Geomorphology 305 (2018) 20–32

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Catastrophic flood disturbance and a community's response to plant resilience in the heart of the Texas Hill Country

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ARTICLE INFO

Article history:
Received 22 May 2017
Received in revised form 10 September 2017
Accepted 10 September 2017
Available online 18 September 2017

Keywords:
Biogeomorphic disturbance
Floodplain stripping
Riparian restoration
Limestone river

ABSTRACT

The Blanco River, which flows through the limestone Balcones Canyonlands of central Texas (USA), experienced catastrophic flooding in May 2015 that resulted in significant biogeomorphic disturbance to its riparian corridor. High-resolution aerial and satellite imagery from pre- and post-flooding for a 55-km reach of river were used to map and categorize patterns of disturbance by degree of severity ranging from complete floodplain stripping to no disturbance. The most severe disturbance occurred within the floodway near the channel and decreased with lateral distance into the 100- and 500-year floodplains. Disturbance patterns previously identified in the literature including meander scour, parallel chute scour, convex bank erosion, and macroturbulent scour were all present following this event, as well as substantial disturbance proximal to tributary confluences. In the aftermath of this event, TreeFolks, a local nonprofit organization, engaged with the community to actively replant and restore the riparian corridor of the Blanco River on public and private lands. These reforestation efforts supplement the natural passive recovery of the riparian corridor, enabling the system to recover more quickly and be resilient to future flood events.

1. Introduction

Biogeomorphic response to and recovery from flood disturbance are important for understanding the resilience of floodplain ecosystems, and particularly so for floodplains embedded within social-ecological systems. During the late night and early morning hours of 23–24 May 2015, the Blanco River watershed, in central Texas, USA, experienced a series of severe thunderstorms directly over its headwaters which produced >33 cm of rain over the period of only a few hours. Given that May 2015 was one of the wettest months in history for this region, with a monthly total of 584 mm, soils were already saturated and this heavy rain became direct runoff into channels and tributaries (NWS, 2015). The Blanco River crested at 14 m, which is 10 m above flood stage in Wimberley, TX, and 4 m higher than the previous flood of record that occurred in 1929 (USGS, 2017). This event led to record-setting flooding of the Blanco River (estimated as >500-year flood recurrence with a peak discharge of 5097 $m^3\ s^{-1}$) and near-record flooding of the confluent San Marcos River (USGS, 2017). The flood resulted in substantial biogeomorphic disturbance of the riparian corridor, in some cases including the complete removal of alluvium and vegetation through the process of floodplain stripping. Even in areas where the alluvium remained intact, much of the vegetation was uprooted, including centuries-old bald cypress (*Taxodium distichum*), some dating back to before eighteenth century Spanish colonization (Gaskill, 2015).

In response to the considerable loss of riparian forest along the Blanco River, TreeFolks (a local nonprofit) was contracted by county authorities to conduct riparian reforestation on public and private lands affected by the flood (TreeFolks, 2016). Riparian vegetation provides numerous ecosystem functions and services because it acts as a buffer between the aquatic and terrestrial zones of the river valley, and this was the primary reason for the county's action. It can slow floodwaters, cycle/sequester nutrients, regulate water quality, increase biodiversity, improve air quality, and enhance longitudinal habitat connectivity, among other benefits (Malanson, 1993; Naiman and Décamps, 1997; Fremier et al., 2015). The reforestation led by TreeFolks helps to sustain these benefits by enhancing the recovery process and promoting the resilience of this social-ecological system following this catastrophic disturbance. Resilience refers to the capacity of a system to recover from disturbance and maintain functions that influence how it responds to and recovers from future disturbances or changing conditions (Walker and Salt, 2006). Social-ecological systems refer to the complex and dynamic, linked interactions between humans and nature (Walker and Salt, 2006).

The May 2015 flood resulted in severe and extensive damage to the Blanco River corridor that the community and riparian environment will be recovering from for a long time. In this study, we have two main objectives linked to the physical and social aspects of this basin. First, we use high-resolution satellite and aerial imagery to map and

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http://dx.doi.org/10.1016/j.geomorph.2017.09.009
0169-555X/

classify the spatial patterns of flood disturbance by degree of severity. Second, we provide an overview of local community tree planting efforts directed toward enhancing the recovery process and resilience of the Blanco River riparian environment. Riparian environments can be more resilient than other ecosystem types to disturbances such as flooding (Naiman and Décamps 1997), and actively restoring them could provide numerous ecological and societal benefits. Of the documented ecosystem services provided by riparian forests, one of the most significant benefits for residents along the lower Blanco River is the moderation of flood discharges. Vegetation aids in the reduction of flood magnitudes by providing roughness (Wolff and Burges, 1994; Walczak et al., 2015; Chase et al., 2016; James et al., 2016), but not all plants are equal in this respect. Denser vegetation patches that provide foliage at several vertical structural levels are more efficient at regulating flood magnitudes than vertically open stands (Anderson et al., 2006; Manners et al., 2014). Manicured grass lawns, consisting of mowed nonnative grasses with sparse trees extending to the river bank are common along the Blanco River. This reduced (or absent) vertical plant structure in the riparian zone may have exacerbated the damage from the floods. Thus, a goal of active reforestation is to plant in areas previously absent of riparian vegetation as well as areas where the vegetation was removed by flood processes.

Revegetation of the riparian zone via active native tree planting and allowing passive regeneration, which are the restoration techniques used by TreeFolks, is a common method of restoring damaged or degraded riparian buffers (Viers et al., 2012; Guillozet et al., 2014). Active techniques involve deliberate vegetation planting (including germinated plants and/or dispersal of seeds), while passive techniques rely on natural revegetation via the soil seedbank or resprouting from live propagules. The goal of this combined active and passive approach is to allow the ecosystem to recover relatively quickly after potential future flood events (Lake et al., 2007; Guillozet et al., 2014).

Restoring the riparian corridor also provides a means for the community to cope with the aftermath of this devastating flood event. The Texas Division of Emergency Management reported that within the Blanco River counties, 416 homes were destroyed, 708 homes were damaged, 2 major bridges washed-out, 1 major bridge was damaged, and 14 flood-related deaths occurred from this event (TDEM, 2016). The only three stream gauges in the basin were destroyed during the flood (prior to the peak of the event); however, five new gages now exist with dual monitoring devices to withstand an even larger event (USGS, 2017). In this manuscript, we provide an overview of floodplain development processes and biogemorphic interactions within the context of an extreme event, quantify disturbance from the May 2015 flood, and describe the restoration efforts directed toward enhancing the recovery and resilience of the Blanco River riparian corridor.

2. Floodplain development and disturbance processes

Traditional floodplain development theories attribute floodplain deposits to lateral and vertical accretion that occur during high flows. According to the classic description by Wolman and Leopold (1957), a river's floodplain will continue to gradually aggrade until the river begins to channelize or incise within the valley, eventually developing a new floodplain and abandoning the older surface as a terrace. Over extended periods (hundreds to thousands of years) and driven by frequent, moderate-scale events, this process will continue within the valley as the river adjusts to changes in discharge, sediment, gradient, and baselevel (Lane, 1955; Wolman and Miller, 1960).

Although Wolman and Miller (1960) showed that the majority of river and floodplain modifications take place during frequent, moderate flow events, Baker (1977) and Nanson (1986) showed that stream-channel responses can vary widely under different climatic and physiographic conditions, including those characteristic of central Texas. The Wolman-Miller model accurately characterizes stream-channel responses for perennial rivers in the central United States, which drain low-relief landscapes characterized by thick soils with infiltration rates that exceed normal precipitation rates and produce low runoff. However, in Central Texas, many of the streams are seasonally intermittent or ephemeral, and they drain rugged landscapes, covered with thin clayey soils and resistant limestone bedrock, producing large-volumes of overland flow. These conditions, when coupled with intense precipitation, can lead to catastrophic flash flooding that rises and falls quickly and, in the process, can erode and reshape the stream channel and floodplain through the process of floodplain stripping (Baker, 1977). In Australia, similar flash-flood conditions have been recorded eroding floodplain surfaces and transporting floodplain sediments (2 m deep and 30 m wide) >500 m downstream in the Clyde and Manning rivers of New South Wales (Nanson, 1986).

