Woody Plant Encroachment Paradox: Rivers Rebound as Degraded Grasslands Convert to Woodlands

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Abstract: The related phenomena of degradation and woody plant encroachment have transformed huge tracts of rangelands. Woody encroachment is assumed to reduce groundwater recharge and streamflow. We analyzed the long-term (85 years) trends of four major river basins in the Edwards Plateau region of Texas. This region, in which springs are abundant because of the karst geology, has undergone degradation and woody encroachment. We found that, contrary to widespread perceptions, streamflows have not been declining. The contribution of baseflow has doubled—even though woody cover has expanded and rainfall amounts have remained constant. We attribute this increase in springflow to a landscape recovery that has taken place concurrently with woody expansion—a recovery brought about by lower grazing pressure. Our results indicate that for drylands where the geology supports springs, it is degradation and not woody encroachment that leads to regional-scale declines in groundwater recharge and streamflows.

1. Introduction

Semiarid and subhumid rangelands have been radically transformed by the related processes of degradation and woody plant encroachment [*Asner et al.*, 2004; *Wilcox*, 2010]. By degradation, we mean the persistent loss of vegetation cover. Woody plant encroachment refers to the increase in trees and shrubs at the expense of perennial grasses. This transformation has been progressing throughout recent human history [*Brandt and Thornes*, 1996], but has accelerated during the last 150 years in response to a number of factors—including overgrazing, fire suppression, and climate change [*Eggemeyer and Schwinning*, 2008]. Because of the extent of rangelands the effects of degradation and woody plant encroachment on ecological, biogeophysical, and hydrological processes is potentially enormous [*Archer et al.*, 2001; *Huxman et al.*, 2005].

Degradation and woody plant encroachment are often initiated by periods of intense overgrazing [*Asner et al.*, 2004]. In the United States, for example, overgrazing of western rangelands beginning around 1875 set in motion a complex succession of ecosystem changes, including expansion of woody vegetation and, in some cases, widespread soil degradation [*Wilcox et al.*, 2008a]. From the Great Plains to California, grasslands and savannas have converted to mesquite, juniper, and creosote woodlands and shrublands. In the desert grasslands, woody plant encroachment may be a part of the desertification process; for example, when desert grasslands convert to creosote shrublands, the increase in woody plants leads to an increase in size and connection of the bare patches which often translates into higher runoff and erosion [*Wainwright et al.*, 2000]. In other environments, such as the mesquite shrublands in Texas, soil degradation does not necessarily accompany woody plant encroachment [*Simmons et al.*, 2008].

Given these large-scale vegetation changes on semiarid rangelands, one would expect to see parallel changes in regional streamflows [*Wilcox*, 2007]. In attempting to answer the question *Does Vegetation Change Lead to Changes in Streamflows?*, it is important to understand how runoff is generated, i.e., by what pathway water moves to the stream channel.

Runoff may be generated as surface flow (overland flow), groundwater flow, or both. If groundwater flow occurs, then rivers and streams will be supplied (at least for a period of time) with a relatively sustained flow called *baseflow*. In contrast, surface flow is associated with a specific rainfall event; referred to as *stormflow*, it lasts for short periods. Separating the streamflow record into baseflow and stormflow, therefore, gives an indication of how much runoff comes from groundwater sources and how much comes from surface water.

Both baseflow and stormflow may be affected by changes in vegetation cover, but the mechanisms leading to change are different for the two types of flow. Baseflows will be affected by vegetation change that results in changes to groundwater recharge. Stormflows will be affected by surface changes that alter the amount of overland flow. For example, as a rule, trees will use deeper water than grasses, thus a prevailing belief is that woody plant encroachment leads to declining groundwater recharge and, thus, lower groundwater contributions (baseflow) to streams. It is true that at smaller scales, both higher rates of evapotranspiration and reduced streamflows have been widely noted as forests expand or tree plantations are established [*Farley et al.*, 2005; *Stednick*, 1996; *Zhang et al.*, 2001], and this has strengthened the perception (both in lay and scientific circles) that woody plant encroachment leads to declines in springs and baseflows [*Miller et al.*, 2005; *Tennesen*, 2008]. At the same time, however, little actual documentation exists for such a cause-and-effect relationship between woody plants and streamflow, especially at larger scales [*Huxman et al.*, 2005].

