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Long-term trends in streamflow from semiarid rangelands: uncovering drivers of change

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Abstract

In the last 100 years or so, desertification, degradation, and woody plant encroachment have altered huge tracts of semiarid rangelands. It is expected that the changes thus brought about significantly affect water balance in these regions; and in fact, at the headwater-catchment and smaller scales, such effects are reasonably well documented. For larger scales, however, there is surprisingly little documentation of hydrological change. In this paper, we evaluate the extent to which streamflow from large rangeland watersheds in central Texas has changed concurrent with the dramatic shifts in vegetation cover (transition from pristine prairie to degraded grassland to woodland/savanna) that have taken place during the last century. Our study focused on the three watersheds that supply the major tributaries of the Concho River – those of the North Concho (3279 km^2), the Middle Concho (5398 km^2), and the South Concho (1070 km^2). Using data from the period of record (1926–2005), we found that annual streamflow for the North Concho decreased by about 70% between 1960 and 2005. Not only did we find no downtrend in precipitation that might explain this reduced flow, we found no corresponding change in annual streamflow for the other two watersheds (which have more karst parent material). When we analyzed trends in baseflow (contributions from groundwater) and stormflow (runoff events linked to specific precipitation events), however, we found that in spite of large increases in woody plants, baseflow for all the watersheds has remained essentially consistent or has increased slightly since 1960. At the same time, stormflows were of smaller magnitude. Animal numbers have declined precipitously in the latter half of the last century. We suggest that these lower stormflows result from generally higher soil infiltrability due to generally improving range condition. There is no indication that the decline in streamflow is related to diminished groundwater flows caused by extraction of subsurface water by woody plants.

Keywords: ecohydrology, grazing, juniper, land cover change, land use, mesquite, precipitation, rangeland hydrology, runoff, streamflow

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Introduction

Changes in land use and in vegetation cover are increasingly recognized as major drivers of global change, including changes in the water cycle (Foley *et al*., 2005). Numerous studies have documented that extreme changes in vegetation cover – such as those resulting from urbanization and agricultural expansion – bring about correspondingly large changes in streamflow (Tilman, 1999; DeWalle *et al*., 2000; Costa *et al*., 2003). Rangelands in arid and semiarid climates in many regions of the world have been dramatically transformed through the related phenomena of desertification and woody plant encroachment (Huxman *et al*., 2005; Newman *et al*., 2006; Wilcox & Thurow, 2006). We know that these changes have implications for the water cycle at the plot, hillslope, and small-catchment scales (Wilcox *et al*., 2003; Ludwig *et al*., 2005), but there have been few assessments of whether and to what extent they may have affected streamflow from large rangeland watersheds (Wilcox, 2007).

The question then remains: Has streamflow in drylands been altered as a result of vegetation changes on

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rangelands, and if it has, to what extent? To address this question, we analyzed long-term trends in streamflow and precipitation for three adjacent catchments within the Concho River basin in central Texas that have been subjected to overgrazing and where woody plant cover has increased dramatically during the past 50 years. We selected this site because of indications that in one of these catchments – the one supplying the North Concho – streamflow has decreased dramatically in the past 50 or so years (Upper Colorado River Authority, 1998). Because these decreases were attributed to woody plant encroachment, the State of Texas implemented a brush removal program in the North Concho watershed with the expectation of tripling streamflow. Between 2001 and 2004, some 1200 km^2 (300 000 acres) was cleared of shrubs in an effort to increase streamflow.

We examine three competing hypotheses that could explain diminished streamflow: (1) the precipitation regime has changed; (2) baseflow (contribution to streamflow from groundwater) is lower due to increased transpiration by woody plants or groundwater pumping; and (3) stormflows (runoff from specific precipitation events) have diminished because infiltration capacity has increased as a result of improving range condition.

The Concho basin – a changing landscape

Overview

The Concho River comprises the North, South, and Middle Concho rivers, in addition to several smaller tributaries. The confluence of the three rivers is at San Angelo in west central Texas (Fig. 1). Floodplain deposits make up around 50% of the North Concho, 22% of the Middle Concho, and 11% of the South Concho, with the remaining portions being mostly Cretaceous limestones (Fig. 1). Springs are much more abundant in the South Concho watershed than in either of the other two, largely because of the higher proportion of limestone parent material, which can locally be very permeable due to karst features. Soils on the Quaternary floodplain deposits of all three rivers are characterized as deep, nearly level, and calcareous (Rioconcho and Angelo soils), whereas those that have developed on the Cretaceous rocks are generally shallow, rocky, and calcareous and often overlie permeable limestones or dolomite (Tarrant and Ector soils) (US Department of Agriculture, 1976).

The climate of the Concho basin is semiarid, with rangelands making up 95% of the area (US Department of Agriculture, 2006). The vegetation is dominantly a mixture of shrubs and short or mid grasses and varies from relatively open mid-grass savannas to dense woodlands, depending on the management history of the site. By 1999, more than half of the Concho basin above San Angelo exhibited a medium-to-heavy density of shrubs (Bednarz *et al*., 2001) The major shrubs are mesquite (*Prosopis glandulosa* Torr. var. glandulosa), redberry juniper (*Juniperus pinchotii* Sudw.), and Ashe juniper (*Juniperus ashei* Buchholz). Mesquite typically occupy the flatter areas, where soils are deeper, while juniper species are dominant on the steeper limestone slopes.

Table 1 Summary of hydrologic parameters for the North, Middle, and South Concho watersheds

	North Concho	Middle Concho	South Concho
Period of record	1926–2005	1940–1994	1942–1994
Drainage area (km^2)	3279	5398	1070
Contributing area (km^2)	3084	2890	917
Precipitation range (mm)	226–949	195–933	214–834
Precipitation mean (mm)	493	455	485
Streamflow range (mm)	0–99	0–48	6–153
Streamflow mean (mm)	7.4	6.3	30.1
Baseflow (mm)	0.8	1.4	20.9
Runoff ratio (%)	1.6	1.4	6.2

The drainage and contributing areas reflect the watersheds above Carlsbad, Tankersley, and Christoval for the North, Middle, and South Concho rivers, respectively.

A legacy of over grazing in the Concho basin

Over the past 150 years, the Concho basin and the surrounding areas have changed from pristine prairie to a predominantly woodland/savanna mosaic (Maxwell, 1979). This transformation was set in motion around the mid-1870s, with the introduction of enormous numbers of domestic cattle – which was facilitated by a number of factors, including newly completed rail lines, near-extermination of the bison by professional hunters, technological advancements such as the windmill, and an influx of foreign capital. The result of such high levels of grazing was predictable – in less than a quarter century, from about 1875 to 1900, vast tracts of highly productive and biologically rich grasslands in west and central Texas that had taken millennia to evolve were essentially wiped out and replaced by a degraded and much depleted landscape (Box, 1967; Bahre, 1991).