2.1. Floodplain stripping

Because of the variability in valley physiography and runoff conditions, various classifications exist for river and floodplain responses to discharge and sediment characteristics. Schumm (1963, 1968) classified channels as three types: stable, eroding, and accreting, depending on discharge and sediment load. Nanson and Croke (1992) classified floodplains into three classes: high-energy noncohesive, medium-energy noncohesive, and low-energy cohesive, relative to stream power and sediment characteristics. These main classes can be further divided by a variety of orders and suborders based on specific floodplain-forming processes that involve accretion, erosion, or stripping. In laterally confined valleys, these development processes can alternate between extended periods of vertical accretion, followed by rapid erosion of the alluvial surface through floodplain stripping. Nanson (1986) suggested that for some rivers in Australia this process can be repeated every few hundred years.

Some notable studies on floodplain development and stripping processes have been described for the Clyde and Manning rivers in southeast Australia (Nanson and Young, 1981; Nanson, 1986; Warner, 1997) which, like the Blanco River, are characterized by hydrologic extremes that include periods of flooding and drought. However, a primary climatic difference between central Texas rivers and those studied in Australia involves temporal rainfall distribution. Southeastern Australia experiences a cyclic shift between flood-dominated periods and drought-dominated periods, each prevailing for about 50 years (Warner, 1997). In this setting, higher discharges and more frequent flooding occur during flood-dominated periods, while lower discharges and infrequent flooding occur during drought periods; and flood and drought periods have distinct morphological effects on the Clyde and Manning Rivers (Warner, 1997). Central Texas rivers (and southern Great Plains rivers more broadly; Matthews et al., 2005) differ from the southeastern Australian rivers in that, even during prolonged periods of drought, the region can experience intense rainfall in parts of a river basin that produce catastrophic flooding and morphologic change over the period of hours to days. Although distinct climatic factors influence southeastern Australia and central Texas, their flooding impacts on longitudinally connected river corridors can result in similar floodplain disturbances, including floodplain stripping.

Floodplain stripping is complex and influenced by a variety of factors including river morphology, valley geometry, riparian vegetation, and sediment characteristics. However, similar patterns of stripping have been identified in previous studies. Warner (1997) described three types of stripping: across meander chutes, parallel chute, and convex bank erosion. Across meander chutes are formed by high flows that cut across a meander and excavate a channel or portions of the floodplain. Chutes can range from low-level chutes that cut to the basal gravels to high-level chutes where grasses or other cover may still be present and small depressions may be cut and filled with sediment and debris. Parallel chutes are carved alongside the main channel during high flows where little alluvium is present at the meander apex. Convex bank erosion occurs on the inner bank of a meander when the concave bank is composed of bedrock.

Other destructive floodplain mechanisms include macroturbulent scour and surface channel scour (Bourke, 1994). Macroturbulent scour occurs when vortices form around obstacles such as large tree stands or debris dams creating 'swirl pits' on the floodplain. Surface channel scour forms when confined back channels along the floodplain are excavated by overbank flow during flooding. Flooding on small central Texas rivers has been shown to cause significant reworking of floodplain sediments resulting in the erosion of scour holes on the floodplain surface as well as the deposition of gravel bars and mid-channel islands (Patton and Baker, 1977).

Although studies have examined severe floodplain disturbances in unstable sand-bed rivers with unconsolidated floodplain sediments (e.g., Julian et al., 2012) during climatically regular flood-dominated periods (Warner, 1997) and in small tributary systems (Baker, 1977), a lack of research exists for the disturbance processes that occur in large river valleys with consolidated sediments such as the Blanco River. Additionally, differentiating and quantifying floodplain stripping processes at the scale of multiple kilometers was not conducted in previous studies. High resolution pre- and post-flood imagery allow this study to examine specific patterns of disturbances along 55 km of river. Understanding these disturbance patterns and floodplain development processes in this region has implications for public and private riparian area management and flood hazard mitigation efforts.

High intensity flooding, with low recurrence intervals, make central Texas one of the highest Flash Flood Magnitude Index (FFMI) ratings in the country (Baker, 1977). The FFMI evaluates the magnitudes of regular flood events in comparison to rare severe flood events (Beard, 1975). Earl and Dixon (2005) suggested that biased data calculations underestimate the flood probability for high magnitude events in this region, and they are more likely to occur than previously expected (for more information refer to the special issue on the Central Texas Flood of 2002 in the journal *Physical Geography* 2005 26(5)). With extreme weather events becoming increasingly common because of climate change (IPCC, 2014), understanding the factors that influence the resiliency of river-floodplain systems is important in light of the effects of high-intensity flood events. Floodplain development processes and riparian vegetation are two factors that contribute to resiliency of social-ecological river-floodplain systems. When managed properly, they provide diverse functions such as sediment retention, floodwater attenuation, nutrient absorption, erosion control, and biodiversity — collectively allowing the system to absorb disturbance and maintain ecological integrity (Walker and Salt, 2006).

2.2. Biogeomorphic role of riparian vegetation

Riparian vegetation in and along the channel and floodplain plays an important role during flood-related disturbances because it decreases hydraulic forces via added roughness and increases hydraulic resistance via root reinforcement (Abernethy and Rutherfurd, 2001; Julian et al., 2016). Further, the aboveground biomass promotes vertical accretion during floods by enhancing suspended sediment deposition via reduced flow velocities and entrainment (Meitzen, 2005). Nanson (1986) proposed a disequilibrium model for floodplain development whereby vertical accretion occurs during normal and moderate flood flows. Vegetation establishes in the accumulated deposits until it forms a stable, mature riparian plant community, and then rather abruptly the riparian area is eroded during a single flood event or cluster of low-frequency, high-intensity flood events. This disturbance process is part of a metastable equilibrium adjustment that essentially restarts the floodplain accretion processes until the next major disturbance takes place, causing the system to once again cross a threshold resetting the riparian development.

The threshold at which a flood magnitude needs to exceed in order to erode a bank usually increases over time as riparian vegetation becomes established. With increasing vegetation density and vertical structural diversity, riverbanks and sediment deposits continue to become more resistant to erosion (Anderson et al., 2006). Well-established native grasses can also stabilize banks with their robust root systems and, in some conditions, provide more mechanical bank stability and cohesion than mature riparian vegetation (Simon and Collison, 2002; Julian et al., 2016).

Riparian species are well adapted to floods as a result of life-history strategies and morphological characteristics that allow them to survive inundation and disturbance. Catford and Jansson (2014) identified numerous adaptations that enable riparian plants to endure submersion, high flow, and anoxia, as well as to disperse easily to ensure their survival. Adaptations such as root structure and reproduction strategy, particularly hydrochory (seed dispersal via flowing water), give riparian plants an advantage in frequently flooded environments (Naiman and Décamps, 1997). An experiment by Kui and Stella (2016) found that some riparian species can survive complete burial by sediment, which can happen with flood deposits. In many cases between major flood events, mid-channel islands and other frequently disturbed areas in or near the channel are colonized by early successional pioneer species, including black willow (*Salix nigra*), which can handle sedimentation and hydraulic disturbances (Hupp, 1992).

Flooding may also increase biodiversity in riparian zones. In a study of plant communities along rivers in Denmark, Baattrup-Pedersen et al. (2013) found a positive correlation between low-intensity floods and species richness (number of distinct species) in the floodplain, indicating that floodplain forests benefit from frequent low-magnitude floods. In a similar study, Greet et al. (2015) studied the effects of floods on riparian sites in the Goulburn-Broken catchment in Australia. They note that species richness of exotics declined following the floods, but native taxa did not decline. Richness of native woody species remained stable, and richness of native annuals increased.