Degradation, on the other hand, should lead to higher overland flows because soils will have less capacity to absorb water during rainstorms [*Wilcox et al.*, 1988] and therefore stormflow should be higher. The positive relationship between surface runoff and degradation has been repeatedly shown at the plot and field scales [*Turnbull et al.*, 2008]. But once again, at larger scales there is little evidence that this relationship holds [*Wilcox*, 2007]. One well-documented example of large-scale hydrological change as a result of degradation is the Sahel region of northern Africa, where conversion of woodlands to fallow agriculture has resulted in significant increases in surface runoff, groundwater recharge, and streamflow [*Favreau et al.*, 2009]. On the other hand, for landscapes that were formerly degraded and are now recovering in terms of vegetation cover (highlighted in Figure 1a), there should be a decline in surface runoff and thus streamflow because of the land's increasing ability to absorb rainfall. This has been observed for some rangelands in Texas [*Wilcox et al.*, 2008a].

The study reported on in this paper examines the extent to which streamflow has changed in the Edwards Plateau region of central Texas (Figure 1b)—a region well suited, in many ways, to an *investigation of how changes in land cover affect streamflow on rangelands*. First and foremost, these expansive rangelands are of enormous importance as a source of both ground and surface water. Even though the climate is semiarid, the underlying karst geology supports the prolific and renewable Edwards Aquifer, as well as many perennial rivers and springs. The Edwards Aquifer is the primary water source for the city of San Antonio and for numerous other smaller municipalities, and feeds an extensive network of irrigation systems for local agriculture. The Edwards Plateau region is the headwaters for several major rivers in Texas, including the Colorado, the Guadalupe, and the Nueces.

Second, these rangelands have undergone a radical transformation in the last 140 years, including both degradation (Figure 1a) and woody plant encroachment. These changes were set in motion by the influx of large numbers of livestock beginning in the late 1800's. For a short period of time, stocking rates at the turn of the last century were perhaps 10 times greater than current levels [*Box*, 1967](Figure 1c).

A simplified description of the complex and extensive land-cover changes that have taken place in this region would include three phases, as depicted in the cartoon in Figure 1c: (1) Before about 1890 woodlands were concentrated in the canyonlands to the south and east and savannas occupied most of the remaining areas; (2) over the next 75–80 years (until about 1960), through a combination of severe overgrazing and cutting of existing woodlands, the landscape was turned into a highly degraded and open one (Figure 1a); and (3) since about 1960, with declining grazing pressure, the landscape has been recovering and is currently more heavily wooded than at any time in the recent past [*Diamond and True*, 2008; *Smeins et al.*, 1997; *Ueckert*, 1997; *Walker et al.*, 2005].

2. Methods

To assess changes in streamflow, we analyzed annual trends in both baseflow and stormflow for the major rivers in this region for which data are available from at least 1925: the Nueces, Frio, Guadalupe, and Llano rivers (Table 1, Figure 1b). As noted above, the distinction between baseflow and stormflow is important because they represent two different flow regimes and runoff pathways. Baseflow is composed entirely of groundwater contributions, coming mostly from springs. Stormflow, on the other hand, is water that is contributed by specific rainfall events; some of this water may arrive via subsurface pathways [*Wilcox et al.*, 2008b], and some via overland flow.