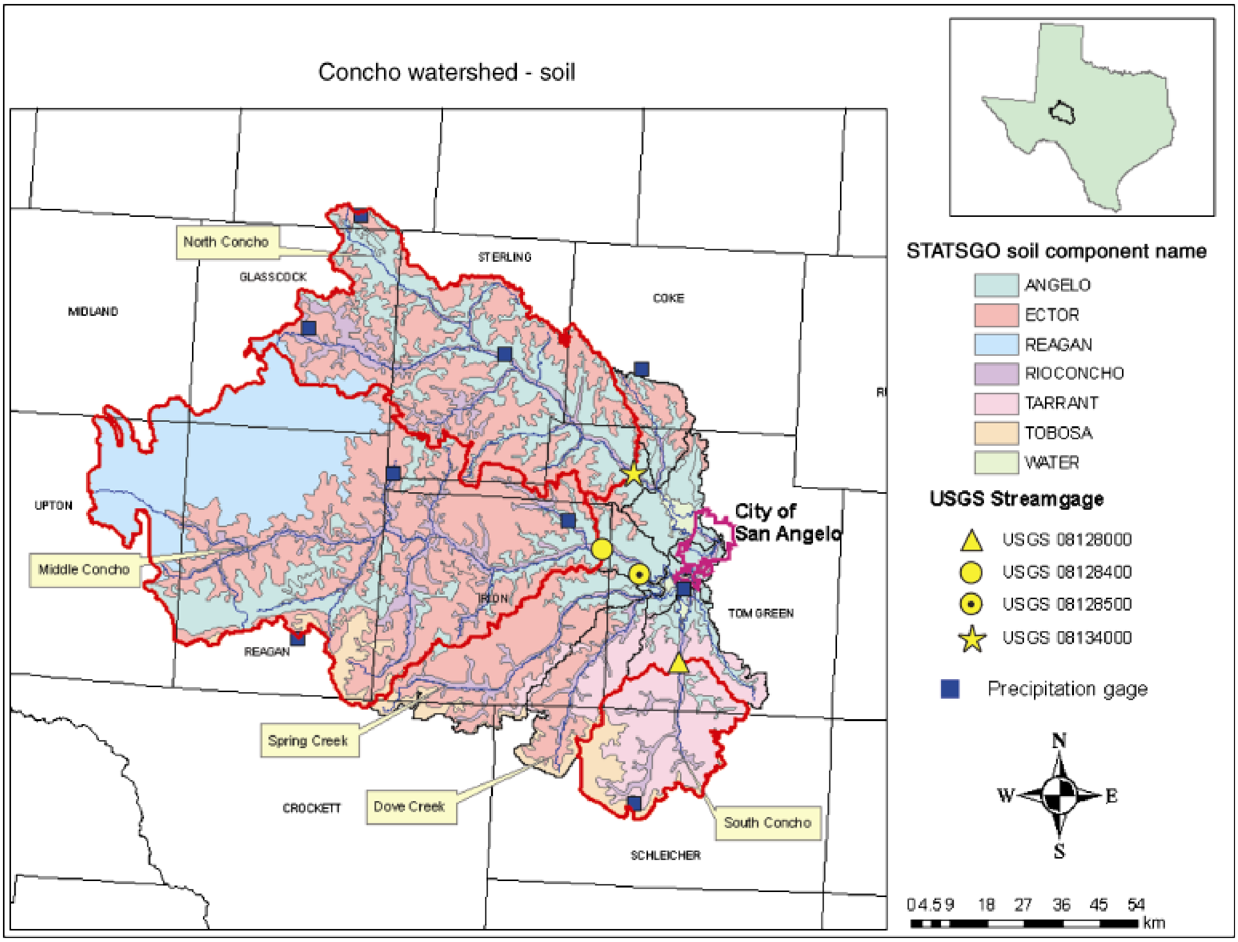

Fig. 1 The Concho River basin upstream from San Angelo. The South Concho, Middle Concho, and North Concho watersheds are outlined in red. Soil information is from the US General Soil Map (STATSGO) database. The Rioconcho and Angelo soils have developed on alluvial surfaces; the others have developed on Cretaceous rock – except for the Reagan soils which have developed on aeolian material. Although part of the Middle Concho watershed, the area with Reagan soils is not considered part of the contributing area for the Middle Concho.

Because of the poor record keeping, we do not know exactly how many cattle were brought into this region of Texas during the boom years of the early 1880s, but the numbers were enormous. Bentley (1898) estimated that in the early 1880s, some stockmen had around 64 cows on each square kilometer of land. Grazing intensities may have been even higher in some locations (Smeins *et al.*, 1997). Animal numbers inevitably collapsed, not only because of almost total loss of forage during dry periods but also because of several very severe winters.

By the turn of the century, record keeping for livestock numbers in Texas had improved. Livestock statistics for 1890 to the present, for six rural and mostly rangeland counties within the basin (Coke, Glasscock, Irion, Reagan, Schleicher, and Sterling counties), highlight several important trends in both animal numbers and animal type (Fig. 2). One of these trends – which brought renewed growth in animal numbers after they had fallen well below their 1880s peak – was the explosive growth of sheep during the first part of the 20th century, fueled by demand for wool during the two world wars. In terms of animal units (for our purposes we assumed that five sheep equals one cow), stocking density hovered between 16 and 20 animal units km^{-2} up to about 1950; we assume that this was around the maximum capacity of the land to support domestic livestock at that time, although it was only about a third of the stocking density of the 1880s, a significant decline in carrying capacity. The decade of the 1950s was characterized by unprecedented drought, which caused stocking rates to drop, and they never really recovered. Between 1950 and 1992, stocking rates were about 40% lower than during the pre-1950 peak period.

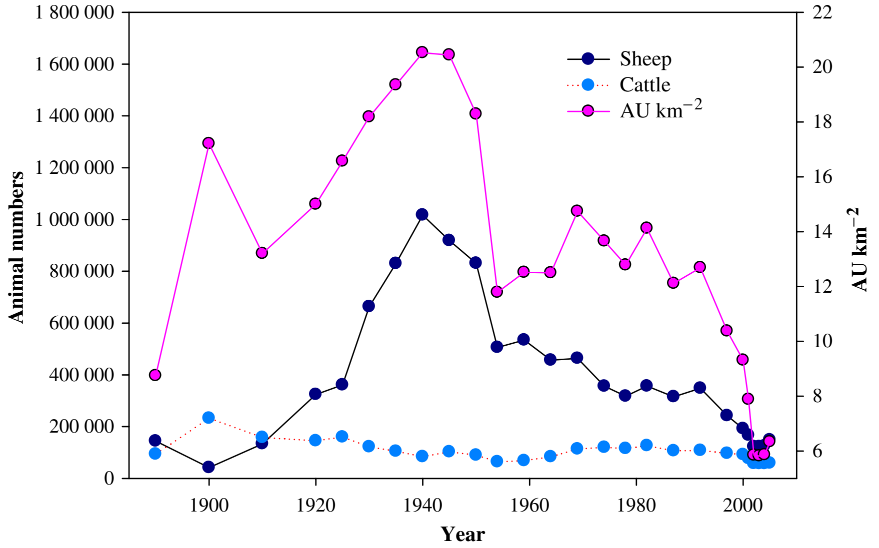

Fig. 2 Numbers of sheep and cattle for Coke, Glasscock, Irion, Reagan, Schleicher, and Sterling counties (1890–2005). The stocking rate is calculated in terms of animal units km^{-2}, and the amount of rangeland is estimated as the difference between total land area and total cropland. Sources: Census of the United States (1895, 1902, 1913, 1923), the United States Census of Agriculture (1927, 1936, 1942, 1952, 1956, 1961, 1967, 1977, 1981, 1983, 1989, 1994, 1999, 2004), and the USDA-NASS online database (2000, 2001, and 2003–2005).