Large floods scour away some plants, creating more heterogeneous patches of vegetation (Jansson et al., 2007). A high-intensity, low-frequency flood on the Sabie River in Kruger National Park, South Africa, stripped some riparian and floodplain vegetation, increasing biodiversity by creating a heterogeneous, patchy landscape (Rountree et al., 2000; Rogers and O'Keefe, 2003; Parsons et al., 2005; Parsons et al., 2006). Some of this heterogeneity was the result of the deposition of large woody debris following floodplain stripping (Pettit and Naiman, 2005; Pettit et al., 2005). Changes in floodplain geomorphology caused by erosion or sedimentation in large floods provide a platform for natural succession processes to occur and promote age diversity in riparian vegetation (Dixon et al., 2002; Van Pelt et al., 2006). Following a disturbance as devastating as the floods of 2015, the riparian forest regenerates naturally through a process of succession. Egger et al. (2015) described this process for rivers in western Montana. The authors found that community structure and succession varied with regards to land use, channel structure, and flow regulation. When a site becomes barren (which occurs with floodplain stripping), the first species to populate the site are those that grow in full sun. After an increase in vegetation, the community shifts to a transition phase marked by the dominance of herbaceous plants such as reeds and sedges. Within 5–15 years, shrubs become dominant, followed by fast-growing trees that increase shading at ground level. Over time, slower-growing, shade-tolerant trees begin to dominate. Finally, barring any additional disturbance, the forest reaches a climax stage marked by long-living tree species.

Successional processes and patterns, among other factors, are responsible for the community composition and structure of the riparian forest. Frequently disturbed communities remain relatively simple in composition, whereas communities that are less frequently disturbed become more complex (Harris, 1999). Disturbances can determine successional patterns by their ability to reshape the landscape. Depositional and erosional processes create microtopography within the floodplain, which affects the composition and structure of vegetation communities

(Turner et al., 1998; Dixon et al., 2002; Latterell et al., 2006). Plants themselves can contribute to the creation of these microtopography and floodplain development processes by trapping sediments during flood events, as seen on the Tagliamento River in Italy (Gurnell and Petts, 2006; Gurnell et al., 2008; Bertoldi et al., 2009). Hefley (1937) and Ware and Penfound (1949) determined that riparian community composition on the Canadian River in Oklahoma occurs along an elevational gradient extending from the water's edge to a terrace above the bank. The vegetation shifts in this community over time was related to dune formation associated with spring floods. Hodges (1997) also found that succession was related to sedimentation following floods. In his synthesis on bottomland hardwood forests, Hodges (1997) noted that sedimentation patterns (over space and time) determine which species become dominant because they create differences in elevation, soil moisture, and other factors that favor some taxa over others. In their study of a previously-logged riparian forest in South Carolina, Kupfer et al. (2010) also found that succession paths can be guided by soil characteristics and flood regimes.

Following a disturbance, riparian restoration projects can aid forest regeneration and complement natural succession. In some cases, rebuilding the riparian zone can facilitate relatively rapid recovery similar to reference conditions (e.g., historical compositional, structural, and functional conditions, or those conditions found in a similar, relatively unaltered riparian ecosystem; Rheinhardt et al., 2007), but recovery of ecosystem functioning can lag behind recovery of forest composition (Lake et al., 2007, Matzek et al., 2016). Planting native species should be considered when developing a comprehensive restoration plan (González et al., 2017), and can be particularly advantageous by facilitating a change in herbaceous vegetation from full sun-tolerant (often dominated by exotic pioneer herbaceous vegetation) to native shade-tolerant species found in later successional stages (Bourgeois et al., 2016). Another crucial component of a successful restoration project is allowing regeneration from the seed bank (O'Donnell et al., 2015). Encouraging natural processes to occur increases the chances for the goals of the restoration to be attained. Restoration projects should focus on supporting or reintroducing natural processes, rather than only recreation or aesthetics. The result should be a resilient system that mimics reference conditions (Wohl et al., 2015).

3. Geographic overview of the Blanco River

3.1. Hydrogeology, soils, and vegetation

The Blanco River watershed drains an area of 1140 km^2 before it reaches its confluence with the San Marcos River, which is part of the greater Guadalupe River Basin. The Blanco River headwaters begin in the Edwards Plateau — Balcones Canyonlands ecoregion and flows 140 km to its confluence with the San Marcos (Fig. 1). The upper watershed is a karst terrain characterized by rolling, eroded limestone hills and a vast network of underground drainage created by dissolution of limestone. This landscape is very hilly, with areas of relief >100 m from valley bottoms to hill tops, and for this reason it has been commonly identified (since ca. 1840), as the 'Hill Country' (Jordan, 1970). This upper and middle portion of the study area is dominated by soils of the Brackett-Eckrant-Real series, including (i) areas of Brackett-Rock outcrop consisting of steep, shallow, calcareous clay loam soils and bedrock with slopes ranging from 8 to 30%; (ii) Eckrant-Rock outcrop made up of steep, rocky, shallow, clay soils; and (iii) Comfort complex soils consisting of shallow, stony, clay soils near the channel with slopes ranging from 1 to 8% (NRCS, 2017). These shallow soils and outcrops of upper Cretaceous limestone, mostly from the Glen Rose and Edwards formations, make up the headwaters, as well as the canyon-entrenched reaches of most of the middle segments (Smith et al., 2015; TWDB, 2017).

The Blanco River is fed by springs throughout the upper and middle drainage basin; however, depending on climate conditions, the main

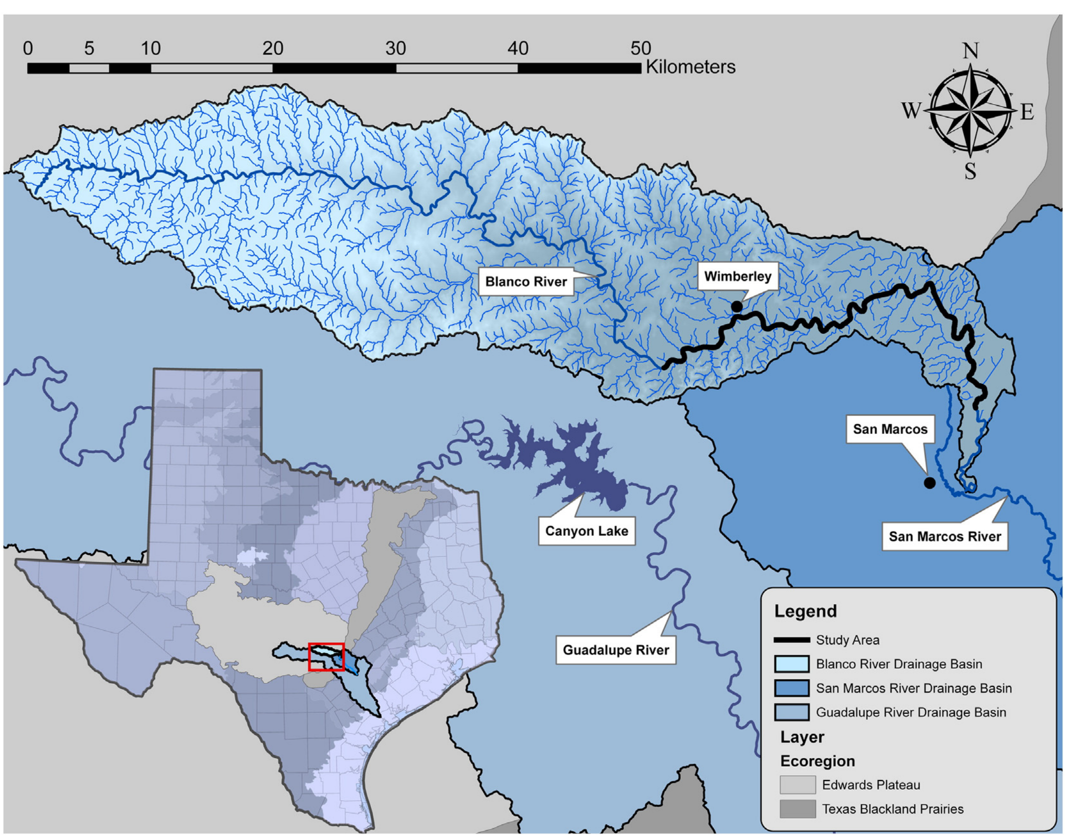

Fig. 1. Study area within the Blanco River drainage basin in central Texas.

stem and tributaries can be perennial, intermittent, or ephemeral. Surface-groundwater interactions are prevalent along the Blanco River as it interacts with Trinity Aquifer units in the upper portions of the river and Edwards Aquifer units in the lower river, becoming a gaining river in some areas and a losing river in areas with fractures and karst swallets (Smith et al., 2015). The Blanco River receives most of its rainfall in late spring (May–June) from regional frontal systems and in the late summer and fall (September–October) from summer thunderstorms and tropical disturbances migrating from the Gulf of Mexico. These are also the seasons when flooding is most frequent (Earl, 2007). Riparian vegetation includes hardwoods such as the bald cypress (*Taxodium distichum*), black willow (*Salix nigra*), and American sycamore (*Platanus occidentalis*), as well as native grasses and shrubs.