To understand the relative contributions of groundwater and surface water to streamflow, and changes in those contributions, we used daily streamflow data to do a baseflow separation [*Arnold et al.*, 1995; *Arnold and Allen*, 1999]. Years for which records were incomplete were excluded. We then aggregated the data into annual values for baseflow and stormflow. We examined directional changes and trends in annual streamflow, baseflow, stormflow, and precipitation by applying the Mann-Kendall trend test, a nonparametric method [*Salas*, 1993] commonly used for determining hydrological trends [*Lettenmaier et al.*, 1994]. We used a two-tailed test with α= 0.10 to determine whether a trend is significant. First-order autocorrelation in the test dataset, if present, was removed through the Cochrane-Orcutt procedure [*Cochrane and Orcutt*, 1949]. The significance of the first-order autocorrelation was judged using Durbin–Watson statistics at a α=0.05 [*Bowerman and O'Connell*, 1993].

In addition to trends in streamflow, we evaluated trends in rainfall over the region, using the composite rainfall record for the Edwards Plateau region compiled by the U.S. National Climate Data Center [*Guttman and Quayle*, 1996]. Average rainfall in the Edwards Plateau region decreases from east to west but trends and patterns within the region should be consistent.

3. Results

For these river systems, streamflow makes up a relatively large percentage of the total water budget because of the large contribution from baseflows (Figure 2). In all cases, baseflow accounts for a higher percentage of streamflow than does stormflow.

The Guadalupe and the Frio are the most productive, with streamflows ranging from 7 to 20 percent of the water budget. The Nueces is somewhat lower but still relatively productive for a semiarid river. The Llano is the least productive.

Despite the fact that annual precipitation for the Edwards Plateau has not changed significantly over the period of record (and this is consistent with more comprehensive analyses [*Groisman et al.*, 2001; *Grundstein*, 2009]), we find that annual streamflow for three of the four rivers has increased—largely because contributions in the form of baseflow have increased (Table 1). Baseflow increased for the Llano as well, but this river did not show an increase in total streamflow. The streamflow record for all the rivers is punctuated by the 1950s drought, following which—in the 1960s—began an upward trend in baseflows that was well established by the 1970s. This relatively high baseflow has been maintained, and baseflows are now almost double what they were in the early part of the last century (Figure 3).

Our findings concerning stormflows are mixed. For the Llano we see a decline, as would be expected with a landscape where vegetation cover in increasing. For the Nueces, there was no change. But for the Guadalupe and Frio rivers, stormflows have been trending upward, albeit to a much lesser extent than baseflows; this upward trend, however, has not been accompanied by increasing peakflows [*Douglas et al.*, 2000].

4. Discussion and Summary

The results of the trend analysis are surprising—and at first glance counter-intuitive, being somewhat at variance with currently prevailing opinions. In the Edwards Plateau region we find no evidence for declining streamflow as a result of woody plant encroachment (Table 1, Figure 2). In fact, we find the opposite. The increases in streamflow are not the result of increasing rainfall, as has been observed elsewhere in the United States [*Groisman et al.*, 2001]. We believe they can be understood only in the context of the complex and extensive land-cover changes that have taken place in this region since about 1890. The landscape has gone through at least three phases: pre-settlement grassland (pre 1890), degraded grassland (circa 1890–1960) and recovering woodland (post 1960). The streamflow record, which encompasses phases 2 and 3, shows that groundwater recharge was lower during phase 2 (degraded grasslands) than during phase 3 (recovering woodland). In large part, these changes—

both degradation and recovery—are directly related to changes in grazing intensity (Figure 1c).

These findings run counter to current thinking in both lay and scientific circles [*Graves and Meinzer*, 2003; *Tennesen*, 2008]. The widely cited Zhang relationship [*Zhang et al.*, 2001], for example, predicts that in a climate like that of the Edwards Plateau region, recharge should have declined by as much 200 mm/yr as tree and shrub cover expanded. But while seemingly counter-intuitive and contrary to conventional wisdom, these findings do make sense in light of two considerations:

- the sequence of land-cover transformation over the period of record, and
- the mechanisms of runoff generation from karst landscapes.