After 1992, livestock numbers fell again. And post-2000 stocking rates are only about a third of their 20th-century high, which is perhaps 10 times lower than the historical highs of the 19th century. A number of factors have contributed to the low stocking rates in the last decade, including a drought in the latter half of the 1990s, reduced government subsidies, and more interest in using rangeland to support wildlife. The dramatic reduction in animal numbers has almost certainly contributed to the improved condition of these rangelands.

As the prairielands became degraded by overgrazing, they began evolving toward the woodlands of today. As early as the 1880s, anecdotal accounts of increasing woody cover began to surface. It seems likely that this process actually began soon after 1900 and continued during the entire 20th century – even with active shrub control measures in some areas. Several regional assessments for Texas and the southwest document a similarly dramatic increase in woody plants during this period (Buffington & Herbel, 1965; Archer *et al*., 1988; Smeins & Merrill, 1988; Ansley *et al*., 1995, 2001; Asner *et al*., 2003).

A sequence of aerial photographs dating back to 1954 confirms that woody plants have expanded greatly in the Concho basin since the 1950s. As highlighted in Fig. 3a, by 1954 there were already extensive areas of woody plants, but the greatest concentrations were in riparian regions and water draws. The light areas in the 1954 photograph are most likely bare ground, as this was taken during the height of the 1950s drought when little or no forage was available. By 1979, woody plants had expanded into almost all areas (Fig. 3b). In 2005, woody plants are still extensive, but each photograph shows some evidence of shrub clearing in selected locations (Fig. 3c).

To summarize, in quite recent history, vegetation in the Concho basin – and on Texas rangelands in general – has undergone three major phases of change, from a pristine prairie savanna (before 1880) to a degraded grassland/shrubland (ca. 1880–1960), and then to a woodland/savanna (post 1960). Because of declining grazing pressure since 1960, rangeland condition has improved, especially since 1990.

Methods

In evaluating what may be driving changes in streamflow, we rely on detailed records of streamflow (including *baseflow* and *stormflow*) and of precipitation (daily, monthly, and annual), as well as analysis of trends. *Baseflow* is sustained runoff, not associated with a particular rainfall event but composed entirely from groundwater contributions; *stormflow* is that part of runoff that is associated with a particular rainfall event. Sometimes it is referred to as *quickflow* or *flood flow*. Stormflow by definition arrives at the channel quickly, and in large semiarid basins would be mostly overland flow. The distinction between *baseflow* and *stormflow* is important for our analysis because the trend in each

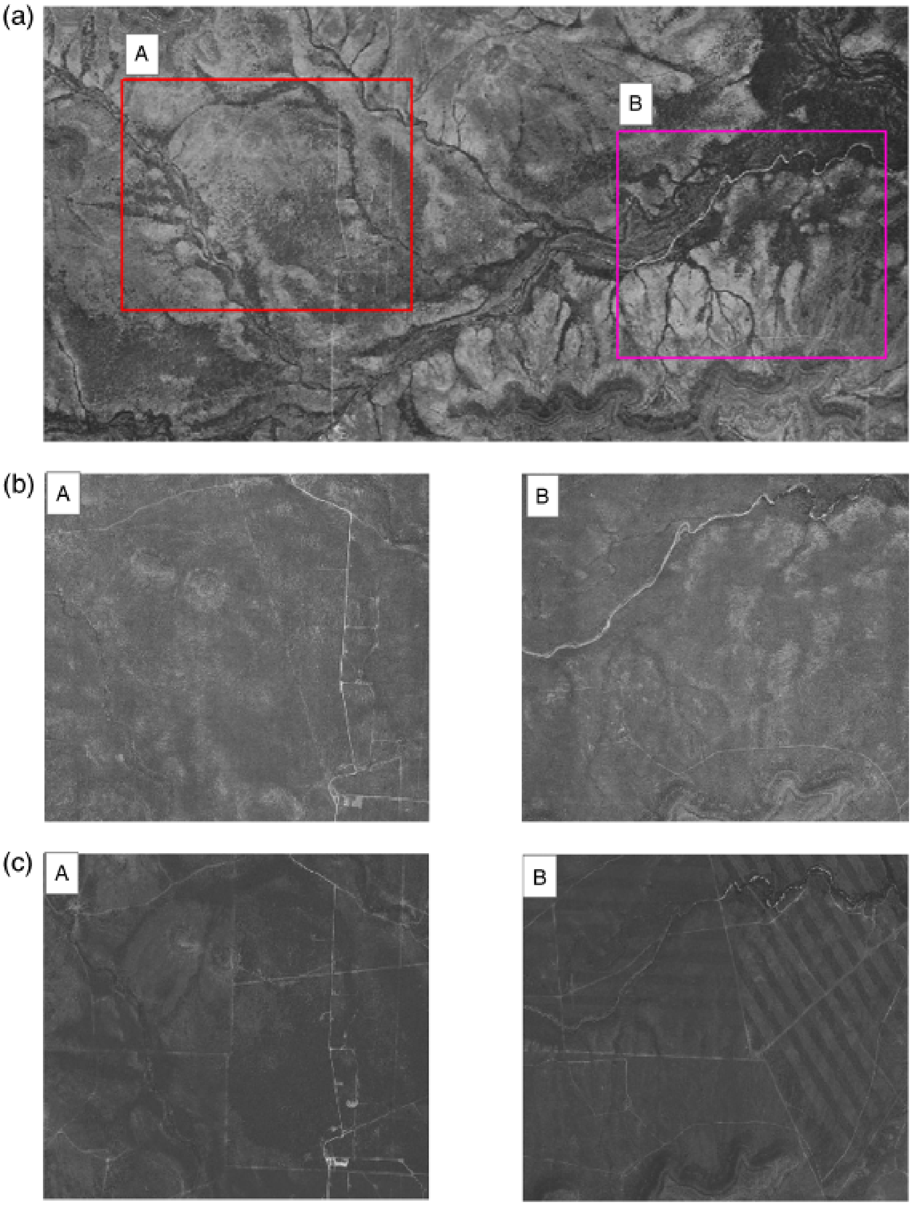

Fig. 3 (a) Aerial photograph of Mulberry Creek, a tributary of the North Concho River. The photograph was taken on May 3, 1954, at the height of the 1950s drought, when herbaceous cover was very low. The lighter areas in the photograph are probably mainly bare ground; dark areas are shrub-dominated (most of the shrubs are located in riparian areas, draws, or low points on the landscape). (b) Aerial photographs taken on September 10, 1979, of locations A and B outlined in (a). By this time both locations had become almost entirely shrub-covered. (c) Aerial photographs of Locations A and B taken in 2005. Woody plants are still dominant, but shrub-clearing operations have opened up some areas.

will be different depending on what is driving the diminishing streamflows. For example, if the driver is higher extraction of soil water and groundwater by woody plants or groundwater pumping, then we would expect to find a downtrend in baseflow. However, if the driver is an improvement in rangeland condition (leading to higher soil infiltration capacity), then we would expect to see a downtrend in stormflow.