Downstream of the Balcones Escarpment, the lower Blanco River valley transitions to the Floodplains and Low Terraces ecoregions, which are part of the Blackland Prairies ecoregion. The dominant soils in this ecoregion are Houston Black, Heiden, and Wilson series that are well-drained permeable soils weathered from Cretaceous to Pleistocene age mudstone. As the floodplain widens downstream, Orif soils (which are moist, frequently-flooded soils with 0 to 3% slope) become more prevalent directly along the channel and floodplain (NRCS, 2017). The lower valley contains a more extensive floodplain and terrace complex compared to the river's confined upper reaches and is characterized by similar forest cover and native grasses such as bluestem (*Andropogon gerardii*) and yellow Indiangrass (*Sorghastrum nutans*) (Griffith et al., 2008).

The ecotone between these two regions contains a mixture of the aforementioned soils from the upper and lower reaches, as well as Lewisville silty clay and Seawillow clay loam which range from moderately deep to very deep, friable clayey soils to deep, fertile loamy clay soils (NRCS, 2017). Where the Blanco intersects the Balcones Escarpment, the river becomes influent (or losing) as it crosses the fractured limestone of the Edwards Aquifer Recharge Zone. The Blanco River's transition from the Balcones Canyonlands to the Northern Blackland Prairie provides a contrast of channel geometries and physiographic conditions that make it a natural experiment on the variability of responses to flood-related disturbances.

3.2. Social-ecological history

This area has a long history of indigenous cultures, with European settlement beginning in the early 1700s when Spanish explorers established outposts and later missions along the fertile land of the Blanco River watershed. The early to mid-1800s saw increased settlement and agricultural land use, with the hillslopes and prairies mostly used as ranges for cattle and valleys for cotton cultivation. Ranching and cultivation were the cornerstone to the local economy throughout the rest of the century with corn (*Zea mays*), barley (*Hordeum vulgare*), and other crops proliferating as railroads were established in the area (Dobie, 1948).

Presently, croplands (wheat (*Triticum aestivum*), hay (*Lolium* spp.), oats (*Avena sativa*), peaches (*Prunus persica*), and pecans (*Carya illinoinensis*) and ranching (sheep, cattle, goats, and turkey) dominate the upper Blanco watershed, while urban development (right up to the river's banks) dominates the middle to lower Blanco River near the cities of Wimberley, Kyle, and San Marcos. Increases in impervious cover occur throughout the watershed, as well as a loss of riparian tree cover mostly replaced by manicured grass lawns. This history of land cover changes has likely reduced infiltration throughout the basin and may have led to increased runoff contributing to the May 2015 flood. Many of these trends are expected to continue in the future (Sansom et al., 2010), especially with Hays County being one of the fastest-growing counties in the nation over the past 5 years and with its location situated mid-way between the Austin and San Antonio metropolitan areas. However, as we will highlight in the post-flood recovery discussion, local community efforts help educate landowners on the importance of maintaining riparian buffers and active and passive restoration planting practices.

4. Geospatial data and methods

This study uses a combination of aerial and satellite imagery integrated within a geographic information system (GIS) to identify and map (via digitizing polygons) patterns of flood disturbance along a 55-km segment of the mainstem Blanco River. The 55-km segment was selected based on the extent of available imagery for pre- and post-flood dates, time allotted to the project for mapping, and stakeholder interest in mapping the river segment that spanned the outskirts of the town of Wimberley. Mapping river channel and floodplain changes is a common technique to examine biogeomorphic responses to disturbances such as floods (Forman and Godron, 1981; Graf, 2006; Meitzen, 2009; Julian et al., 2012). Post-flood changes were mapped using high-resolution aerial and satellite imagery. The aerial imagery was granted courtesy of the Texas Google Imagery Service Pilot Project (TNRIS, 2017), and the high-resolution multispectral satellite imagery was granted courtesy of the DigitalGlobe Foundation (Digital Globe, 2017). The Google Imagery Service aerial imagery was true color and had a spatial resolution of 0.15 m. We used aerial imagery from 2 October 2014 and 18 January 2015 for pre-flood and 13 July 2015 for post-flood. The DigitalGlobe satellite imagery data is from the WorldView-2 sensor which had a spatial resolution of 1.84 m. The pre-flood satellite imagery was captured on 14 March 2015 and the post-flood imagery date was 29 May 2015. The pre-flood aerial imagery covered the entire Blanco River watershed, and the post-flood aerial imagery missed some of the western portions of the study reach. For these portions, we used the satellite imagery in order to have full coverage.

Because the satellite imagery had a coarser spatial resolution than the aerial imagery, it was initially difficult to identify disturbance patterns at the target scale of 1:800. Thus, we pan-sharpened the WorldView-2 imagery using the 'Create Pansharpened Raster Data set' tool (with the Intensity Saturation Hue method) in the arcpy library, which fuses data sets with their higher resolution panchromatic raster (ESRI, 2017). This technique increased the spatial resolution of the imagery from 1.84 m to the 0.46 m resolution of the panchromatic band. At this new resolution, disturbance patterns could be identified and categorized at a 1:800 scale. The satellite imagery was also slightly misaligned with respect to the aerial imagery owing to the sensor being off nadir. We reprojected the data to match the Google Imagery Service (WGS 1984 Web Mercator Auxiliary Sphere) and georeferenced using houses and other fixed objects along the river as ground control points.

Using on-screen digitizing, we mapped the areas of disturbance that occurred along the Blanco River. The Federal Emergency Management Agency (FEMA) floodway and 100- and 500-year floodplain boundaries (FEMA, 2017) were used to guide the mapping procedures; all disturbance within the layers were mapped, as well as disturbances that occurred beyond the 500-year boundary. The mapped disturbances within each FEMA floodplain boundary were then categorized by the degree of disturbance. A two-part scheme consisting of attributes that captured riparian vegetation disturbance and geomorphic disturbance was developed. The riparian vegetation disturbances include five main categories of disturbance and a category for no change. The geomorphic categories include three additional disturbance categories and one category for areas of no change (Fig. 2). Over 950 polygons were digitized for riparian disturbance and almost 500 for geomorphic disturbance over the 55-km study reach.

Total area of riparian and geomorphic disturbances were calculated for each category for the entire study area and relative to the three FEMA floodplain boundary layers. Descriptive statistics are reported for total area for each disturbance category for each of the FEMA boundaries and as the percent of disturbance represented for each boundary area (results Tables 1 and 2) and as percent of each disturbance category

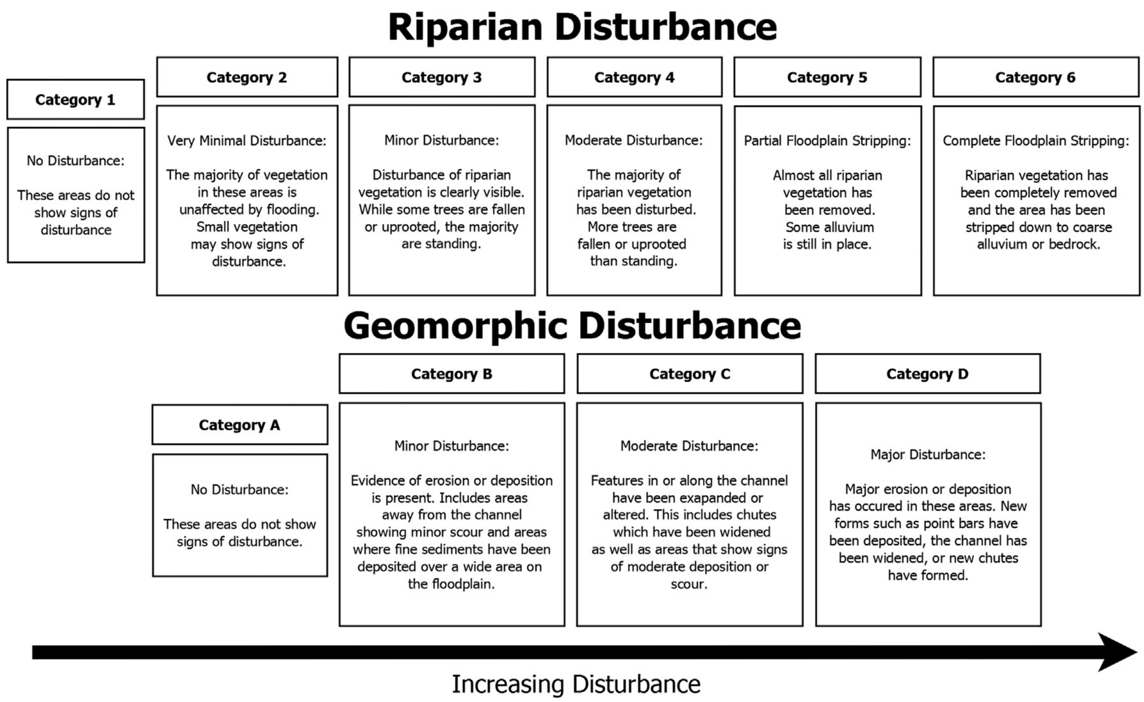

Fig. 2. Category schema for describing riparian and geomorphic disturbance patterns.