During the third (recovery) phase of the land-cover transformation sequence, woody plant cover has increased; but because of declining grazing pressures, herbaceous vegetation has likely increased as well. The increase in both types of vegetation cover should contribute to higher infiltration of water into the soil [*Wilcox et al.*, 2008b] and thereby to higher groundwater recharge, which is the source of much of the baseflow in these rivers. Concurrently, the karst geology of this region has facilitated the rapid transport of water from the surface to storage as groundwater. Presumably recharge to regional aquifers, such as the Edwards and Edwards Trinity, have increased as well, for the same reason.

Our findings are pertinent to semiarid and subhumid rangelands in which springs and intermittent or perennial streams are found (karst, fractured bedrock, sandy substrate). They suggest that at regional scales, groundwater recharge (and thus baseflow and discharge from springs) may decline when these landscapes become degraded — But they challenge the notion that woody plant encroachment in these landscapes leads to declining groundwater recharge. In fact, they suggest that when woody plant encroachment follows on the heels of degradation it may even help reverse such declines.

These findings, then, shed new light on how both degradation and woody plant encroachment affect the hydrologic cycle. Nevertheless, questions remain. One of them is why total streamflow has increased for the Guadalupe, Frio, and Nueces rivers. The increases in baseflows were not compensated for by commensurate declines in stormflow. One possible explanation is that the collection area for the headwater springs of these three rivers extends beyond the boundary of the watersheds into the Llano watershed to the north (Figure 1b). In other words, as the rangelands have recovered, the gains in streamflow for these watersheds have come at the expense of declining stormflows on the Llano river.

A second question is, how do current baseflow conditions compare with those during the pre-settlement period (which is not included in the streamflow record on which our findings are based)? The question is an important one, because the rationale for restoring current woodlands to savannas relies heavily on the notion that doing so will increase groundwater recharge and streamflows. Investigations at the field and small-catchment scales (<20 ha) would suggest that conversion of woodlands to healthy grasslands results in additional groundwater recharge [*Wilcox et al.*, 2006], but these results need to be confirmed through studies at larger scales. A more provocative hypothesis is that baseflows are higher now than in pre-settlement times, because rooting by trees has facilitated groundwater recharge. But whatever the mechanisms, we can be certain that removal of woody plants will not result in additional groundwater recharge if at the same time poor management practices allow the landscape to become degraded.

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Table 1. Results of the trend analysis for the four river basins. Values in blue indicate a significant increase in flow; values in red indicate a significant decrease in flow.

Basin	**Size (km^2)**	**Streamflow**	**Baseflow**	**Stormflow**
			P values	
Guadalupe	2117	0.0038	0.0005	0.0992
Frio	626	0.0019	0.0020	0.0111
Nueces	1186	0.0065	0.0005	0.3037
Llano	2984	0.1095	0.0868	-0.0076

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Figure 1. Panel A: Paired photographs from the Sonora Research Station on the Edwards Plateau. The upper photo, taken around 1940, highlights the degraded state of the rangelands at that time. It is probable that most of the Edwards Plateau was in a similarly degraded state from around 1890 to the 1960s. The lower photograph, taken at the same location in 1993, highlights the improvement in condition seen for much of the Plateau since 1960. (photographs provided by Dr. Charles Taylor). Panel B: Location map of the study site. Panel C: Grazing by domestic livestock on the Edwards Plateau has declined dramatically since the early 1900s. The red lines represent the changes in livestock units by breeding females of different species for the Edwards Plateau region [*Walker et al.*, 2005]. The points are the historical stocking rates for the Sonora Research Station [*Smeins et al.*, 1997].

Figure 2. Panel 1: Composite annual precipitation for the Edwards Plateau region. The columns represent annual precipitation, and the solid line is the 10-year moving average. Panels 2–5: Components of streamflow for the Guadalupe, Frio, Nueces, and Llano rivers. Columns represent annual totals for baseflow, and solid lines the 10-year moving averages for streamflow, baseflow, and stormflow.

Figure 3. Box plots comparing baseflow for the period before 1950 with the period after 1970. The blue line is mean baseflow.