We carried out analyses of precipitation and streamflow in three of the principal watersheds in the headwater area – the North, Middle, and South Concho – using available data for the period of record (Table 1). Daily precipitation data for the North Concho date back to 1926; those for the Middle and South Concho watersheds cover the period from around 1940 to the present. These data are reasonably comprehensive and of good

Table 2 Precipitation stations used in analysis of streamflow for the Concho River basin

Location	Years	Notes
Big Lake	1941–2005	
Cope Ranch	1948–2005	Combined record of three nearby stations
Eldorado	1941–2005	
Forsan	1949–2005	
Funk Ranch	1948–2004	
Garden City	1926–2002	Combined record of two nearby stations
San Angelo	1946–2005	
Sterling City	1926–2005	Combined record of three nearby stations
Water Valley	1926–2005	Combined record of two nearby stations

quality, coming from the National Oceanic and Atmospheric Administration (NOAA) database (Table 2). The Thiessen polygon method was used to determine the spatial average precipitation.

We estimated baseflow for each of the watersheds using an automated baseflow filter (Arnold *et al*., 1995; Arnold & Allen, 1999). The mechanism of filtering stormflow (high-frequency signals) from baseflow (low-frequency signals) is analogous to the filtering of high-frequency signals in signal analysis and processing. The technique is objective, reproducible, compares well with manual techniques, and is broadly applied (Arnold *et al*., 2000; Santhi *et al*., 2001; Kalin & Hantush, 2006).

Directional change and trend were determined by applying the nonparametric Mann–Kendall trend test to daily, monthly, and annual streamflow and precipitation series. For the daily series, incremental percentiles on an annual basis were used. This test has been used widely in climatic and hydrologic research (Lettenmaier *et al*., 1994; Gan, 1998; Douglas *et al*., 2000; Zhang *et al*., 2001). To calculate the magnitude of a trend, we used a Sen-slope estimation (Sen, 1968); and to determine whether a trend was significant, we used a two-tailed test with a significance level of 0.10. Because the Sen-slope estimation varies according to the unit of measurement, we devised a normalized Sen-slope estimation to facilitate comparison of trends among the watersheds. (A Sen slope is normalized by dividing the slope by the central tendency of the original dataset. In our study, the central tendency is represented by a median, because most of the distributions are skewed owing to the number of extreme events.)

Although the Mann–Kendall test does not require that the distribution be normalized, the presence of an autocorrelation in the dataset violates the independence assumption. In this case, the effective degree of freedom will be less than the number of observations. Consequently, if the autocorrelation is not taken into account, the resulting trend will be spurious. In our dataset, a first-order autocorrelation, if present, was removed through the following Cochrane–Orcutt procedure (Cochrane & Orcutt, 1949):

$$Y'_{\mathrm{t}} = Y_{\mathrm{t}} - rY_{\mathrm{t}-1},$$

where Y'_{t} is the transformed time series values, Y_{t} the original time series value, and r the estimated serial correlation. The significance of the first-order autocorrelation was judged using Durbin–Watson statistics at a 0.05 significance level (Bowerman & O'Connell, 1979). If an autocorrelation was present, trend analysis was performed on a transformed series.

Results

Comparison of the watersheds

The three watersheds are similar with respect to precipitation (Table 1): the pattern is bimodal, with peak precipitation in May and September; amounts range from 200 to 900 mm yr^{-1} (averaging around 480 mm yr^{-1} for the North Concho and South Concho, and 450 mm yr^{-1} for the Middle Concho). As is typical for semiarid climates, streamflow generally makes up a small part of the total water budget but can be enormous during occasional storms that produce flooding. Whereas annual streamflow averages $<2\%$ of precipitation in the North and Middle Concho watersheds, it is four to five times higher in the South Concho. This difference can be attributed mainly to the baseflow component of the South Concho (Table 1), which is at least 20 times greater than that of either the North or Middle Concho (South Concho baseflow accounts for about 70% of total streamflow, in contrast to only 10% for the North Concho and 20% for the Middle Concho). The principal reason for this difference is geology: owing to the greater extent of karst parent material (highly permeable limestones and dolomite) in the South Concho watershed, the river is fed by numerous prolific springs.

Annual precipitation and streamflow for the period of record for the three watersheds are plotted in Fig. 4. The significant decline in streamflow for the North Concho is confirmed by trend analysis: Sen-slope estimation shows that in a period of about 80 years, mean annual streamflow has declined by around 7 mm annually – a reduction of approximately 70% (most of which has taken place since 1960). There has been no corresponding significant decline in annual streamflow for the South or Middle Concho (although the early record for the South Concho shows several years of very

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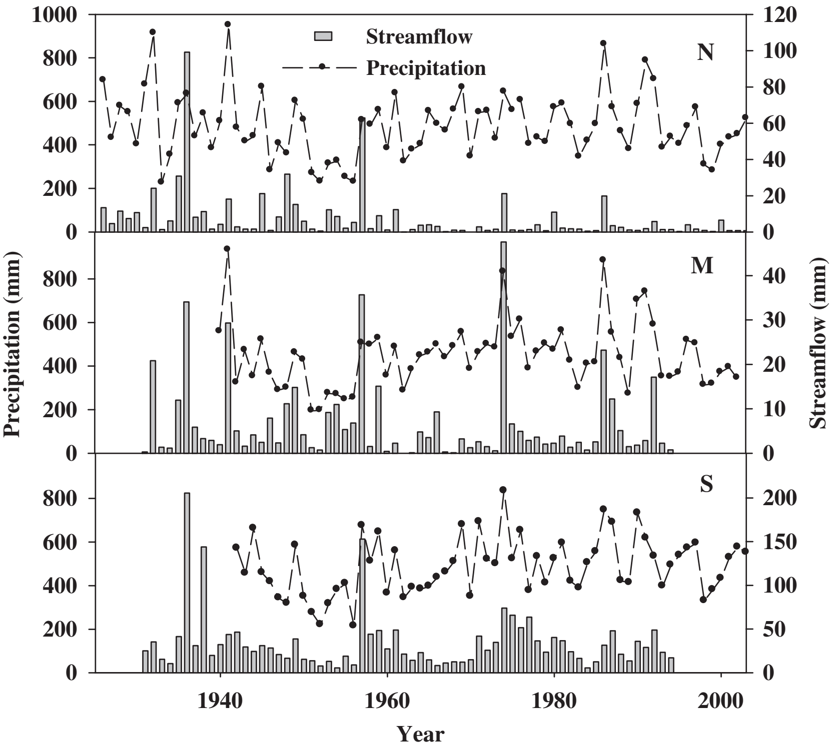

Fig. 4 Annual total streamflow and precipitation for the North, Middle, and South Concho watersheds. Basin-wide precipitation is obtained using the Thiessen polygon method. Annual streamflow data reflect USGS measurements at the Carlsbad, Tankersley, and Christoval gauging stations, for the North, Middle, and South Concho, respectively.

high flow), nor has there been a significant decrease in annual precipitation for any of the watersheds.