total per FEMA floodplain boundary (results Figs. 3 and 4). A spatial overlay comparison intersecting the riparian and geomorphic disturbances was examined using Pearson's correlations to test the agreement of their different disturbance category schemas (results Table 3). The expectation here was that categories for riparian and geomorphic disturbance would correlate relative to severity of disturbance. We also performed a separate overlay quantifying the percent of area for the active restoration tree-planting efforts that occurred within the different riparian and geomorphic disturbance categories (results Table 4).

5. Results

5.1. Riparian disturbance

The total area of riparian disturbance, including all five categories, covered 9,322,231 m^2 (Table 1). Total disturbance area was highest with the least severe category-1 (2,390,415 m^2) and lowest with the most severe category-5 (1,112,288 m^2). The no change category-0 represented the largest mapped area (18,204,985 m^2) within the floodplain boundaries. These broad-scale patterns are also consistent with increasing distance from the channel for the FEMA boundaries for the floodway and the 100- and 500-year floodplains. Relative to each category of disturbance, the greatest area of the most severe disturbances occurred proximal to the channel in the floodway and decreased with increasing disturbance (Fig. 3).

Another observed pattern associated with the floodplain boundaries was a decrease in the area of disturbance for each disturbance category with increasing distance away from the channel as depicted by floodplain boundaries (Table 1). The small exception to this trend is the lowest severity category-1, which had an area of 784,060 m^2 in the floodway (8.9% of the floodway) compared to an area of 957,341 m^2 in the 100-year floodplain (9.8% of the floodplain); and when viewed relative to percent of total disturbance per disturbance category, the former is 32% while the latter is 40% (Fig. 3). The area of disturbance,

Table 1
Riparian disturbance category totals (area in m^2, percent is out of total disturbance for FEMA floodplain boundary).

Disturbance	Floodway		100-year floodplain		500-year floodplain		Outside floodplain		Total area
0	3,142,443	35.7%	7,321,478	74.8%	7,741,064	91.7%	0	0.0%	18,204,985
1	784,060	8.9%	957,341	9.8%	407,566	4.8%	241,448	49.3%	2,390,415
2	1,150,184	13.1%	811,950	8.3%	189,636	2.2%	173,542	35.5%	2,325,312
3	1,573,610	17.9%	422,364	4.3%	66,204	0.8%	62,244	12.7%	2,124,422
4	1,151,172	13.1%	180,175	1.8%	32,967	0.4%	5480	1.1%	1,369,794
5	1,007,563	11.4%	92,354	0.9%	5607	0.1%	6764	1.4%	1,112,288
Total − Cat 0	4,515,417	64.3%	2,464,184	25.2%	701,980	8.3%	489,478		9,322,231

Table 2
Geomorphic disturbance category totals (area in m^2, percent is out of total disturbance for FEMA floodplain boundary).

Disturbance	Floodway		100-year floodplain		500-year floodplain		Outside floodplain		Total area
A	3,188,241	36.2%	8,433,580	86.2%	8,179,074	96.9%	0	0.0%	19,800,895
B	2,061,829	23.4%	904,268	9.2%	187,573	2.2%	67,507	43.9%	3,221,176
C	2,122,030	24.1%	331,264	3.4%	62,810	0.7%	74,648	48.5%	2,590,752
D	1,439,073	16.3%	116,488	1.2%	13,567	0.2%	11,746	7.6%	1,580,874
Total − Cat A	5,622,932	63.8%	1,352,020	13.8%	263,950	3.1%	153,901		7,392,902

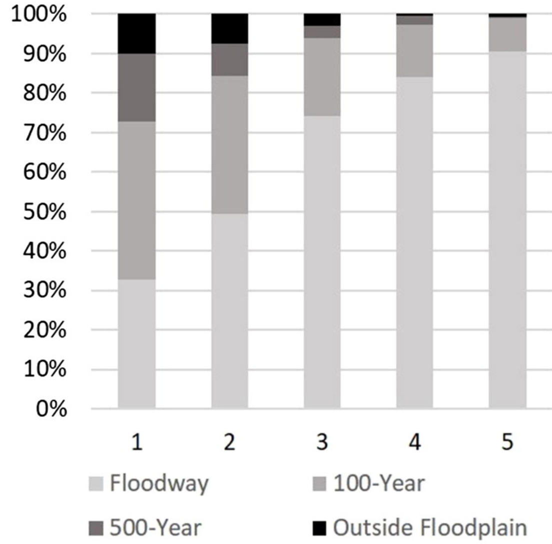

Fig. 3. Percent of riparian disturbance area for each FEMA floodplain boundary (floodway, 100-year, and 500-year) calculated relative to total disturbance for each disturbance category.

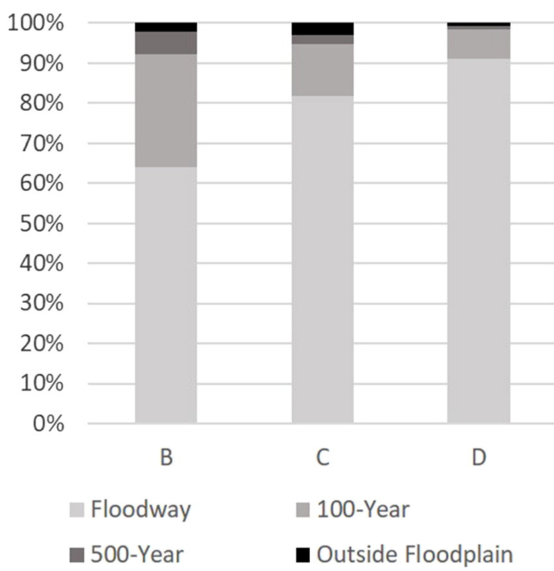

Fig. 4. Percent of geomorphic disturbance area for each FEMA floodplain boundary (floodway, 100-year, and 500-year) calculated relative to total disturbance for each disturbance category.

however, was lower in category-1 with the 500-year floodplain and outside of the floodplain compared to the floodway and the 100-year floodplain, which is consistent with the patterns for the other disturbance categories (Fig. 3). Disturbance linked to all five categories occurred outside of the 500-year floodplain and covered a total area of 489,478 m^2, which represented 5.3% of the total disturbance. Disturbance area also decreased with disturbance severity outside of the FEMA floodplain, apart from category-5, which had ~1300 m^2 more area outside of the floodplain than category-4. Total erosional channel area changes (i.e., erosion of river bank) summed to 793,048 m^2, representing 8.5% of the total amount of disturbance (9,322,231 m^2).

Table 4
Pearson correlations between overlap of riparian and geomorphic disturbance categories.

	CAT-A	CAT-B	CAT-C	CAT-D
CAT-0	**0.530****	−0.166**	−0.207**	−0.059**
CAT-1	−0.010	0.202**	−0.173**	−0.008
CAT-2	0.032*	0.280**	−0.197**	−0.009
CAT-3	−0.157**	**0.378****	0.042**	−0.283**
CAT-4	−0.102**	−0.301**	**0.371****	0.068**
CAT-5	−0.214**	−0.302**	0.108**	**0.388****

* Correlation is significant at the 0.05 level (2-tailed), bolded values reveal the strongest relationships.
** Correlation is significant at the 0.01 level (2-tailed).

