff coefficient. However, using measurements of peak discharge, the 'flashiness' of the catchment during each period can be compared, by using quantile regression to evaluate differences in the patterns of relationships between event rainfall and peak discharge (Fig. 8). The 0.95 quantiles indicate that both periods experienced flashy runoff events where high peak discharges were experienced relative to the total amount of rainfall. However, the 0.5 and 0.75 quantiles show that aside from these particularly extreme, flashy events, period 1 had a much flashier response than period 2.

Table 1
Kolmogorov–Smirnov test to determine of the probability distribution functions between period 1 (1977–1985) and period 2 (2003–2011) are significantly different.

	D	*p*
Daily rainfall	0.04	0.99
Runoff-generating event rainfall	0.52	<0.005
Runoff	0.49	<0.005

4. Discussion

As stated previously, it is widely anticipated that the southwestern USA will experience a decrease in rainfall which will be

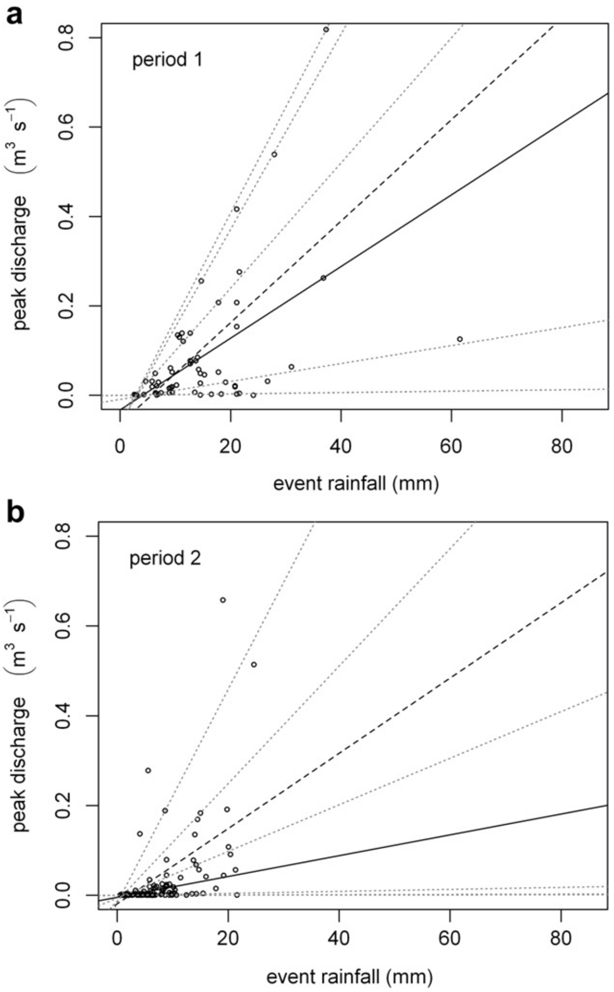

Fig. 8. Quantile regression demonstrating the relationship between event rainfall and peak runoff for (a) period 1 (1977–1985) and (b) period 2 (2003–2011). In both of the graphs the solid black line is the ordinary least squares regression, the dashed black line is the regression on the median of the data and the dashed gray lines are the regressions on the 0.05, 0.10, 0.25, 0.75, 0.90 and 0.95 quartiles.

associated with an increase in extreme rainfall events (Christensen et al., 2007, p. 888). In general, extreme rainfall events cause more runoff. Results from this study demonstrate that the opposite has in fact happened in this catchment, with less runoff occurring because of the reduced magnitude of rainfall events, in spite of an increase in the annual amount of rainfall. However, caution should be exercised when extrapolating results of this study across broader spatial scales because of spatial rainfall variability in this region (see Wainwright, 2005, for a detailed analysis of rainfall variably at the Jornada Experimental Range).

Curiously, results show that although there is not a significant difference in the distribution of daily rainfall totals between the two periods (Fig. 4a) there is a significant difference in the distribution of runoff-generating rainfall events (Fig. 4b). The fact that the distribution of daily rainfall totals is not different between the two periods, while the runoff response is different (assuming that other factors such as vegetation type and density have remained the same as indicated by maps of vegetation change for this period (Gibbens et al., 2005)) suggests that there is a difference in rainfall intensity, with rainfall events experiencing lower intensity rainfall in period 2 that is insufficient to generate a runoff response. Furthermore, even though some of the rainfall events during period 2 do generate runoff, the observation of smaller and in general less flashy flows during period 2 also indicates that rainfall intensities are likely to be the driver of the different runoff responses. These results indicate that an increase in annual rainfall does not translate to an overall increase in runoff, likely to be because reduced rainfall intensities cause a reduction in runoff generation.

The decrease in the general flashiness of runoff responses as indicated by event peak discharges (Fig. 8) has considerable implications for erosion dynamics and sediment transport. Erosion increases greatly with an increase in rainfall and runoff (e.g. Parsons and Abrahams, 1992; Parsons et al., 2006), because higher discharge increases the detachment and transport of sediment (Wainwright et al., 2008). Therefore, it is probable that, despite increased rainfall, erosion has reduced between the two periods, based on the observed changes in flow characteristics. A continued decrease in the magnitude of rainfall events and concurrent reduction in the amount of runoff as observed here may signify a reduction in erosion from this shrub-dominated catchment. However, this argument only stands for ecosystems not undergoing vegetation change. If future climate change and changes in rainfall characteristics do cause a change in the structure and function of vegetation, such as shrub invasion of grassland, it is probably that for a given rainfall amount, the amount of runoff and thus erosion will increase (Turnbull et al., 2008). If there is a reduction in annual rainfall and an increase in extreme events, the clustering of dry days and occurrence of extreme runoff-generating rainfall events will likely increase the sensitivity of the landscape further, since extreme dry periods will increase plant mortality reducing the sheltering and stability of the soil surface, thus rendering soil more susceptible to erosion during extreme runoff events.

5. Conclusion

This study has provided evidence to suggest that there has actually been a reduction in the magnitude of runoff events between period 1 (1977–1985) and period 2 (2003–2011). This study demonstrates that when making projections of the effects of climate change on runoff dynamics in drylands, it is imperative that attention be paid to rainfall event size and rainfall intensity, which at present are difficult to predict using regional climate models. Without this consideration, estimates of the effects of rainfall changes on the partitioning of rainfall between infiltration and runoff and effects on other water-related ecosystem processes such as erosion, biogeochemical cycling and vegetation dynamics are all likely to be erroneous.

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