Trend analysis results for the stormflow and baseflow components of streamflow are presented in Table 3, and baseflows are plotted in Fig. 5. The analysis suggests that stormflow has decreased in each of the watersheds, but most significantly in the North Concho; the data for baseflow indicate (1) a slight decrease for the North Concho, (2) no significant change for the South Concho, and (3) an increase for the Middle Concho.

To gain additional perspective on the magnitude of the changes, we calculated average water budgets for each of the watersheds for two 18-year periods: 1931–1949 and 1977–1994 (Fig. 6). We selected these periods because they are comparable in terms of average rainfall and the absence of any extended drought periods. We considered both the baseflow (a good approximation of recharge) and stormflow components of streamflow, as well as evapotranspiration (assumed to be equivalent to the difference between precipitation and streamflow, a reasonable assumption for semiarid climates such as this). This comparison shows that during the later period, stormflows were two to three times lower than during the earlier period, and that for the Middle and South Concho watersheds, there was some corresponding gain in baseflow. Further, it is clear that evapotranspiration dominates the water budget for these dryland river systems. These changes, while small in terms of millimeters of water and of the total water budget, significantly affect the amounts of water in the streams because of the size of the watersheds.

Precipitation and streamflow on the North Concho

Given the rather dramatic decrease in streamflow for the North Concho, and because the available data for

Table 3 Direction and statistical significance of changes in the flow components for the North, Middle, and South Concho watersheds

	Streamflow	Baseflow	Stormflow
North	⇓ Significant ($P<0.001$)	⇓ Significant ($P = 0.05$)	⇓ Significant ($P<0.001$)
Middle	⇓ Not significant ($P = 0.30$)	⇑ Marginal ($P = 0.102$)	⇓ Significant ($P = 0.02$)
South	⇓ Not significant ($P = 0.74$)	⇑ Not significant ($P = 0.77$)	⇓ Marginal ($P = 0.116$)

Significance is attributed for $P<0.1$. A down arrow signifies a downward trend while an up arrow signifies an upward trend.

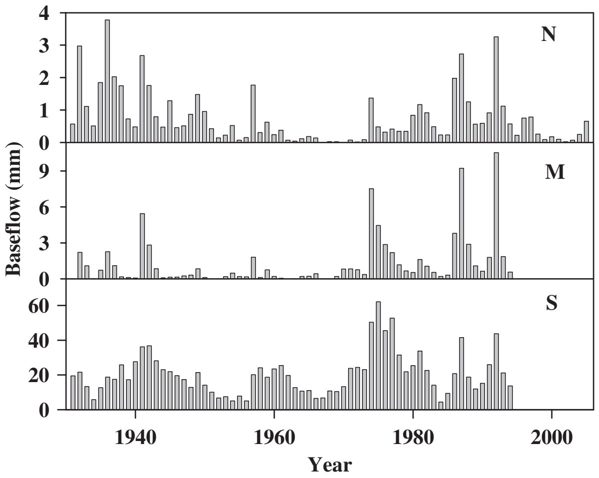

Fig. 5 Annual mean baseflow in the North (Carlsbad), Middle (Tankersley), and South (Christoval) Concho River watersheds, based on the Arnold baseflow separation method. Note that the baseflow scale is different for each watershed.

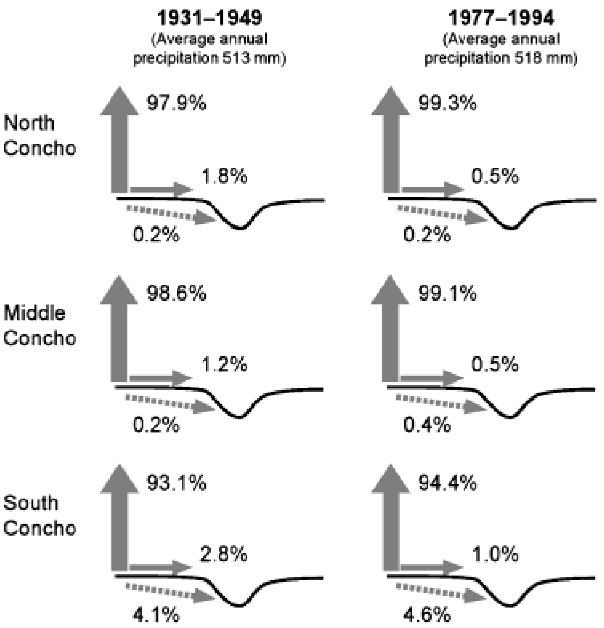

Fig. 6 Estimates of evapotranspiration (solid vertical arrow), stormflow (solid horizontal arrow), and baseflow (dashed downward arrow) for the North, Middle, and South Concho watersheds for the periods 1931–1949 (left panel) and 1977–1994.

this watershed are more complete, we examined the streamflow and precipitation trends for the North Concho in more detail. Precipitation and runoff data were aggregated several ways, including by day, by month, and by 'event.' Rainfall was considered to belong to one event unless separated from the next rainfall by at least 2 no-rain days. This aggregation shows a nonsignificant serial correlation between rainfall events ($\alpha = 0.1$). Runoff produced by a rainfall event was aggregated from the beginning of that event until the beginning of the next rainfall event.

As highlighted in Fig. 7, most of the runoff in the North Concho watershed is accounted for by relatively few runoff events. For example, the largest runoff event on record accounted for 16% of the total runoff during the 79-year period of record, and the largest six events accounted for 38% of the total. On average, each year's largest event accounted for 65% of that year's runoff.

Analysis of trends in daily flow, from the 50th percentile up to the maximum, all showed a significant downward trend for the period of record (Table 4), and this trend was more significant for the higher flows. Streamflows declined in all months except January, with the strongest declines during the spring months (Table 5).