Table 5
Percent of planting area by TreeFolks relative to riparian and geomorphic disturbance categories (note that 30.9% of the area of planting is located outside of the mapped disturbance area and occurs either upstream, downstream, or beyond the lateral extent of mapped disturbance area).

	Area (m^2)	% of planting area per category
Riparian disturbance		
Category-1	19,511	5.8
Category-2	31,047	12.4
Category-3	75,354	14.1
Category-4	94,278	17.7
Category-5	101,960	19.1
Outside of study area	163,063	30.9
Geomorphic disturbance		
Category-B	105,647	19.9
Category-C	170,186	32.1
Category-D	88,817	17.1
Outside of study area	163,063	30.9

5.2. Geomorphic disturbance

The total area of geomorphic disturbance covered 7,392,902 m^2, and in general, the area of disturbance decreased with increasing severity of disturbance, as well as with increasing distance from the channel for the floodway and the 100- and 500-year floodplains (Table 2 and Fig. 4). The least severe category-B covered a total of 3,221,176 m^2, while the most severe disturbance category-D covered an area of 1,580,874 m^2.

The trend of increasing area per decreasing disturbance severity seen in the riparian categories did not occur in the floodway for geomorphic disturbance but did occur in the 100- and 500-year floodplains. For the floodway area, category-C and category-B covered about the same area (1% difference between the two), and collectively these

Table 3
Area of intersection between riparian and geomorphic disturbance categories presented as total area m^2 and as a percent in () of the total relative to geomorphic categories.

		Geomorphic disturbance			
		Category A	Category B	Category C	Category D
Riparian disturbance	0	**17,374,697 (87.7)**	168,263 (5.2)	207,111 (8.0)	455,156 (28.9)
	1	**1,284,534 (6.5)**	**807,858 (25.1)**	103,042 (4.0)	18,641 (1.2)
	2	**890,614 (4.5)**	**1,047,708 (32.6)**	196,892 (7.6)	48,554 (3.1)
	3	196,843 (1.0)	**979,384 (30.4)**	**798,229 (30.9)**	125,610 (8.0)
	4	39,210 (0.2)	201,049 (6.2)	**881,471 (34.1)**	**246,347 (15.6)**
	5	15,000 (0.1)	14,498 (0.5)	398,465 (15.4)	**681,896 (43.3)**
Total		19,800,898	3,218,759	2,585,211	1,576,204

The values in bold highlight the overlap of categories with the strongest relationships between the riparian and geomorphic disturbance intensities.

covered an area much greater than the most severe category-D. A similar pattern also occurred outside of the 500-year floodplain: 48.5% of this disturbed area occurred in category-C, 43.9% occurred in category-B, and the remaining 7.6% represented category-D disturbance. Total disturbed area outside of the 500-year floodplain covered 153,901 m^2, representing only about 2% of the total disturbance (7,392,902 m^2). However, relative to each category of disturbance, the greatest area of the most severe disturbances occurred proximal to the channel in the floodway and decreased with increasing disturbance (Fig. 4).

5.3. Disturbance intersections and restoration tree planting areas

The area of intersect relative to riparian and geomorphic disturbance severity align (Table 3). The least disturbed geomorphic category-B overlaps 88% with the lower riparian disturbance categories-1, -2, and -3; the moderately disturbed geomorphic category-C overlaps 65% with the moderate to severe riparian categories-3 and -4, and the most severe categories representing floodplain stripping for riparian and geomorphic overlap 58.9% (Table 3). Pearson correlations calculated among the total area per riparian and geomorphic disturbance categories showed significant ($\alpha = 0.05$) agreement for related disturbance indices (Table 4). The geomorphic no change category (category-A) showed a moderate positive relationship with the riparian no change category (category-0; $R = 0.530$, $P = 0.01$). Category B had its strongest relationship with category-3 ($R = 0.378$, $P = 0.01$), category-C had its strongest relationship with category-4 ($R = 0.371$, $P = 0.01$), and category-D had its strongest relationship with category-5 ($R = 0.388$, $P = 0.01$). Another correlation pattern revealed that the less severe geomorphic categories had weak negative relationships with the more severe riparian categories; and similarly, the less severe riparian categories had a negative relationship with the more severe geomorphic categories.

The active tree planting efforts by TreeFolks spanned all riparian and geomorphic disturbance categories (Table 5). Their area of reforestation was greater than the area mapped for disturbances; however, where the projects overlapped, 51% of the planting areas occurred in more severely disturbed riparian categories-3, -4, and -5; and 49.2% of their plantings occurred in the more severely disturbed geomorphic categories-C and -D. The 30.9% of tree-planting area that occurred outside of the study area includes areas upstream or downstream of the area mapped for disturbances and areas of no-disturbance that are beyond the lateral extent of mapped disturbances.

6. Discussion

6.1. Patterns of disturbance

The majority of the disturbance and area of the greatest severity (category-5 for riparian and category-D for geomorphic) occurred within the FEMA floodway boundary, and disturbance for all categories decreased moving away from the channel into the 100- and 500-year floodplains. This trend is especially evident with the most severe riparian and geomorphic disturbances. For riparian category-5, 90.6% of its disturbance occurred within the floodway, only 8.3% in the 100-year floodplain, and 0.5% in the 500-year floodplain. Likewise with geomorphic category-D, 91% occurred in the floodway and only 9% of its total disturbance occurred within the other floodplain boundaries. Thus, for severe disturbance, a sharp gradient of disturbance moved away from the channel. The most intense disturbance was located in the channel, on mid-channel alluvial and bedrock islands, or directly alongside the channel, with the less severe disturbances located primarily on the 100- and 500-year floodplains outside of the channel. This pattern was similar to observations by Parsons et al. (2006) where floods resulted in floodplain stripping in areas near the channel, causing channel widening through the removal of riparian vegetation and alluvium.

This pattern of the disturbance gradient moving outward from the channel is illustrated with several meander bends (e.g., Fig. 5). The inside bend of the meander was completely stripped of vegetation, and major geomorphic disturbance was evident. Moving inward, severe stripping was still evident, but some grass and vegetation was still present as seen in the orange category-4 area. Farther inward on the floodplain surface, category-3 shows a tree stand that has been downed. The majority of trees have fallen or been uprooted but still remain in place. This was also the case across the river on the convex bank. Moving outward on both sides of the river were signs of minor geomorphic and riparian disturbance, placing the areas in category-B and category-1.

The strong correlations in the intersection of the riparian and geomorphic disturbances relative to disturbance severity provide a useful proxy for verifying the subjectivity of the digitizing process, particularly with the most severe categories. Because floodplain stripping is a biogeomorphic process that involves riparian and geomorphic change, a larger portion of the high severity geomorphic disturbance categories should intersect spatially with the high severity riparian disturbance categories. An interesting trend is evident between riparian categories-1, -2, and -3 and geomorphic categories-B and -C. These areas experienced minor to moderate disturbance. The flood was of a capacity and competence to transport moderate amounts of sediment and/or cause moderate erosion but not of a great enough force to completely erode the alluvial river bank and remove vegetation and was, therefore, just beyond the threshold of floodplain stripping. This is likely because of increased resistance from vegetation and root reinforcement, and the influence of these on floodplain roughness and reduced overbank flow velocities (Abernethy and Rutherford, 2001; Simon and Collison, 2002; Anderson et al., 2006).

6.2. Floodplain stripping, meanders, and tributaries

Floodplain stripping was widespread throughout the entire study area occurring in or directly adjacent to the channel (noted by riparian categories-4 and -5 and geomorphic category-D). Because floodplain stripping is a riparian and a geomorphic process, the most severe geomorphic category-D had a 58.9% intersect with the two most severe riparian categories, categories-4 and -5, respectively described as partial- and complete-floodplain stripping.