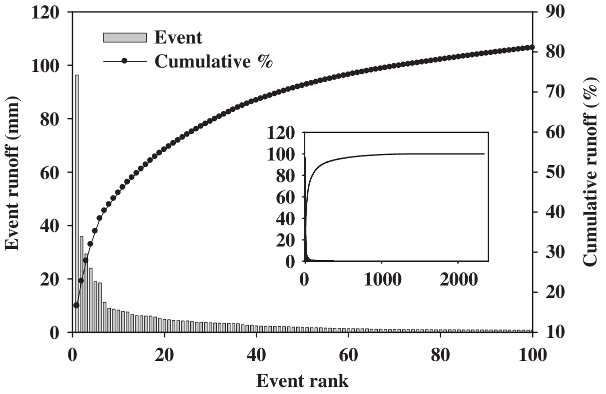

Fig. 7 Runoff events (ranked from high to low) and percentage cumulative runoff for the entire period of record for the North Concho watershed. The main graph plots only the largest 100 out of 2437 runoff events. The smaller inset graph, which has the same axis parameters as the main one, plots all the events in the period of record.

Table 4 Trends in daily streamflow and precipitation for the North Concho River watershed

Category	Variable (%)	Trend	*P*-value
Daily flow percentile	75	Decreasing	0.0701
	90	Decreasing	0.0004
	98	Decreasing	<0.001
	Maximum	Decreasing	0.0001
Daily precipitation percentile	80	Increasing	<0.001
	85	Increasing	<0.001
	90	Increasing	0.0543
	95	Insignificant	0.4580
	98	Decreasing	0.0185
	Maximum	Insignificant	0.3898

With respect to precipitation, daily percentiles did show an increase for the 80th and 90th percentiles and a decrease for the 98th percentile, but these were all very small (Table 4). No significant change was detected for maximum daily or event precipitation. Similarly, there were no significant trends in either the annual or the monthly precipitation (Table 5). In other words, the declines in streamflow took place largely without any significant changes in precipitation.

Table 5 Trends in monthly and annual streamflow and precipitation for the North Concho River watershed

	Monthly and annual streamflow		Monthly and annual precipitation	
Variable	Trend	*P*-value	Trend	*P*-value
January	Insignificant	0.2317	Insignificant	0.2497
February	Decreasing	0.0022	Insignificant	0.1677
March	Decreasing	0.0167	Insignificant	0.6447
April	Decreasing	0.0014	Insignificant	0.3944
May	Decreasing	<0.001	Insignificant	0.4323
June	Decreasing	0.0045	Increasing	0.0576
July	Decreasing	0.0018	Insignificant	0.4545
August	Decreasing	0.0329	Insignificant	0.1878
September	Decreasing	0.0076	Insignificant	0.6657
October	Decreasing	0.0422	Insignificant	0.5008
November	Insignificant	0.1142	Insignificant	0.2947
December	Decreasing	0.0078	Decreasing	0.0868
Annual mean	Decreasing	<0.001	Insignificant	0.7054

The analysis so far leads us to conclude that a fundamental shift in the relationship between streamflow and precipitation took place on the North Concho around 1960. To further examine this premise, we compared streamflow–precipitation relationships for two 24-year periods having comparable precipitation: 1926–1949 (period A) and 1974–1997 (period B). We found that streamflow for period B was less than a third of that for period A. We then compared the runoff–rainfall relationships for the 63 largest runoff-producing events of each period (which accounted for 87% of total runoff in period A and 80% in period B). The total amounts of rainfall for the two sets of 63 events are roughly equal (Pearson correlations of rainfall and runoff were 0.75 for period A and 0.71 for period B). In addition, we plotted the 12 largest runoff events for the years 2001–2005, the period after which large-scale brush control was implemented. The results, shown in Fig. 8, are striking in that they highlight the declining ratio of runoff to rainfall from the earlier part of the century to the later. In the earlier period, runoff was much more sensitive to rainfall – in other words, the landscape was much more prone to flooding. At the same time, we found no evidence that the extensive brush control that took place on the watershed between 2001 and 2005 had any fundamental effect on the rainfall–runoff relationship (if anything, runoff appears to be even less sensitive to precipitation during this period).

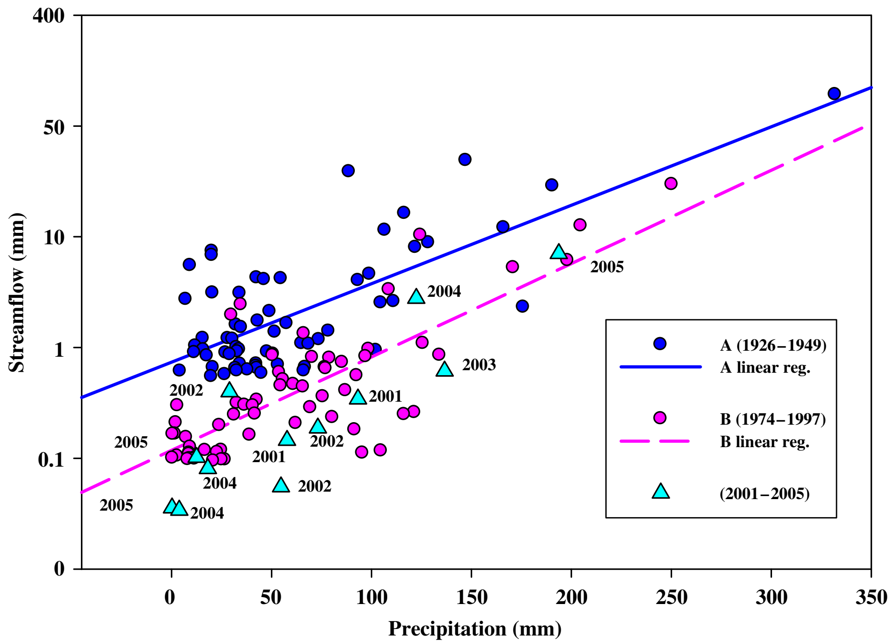

Fig. 8 The 63 largest runoff-producing events for the North Concho River during the two 24-year periods (1926–1949 and 1974–1997), plotted against rainfall for each event. The 12 largest events for the period 2001–2005 are also shown.

Discussion

A re-examination of potential drivers of streamflow change in the Concho basin

Our analysis confirms that since the middle of the last century, streamflow in the North Concho has declined sharply, mainly because of reduced stormflow. Although the other two watersheds also saw lower stormflow, baseflow (groundwater flow) increased slightly for both and thus there was no decline in overall streamflow.

The North Concho, because of the significant decline in streamflow, has received the most regional attention and several observers have proposed explanations for it. Sauer (1972) attributed the diminished flow to lower precipitation. More recently, others have suggested that the cause is significantly higher rates of evapotranspiration (loss through interception and transpiration) associated with the greater coverage of woody plants (Upper Colorado River Authority, 1998). It is on this basis that a basin-wide brush-control program was implemented, with some 1200 km^2 (300 000 acres) of land cleared of woody plants between 2001 and 2005 (Upper Colorado River Authority, 2006).

Our detailed analysis of streamflow and precipitation in the Concho basin, along with the historical data on changes in vegetation and grazing, enables us to evaluate these two proposed ‘drivers’ of the reduced streamflow in the North Concho – and to suggest a third.

Change driver 1: Precipitation regime has changed. On the basis of our analysis, we reject this explanation. There are no detectable downtrends in precipitation for the period of record that would account for changes in streamflow – particularly the 70% reduction on the North Concho. At the time of Sauer’s study (Sauer, 1972), there was a limited amount of data available; we believe his conclusion – that climate variation was responsible for the lower flow of the North Concho river between 1962 and 1968 than during the previous 40 years – was faulty.

Change driver 2: Groundwater contributions have declined, due either to woody plants or groundwater pumping. On the basis of our analysis, we reject this explanation as well. If higher evapotranspiration (owing to the greater density of woody plants) or groundwater pumping were contributing to the drop in streamflow, there would be a corresponding drop in the baseflow component (baseflow being derived directly from groundwater or soil water). We did see a very small decline in baseflow from the North Concho (about 10% of baseflow or 0.1 $mm\,yr^{-1}$), which may indeed be a response to the greater number of woody plants, especially along the river channel. But this decline represents a tiny fraction of total streamflow and cannot by itself explain the overall change in streamflow. Further, woody plants have increased in the Middle and South Concho watersheds as well, but there was no drop in baseflow (in fact, for the Middle Concho there was a marked increase). Groundwater pumping, although an important driver of streamflow change in many semiarid catchments (DuMars & Minier, 2004; Stromberg *et al*., 2005), is not a factor here because irrigated agriculture is quite limited in the basin and much of the groundwater that is used comes from deeper regional aquifers.

Change driver 3: Stormflows are lower because of improving range condition. Our analysis makes it clear that most of the streamflow in the Concho basin is produced by stormflow – episodic flooding events that fill reservoirs. Such events have decreased in magnitude in all the Concho watersheds over the past 50 or so years, even though precipitation has remained essentially constant. We propose that the most likely explanation for the decreased stormflow is higher soil infiltrability; and the most probable reason for higher soil infiltrability is greater vegetation cover – both woody and herbaceous plants. It has been broadly demonstrated, for many vegetation types, that rates of infiltration are higher beneath shrub canopies than in adjacent intercanopy areas (Lyford & Qashu, 1969; Seyfried, 1991; Joffre & Rambal, 1993; Bergkamp, 1998; Schlesinger *et al*., 1999). For example, on heavily grazed rangelands in north Texas, infiltration rates were more than twice as high under shrubs as in the intercanopy (Wood *et al*., 1978). Likewise, work in the Edwards Plateau region has documented the very high infiltration capacities of soils under both juniper (Gregory, 2006; Taucer, 2006) and oak canopies (Knight *et al*., 1984). The strong relationship between infiltration capacity and vegetation cover has also been demonstrated with respect to herbaceous cover, at scales ranging from that of the plot to that of the small watershed (Wilcox *et al*., 1988, 2003; Reid *et al*., 1999; Bartley *et al*., 2006). Infiltration rates decline in direct proportion to grazing pressure – dropping precipitously when the land is very heavily grazed (Blackburn *et al*., 1982).

From all this evidence, we conclude that in the Concho basin, the increases in vegetation cover – both woody and herbaceous – led to higher soil infiltration capacity, which significantly diminished the amount of stormflow in all three watersheds. In the case of the North Concho, the lower stormflow is the most likely driver of the reduced streamflow. For the

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Middle and South Concho, increases in baseflow have compensated for the decreased stormflow, explaining the absence of obvious long-term changes in streamflow. In other words, as highlighted in Fig. 6, increases in vegetation cover have resulted in a shifting of the water budgets with less water running off as stormflow and more water being stored in the soil. The additional water stored in the soil becomes available for either evapotranspiration or recharging the groundwater (baseflow). Increases in baseflow were observed only in the karst-dominated watersheds.

The influence of large-scale shrub removal on streamflow

The watershed-wide brush control program in the North Concho has provided a valuable opportunity to assess whether streamflow can be increased by managing woody plants in this region, a topic of considerable interest and controversy (Wilcox, 2002, 2006; Huxman *et al*., 2005). As of 2005, shrub control had been completed on about a third of the watershed. Although there are reports of localized increases in groundwater levels and streamflow in selected tributaries (Upper Colorado River Authority, 2006), we find no evidence (through 2005) of increased streamflow in the North Concho – either annual (Fig. 4) or event-based flow (Fig. 8). Our interpretation of the data available thus far, is that the historically low stocking rates in the watershed since 2000 (Fig. 2), in combination with shrub control, have allowed the regrowth of herbaceous cover, which in turn has maintained or even increased the infiltration capacity of the soils. As a result, stormflows have remained low. The net result is that on average, about 7 mm more water is stored in the soil than during the period of high degradation. This is a small amount compared with the total water budget, and most of it is probably evapotranspired, but it still can account for a significant reduction in streamflows and therefore water supply. Removal of woody plants had little impact on the community-level evapotranspiration. In other words, the total evaporative demand of the replacement vegetation (grasses and forbs) was comparable to that of a woody-dominated plant community.

Vegetation change and hydrology

The long-term trends in streamflow discussed in this paper can be fully understood only in the context of vegetation change. Vegetation cover in the Concho basin has undergone at least three distinct phases over the last 200 years, each of which has hydrological implications (Fig. 9).

Phase 1: Prairie savanna. Before settlement began in the 1870s, the basin was an open grassland or prairie savanna with good vegetation cover (mainly herbaceous) and intact soil. These vegetation and soil conditions would have kept erosion minimal. And with soil infiltration generally high, more water would be available for baseflow.

Phase 2: Degraded grassland. The severe overgrazing between 1875 and 1900 led to soil erosion and degradation of the grassland, conditions less and less able to support herbaceous species and susceptible to encroachment by woody plants. This state was maintained by relatively heavy grazing in the first half of the 20th century, during which time the number and size of woody plants continued to increase. Infiltration rates would have been much diminished compared with Phase 1; and as a result, overland flow and erosion would have been much higher, leading to increased stormflows and a reduction in baseflow and springflow.

Phase 3: Woodland/savanna. By the latter half of the 20th century, many areas of the basin were essentially closed woodlands. Some open areas have been maintained through brush clearing, and the better management practices have allowed herbaceous cover to begin coming back. As herbaceous cover continues to increase, we would expect to see hydrological recovery – lower overland flow, declining erosion, and increases in baseflow.

The hydrological transitions that would have accompanied these changing vegetation states are summarized in Fig. 9. Range condition was at its best during the prairie savanna phase, then declined precipitously with the abrupt transition to degraded grassland. From 1880 to the 1950s, with grazing pressure remaining very high, rangeland condition was poor. When grazing pressure began to decrease around 1960, and woody plant coverage increased dramatically, range condition began to improve. Then in the 1990s, grazing pressure began to drop sharply, which has further improved range condition. Changes in rangeland condition are directly reflected in stormflow or propensity to flood: when range condition is good, stormflow is low; and when range condition is poor, stormflow is high.