Aside from the intuitive patterns described above, we observed an interesting pattern associated with meander bends. Bends with a sharp curve, bound on one side by limestone canyon walls, experienced more severe disturbance and stripping on the inside point bar, while less severe disturbance occurred on the outside cutbank. These are instances of convex bank erosion that occur in areas with a resistant outer bank, similar to those reported by Warner (1997). In these confined, entrenched meander canyons, the point bars appear to have accreted with coarse limestone alluvium that, over time, became vegetated. During this flood event, these depositional surfaces were completely stripped, resetting the process of alluvial accretion and revegetation within the floodway. Another interesting pattern with meander bends involved places where floodwaters scoured chutes across the inside of the meander and/or parallel to the channel; similar disturbance patterns were reported by Warner (1997). Isolated scour holes, as reported by Bourke (1994), were also present on the Blanco floodplain and in the channel throughout the study area.

In addition to obvious erosional processes, the flood also contributed to floodplain construction, particularly where bedload deposits were transported overbank and deposited on the floodplain as splay deposits (sensu Bourke, 1994). These blankets of sediment were categorized as either category-B or -C according to the amount of sediment deposited. Another geomorphic form that was seen throughout the study area was the deposition of large side-channel gravel bars and mid-channel islands. These bars and islands represent major geomorphic disturbance as new forms were created and were labeled category-D. The formation of these features lends credence to Patton and Baker (1977) who wrote about the major reworking of less resistant floodplain sediments within limestone channels with extremely resistant limestone bedrock. These


N
W
E
S
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50
0
100 Meters
Woodcreek
Wimberley
1045 ft
10,000
5,000
0
10,000 Meters
Legend
Geomorphic Disturbance
Riparian Disturbance
1
2
3
1
2
3
4
5

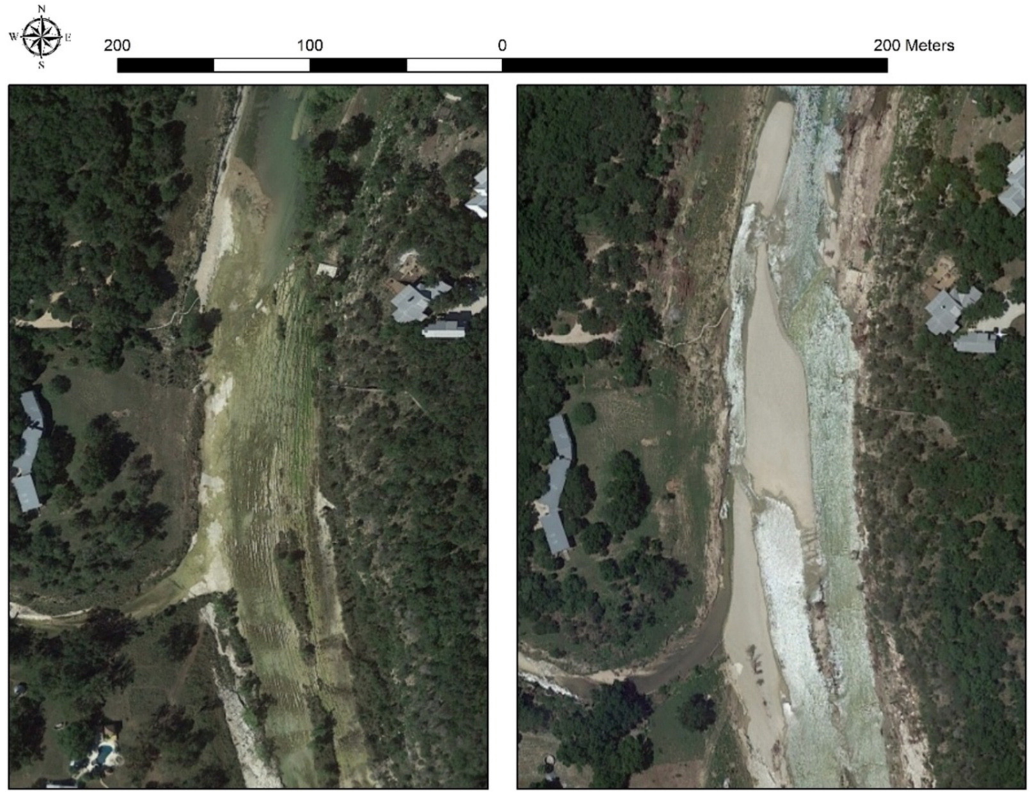

Fig. 6. Sediment deposits at the confluence of Lone Man Creek and the main channel. The image to the left is pre-flood and the right is post-flood.

mid-channel islands would be good candidates for future monitoring to see if vegetation is able to establish on them before they are eroded by the next major flood event (Hupp, 1992).

In many areas along the floodplain, portions of the hardwood, shrubby, and herbaceous vegetation were either uprooted or completely removed; yet the majority of the underlying alluvium and grasses remained. These areas were labeled as riparian categories-2 and -3 and geomorphic categories-A and -B. One possibility for this occurrence is that the grasses and their deeper roots increased the cohesiveness of the soils (Simon and Collison, 2002), but the force exerted on larger aboveground biomass of the shrubs and trees was too strong to keep their shallow roots in the ground.

Zones of major riparian and geomorphic disturbance (i.e., floodplain stripping) were observed at most tributary confluences (Fig. 6), with the greatest extent at the mainstem confluences of Lone Man, Cypress, and Halifax creeks. Similar patterns of floodplain stripping were seen at all three confluences, despite them being located along various reaches of the upper, middle, and lower sections of the study area respectively. The mechanisms that caused these patterns of disturbance at confluences are not entirely clear but is likely from interacting effects between complex hydraulic forces and channel biogeomorphology in terms of channel geometry (mainstem and tributary), the angle of confluence, local gradient, and vegetation type/structure (Guillén-Ludeña et al., 2016; Julian et al., 2016).

Of the tributary confluences, Lone Man Creek was of particular interest because it is dammed immediately upstream before it flows into the Blanco River. Dams typically limit sediment supplies (Graf, 2006; Julian et al., 2016); yet at this confluence, three large new sediment bar deposits were observed (Fig. 6). Because the first of these occurs upstream of the confluence, their presence is likely attributed to main stem sediment sources that were deposited by the reduced velocity proximal to the tributary confluence.

6.3. Planting riparian resilience

Significant natural disturbances, such as the May 2015 flood, can be devastating to vegetation communities. The damage typically is compounded in communities that have already been exposed to stressors, and frequent disturbances can ultimately lead to riparian degradation (Obedinski et al., 2001). Frequent disturbances can reduce the health of the ecosystem and result in its transformation to a less-dynamic state that differs in structure and function from resilient conditions (Obedinski et al., 2001; Walker and Salt, 2006). In the Texas Hill Country, periods of intense drought are known to occur on a regular basis (Smith et al., 2015); and leading up to the May 2015 flood, this region experienced extreme widespread drought from 2010 to 2015 (NDMC, 2017). A La Niña event triggered this drought which produced hot and dry conditions in the south-central United States and Mexico, and 2011 set an annual drought of record for much of Texas (Fernando, 2014). This prolonged extreme drought may have heavily stressed the riparian forest, increasing its vulnerability to the high-magnitude flood.

Following the aftermath of this catastrophic flood, TreeFolks, a local nonprofit organization, was approached by authorities in Hays County to propose a tree planting program to reforest the riparian zone of the Blanco River. This area included a 98-km stretch of 1060 residential properties that were affected by the flood disturbance. By September 2015, TreeFolks had embarked on a 4-year campaign intended to reforest the riparian zone on public and private land free of charge to landowners. Central to the project's goal is education; the extent to which

Fig. 5. Pattern of disturbance gradient moving laterally from the channel in order from top to bottom: pre-flood, post-flood, and riparian and geomorphic categories of mapped disturbance.

a private-land reforestation program is successful is the extent to which landowners understand the issues and are able to care for riparian forests into the future. Educating the landowners and other stakeholders aids the success of any restoration project by communicating clear goals and promoting an understanding of restoration measures (Reich et al., 2011).

This element of working with the community is at the core of the biogeomorphic and social-ecological resilience of the Blanco River's forests. By involving the community through volunteer events, landowner engagement, and the promotion of riparian management best practices, this project aims to enable the community of Wimberley to enhance their ability to withstand future floods. The project's visibility through signage and flags in newly planted areas helps to normalize the presence of riparian buffers on what were historically manicured lawns prior to the 2015 flood. Land-management education and volunteer events benefit the social resilience of the community by nurturing a sense of pride and support for the overall ecological goals of the project. Community involvement has contributed to the success in past restoration projects geared toward enhancing resiliency; the restoration of the Kristianstad wetlands in Sweden exemplifies this idea (Walker and Salt, 2006). The wetlands degraded from agricultural activities, urbanization, and flood control projects; and restoration managers were able to restore the Kristianstads through landowner engagement, education, and the incorporation of local knowledge and support (Walker and Salt, 2006).

TreeFolks received 'seed money' for this project from Hays County in the winter of 2015 to create a reforestation plan, begin community outreach, and plant two small pilot sites. Involvement by private landowners is completely voluntary, and they must submit reforestation applications with TreeFolks to be included in the program. To date, landowners have submitted reforestation applications with this program for 230 parcels. These are primarily private residences, and only 2 were classified as working ranches; at the ranches, only the riparian buffer was planted and no planting occurred in areas with actively grazing livestock. Site consultations began in the late spring of 2016, and Year 1 tree planting took place between November 2016 and February 2017. During the 2016–2017 season, TreeFolks planted 75 private properties, restoring 30 ha of the critical riparian ecosystem along the Blanco River in Hays County.

Program methodology includes three main components: (1) on-site consultation with participating landowners and several follow-up visits to establish and mark planting boundaries; (2) active planting and reforestation of the riparian areas; and (3) conducting survival studies. Each field site visit for parts 1–3 serves as an opportunity for in-depth reforestation education with the local landowners and their neighbors, as well as other community members in Hays County. These site visits help establish and promote the benefits of 'grow zones' where mowing will cease, in perpetuity, to allow a healthy, near-channel riparian forest to develop. Landowners were receptive to the educational outreach and concept of the 'grow zones', with many landowners establishing such zones in areas that were previously mowed. While tree planting is the only direct restoration activity provided by TreeFolks, their consultation is used to recommend local resources for other activities, such as grass seeding and erosion control.

TreeFolks provides the native tree seedlings, planting labor, and labor management at no cost to the landowners (Fig. 7). A mix of 20 native Texas riparian species grown from local seed sources by either local nurseries or a corporate grower were provided, including but not limited to bald cypress (*Taxodium distichum*), box elder (*Acer negundo*), sycamore (*Platanus occidentalis*), cedar elm (*Ulmus crassifolia*), rough-leaf dogwood (*Cornus drummondii*), and flame leaf sumac (*Rhus lanceolata*). Restoration planting plans separate facultative and obligate species into zones, relative to local hydrogeomorphology. A variety of tree planting events are implemented during the winter planting season (November–February), including community volunteers, youth service crews, and a private vendor.

Fig. 7. TreeFolks staff leading a planting demonstration for a group of volunteers from the local community.

Though the outlook for this active reforestation method is optimistic, monitoring is an important aspect, as it should be with any riparian management scheme (Winward, 2000; Piégay et al., 2016; González et al., 2017). Survival plots are established at that time, with a 20% survival target to mimic natural stocking rates. During site visits, each property's individual characteristics are also assessed using a Riparian Functional Analysis (RFA), designed after Jones-Lewey (2016) to rate riparian health in terms of ecosystem functioning. Additional studies are currently underway to monitor the reforestation of the riparian revegetation along the Blanco River in order to better understand the combined approach of the natural passive revegetation processes and the success of the active tree-planting restoration conducted by TreeFolks. Future studies will also integrate the recovery status for different sites relative to their riparian and geomorphic disturbance classification following the flood event to better understand recovery relative to disturbance severity.

TreeFolks reforestation projects on privately owned lands are unique nationally and are being recognized as an effective, cost-efficient model for tree planting relief after a disaster, and on the Blanco River they represent a fundamental step to biogeomorphic and social-ecological riparian resilience in the heart of the Texas Hill Country.

6.4. Social and ecological benefits of active reforestation

One of the common goals of restoration is to maximize the benefits provided to humans by natural systems. Plants are important biogeomorphic agents in fluvial systems (Gurnell et al., 2012; Julian et al., 2016). They contribute to the development of floodplain landforms and moderate flood processes. The canopy provided by riparian forests controls light availability within the stream, which in turn governs primary production and influences instream ecogeomorphic processes (Julian et al., 2011; Warren et al., 2016). The longitudinal structure of the riparian zone makes it ideal as a corridor, providing connectivity for faunal taxa and allowing the dispersal of flora (Fremier et al., 2015). A riparian buffer can also counteract changes in inputs of sediment and water brought about by human-induced land use changes (Jansson et al., 2007; Chase et al., 2016).

Most importantly with regards to the Blanco River restoration, vegetation within the floodplain acts to slow floodwaters. The vegetation provides roughness, which lowers the velocity of flows (Manners et al., 2014; Walczak et al., 2015), especially for low magnitude floods (Anderson et al., 2006). Manners et al. (2014) found that patches of vegetation perform better at moderating flood velocity than individual plants. A great amount of foliage density provides the most roughness (Walczak et al., 2015). These potential ecosystem services provided by the riparian forest guide restoration managers in prioritizing target outcomes for the project.

A growing concern is that climate change may increase the need for restoration to encourage riparian resilience to extreme weather events such as droughts and floods (Rivaes et al., 2013; Perry et al., 2015). In certain regions, the effects of climate change are already being observed with regards to disturbances, habitat loss, and erosion (Osterkamp and Hupp, 2010). Seavy et al. (2009) advised adapting restoration practices to projected climate change metrics in order to increase ecosystem resilience. Emphasizing such ecosystem services such as water temperature regulation and habitat connectivity have benefits not only to the immediate environment but to adjacent ecosystems as well.

A successful restoration project includes more than ecological factors. Social issues should also be taken into account (Piégay et al., 2016). Designing a project to include all stakeholders and consider factors such as recreation, aesthetics, and community support can improve the results (Nemec et al., 2013). Finally, restoration projects should include monitoring and assessment during and after completion of the project (Piégay et al., 2016). Evaluation of the functioning of a riparian forest should take place in all four dimensions: vertical, lateral, longitudinal, and temporal (Magdaleno and Martinez, 2014). This ensures a comprehensive understanding of the outcomes of the project.

7. Conclusions

Flood processes are a primary control on riparian biogeomorphic disturbance, and active and passive reforestation can contribute to its recovery. High resolution pre- and post-flood imagery are useful for mapping, categorizing, and quantifying severity of riparian and geomorphic disturbances caused by catastrophic flooding. Total disturbance area and severity of disturbance decreases with increasing distance away from the channel depicted by the floodway and the 100- and 500-year floodplains. Patterns of biogeomorphic disturbance, including across meander scour and parallel chute scour, were identified, as well as patterns of severe disturbance at tributary confluences. Mapping and characterizing the flood disturbance provides an important baseline to monitor the recovery of the Blanco River riparian corridor.

The May 2015 flood was ecologically and socially devastating to the Blanco River floodplain and its community. Following this tragedy, the city of Wimberley, located in the heart of the destruction, created the slogan 'Wimberley Strong', a message of unity, strength, and the resilience of the local community to recover from this event. The community outreach and riparian restoration efforts led by TreeFolks go hand-in-hand with this message by providing the resources to aid the recovery of this social-ecological system. The reforestation project will ultimately increase the floodplain vegetation density and structure along the Blanco River and potentially slow future floodwaters. Natural passive successional processes and the active revegetation by TreeFolks will eventually result in a functional forested floodplain that will provide significant benefits to the residents of the Blanco River watershed and those downstream. The willingness of local landowners to restore their riparian buffers is a necessary action to ensuring the resilience of this system and its ability to withstand and recover from future flood events.

Acknowledgments

The authors would like to acknowledge the following individuals for engaging in conversations and collaborations regarding research on the Blanco River May 2015 flood event: Chris Van Dyke, Kevin M. Yeager, Judy Haschenburger, and Jonathan D. Phillips. We thank Texas Natural Resource Information Systems (TNRIS) for use of the aerial imagery and DigitalGlobe Foundation for use of the satellite imagery, both were made available at no-cost through educational use agreements. We would like to acknowledge Andreina Alexatos, a staff member at TreeFolks, for engaging with the authors in the field and organizing numerous volunteer reforestation efforts on the Blanco River. Finally, we thank the anonymous reviewers for helping us improve the manuscript, and Dave Butler for inviting this submission as part of the special issue on Resilience in Biogeomorphic Systems.

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