The relationship of baseflow to range condition is a little more complicated, being largely a function of geologic parent material. The North Concho, recall, has broad floodplains with deep soils, which would not facilitate high groundwater recharge. In contrast, a greater percentage of the parent materials in the Middle and especially the South Concho watersheds are limestone that is locally highly permeable (karst). Even during the prairie savanna phase, North Concho base-

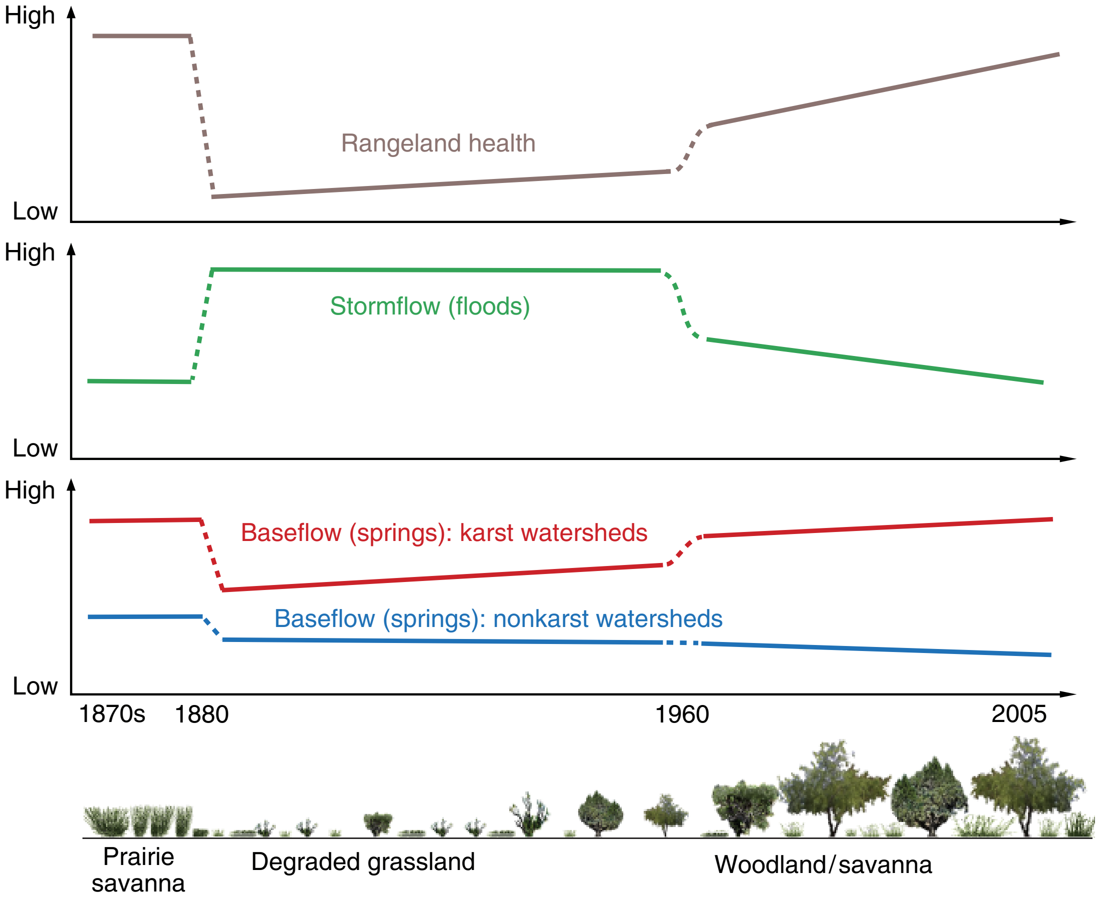

Fig. 9 Conceptualization of the hydrological and vegetation changes that have occurred in the lower plains of Texas since 1870.

flow was probably relatively low; and with the transition to a degraded state, with its higher stormflows, baseflow probably decreased somewhat. Baseflow has been about 10% lower for the North Concho watershed since 1960 than before, possibly reflecting the increased woody plant coverage along the riparian corridors. But this decline in baseflow represents only a very small percentage of total streamflow.

For the limestone-dominated watershed of the South Concho, baseflow remained relatively high even during very degraded conditions, which suggests a certain resilience to disturbance. One possible explanation is that recharge features on the landscape (sink holes, cave openings, fractured areas) act as buffers, capturing much of the additional overland flow brought about by landscape degradation. In addition, increasing vegetation cover and improved range condition means more water infiltrating into the soils, which contributes to baseflow.

A final point that is worth emphasizing: the changes in vegetation have had a major effect on streamflow, especially the stormflow component. But even though this has translated to a very significant decline in water supply and streamflow (about 70%) for the North Concho watershed, the change in the overall water budget is relatively small – averaging about 7 mm of water per year. Given the relatively deep soils on much of the North Concho, it is likely that this water is stored in the soils and made available for use by plants.

Conclusions

The last 150 years have seen unprecedented changes in vegetation on Texas rangelands and in the southwestern United States, initiated by overgrazing at the end of the 19th century. We have found that stormflow in the Concho basin is significantly lower now than before 1960, and we attribute this decline to the 'hydrological recovery' that has occurred since 1960 as vegetation cover – both woody and herbaceous – has increased. In other words, the relatively high streamflow pre-1960 was a product of overgrazed and generally degraded rangelands.

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These results are significant for a number of reasons. First, they demonstrate a large-scale hydrological response to degradation and then to recovery on a rangeland watershed. A basic tenet of range science and watershed management is that the water cycle reflects the health of the watershed. The close coupling between vegetation and runoff has been repeatedly demonstrated at small scales, but very rarely – if at all – at larger scales. In fact, to our knowledge, this is the first demonstration of streamflow changes on rangelands in response to degradation and recovery at the watershed scale.

Second, our results provide a new explanation for declining streamflow in the Concho basin, particularly within the North Concho watershed. The relatively high streamflows that were typical before 1960 resulted from a cycle of land degradation that began around 1880 with catastrophic overgrazing. We have demonstrated that the declines in streamflow after 1960 in the North Concho are a signal of hydrological recovery rather than the usurping of subsurface water by woody plants. This hydrological recovery, ironically, has in large part been facilitated by the increase in woody plants. In other words, in contrast to the widely held belief that woody plants contributed to the degradation process, we find that they have actually been part of the recovery – providing cover and protection to the soils when there was little else in the way of vegetation. In fact, it is probable that the catastrophic flooding in San Angelo in 1936 and 1957 can be at least partially attributed to the degraded conditions in the Concho basin. With the post-1960 hydrological recovery, the magnitude of floods has been reduced.

Finally, our results suggest that for many semiarid rangelands (where baseflow is a small component of streamflow), large-scale shrub clearing in combination with sound range management will not lead to significant – if any – increases in streamflow. This is because proper management will enable a vigorous vegetation cover to be maintained, which means that infiltration rates will remain high and water will be retained in the soil and eventually used by plants.

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