Mobility of large woody debris (LWD) jams in a low gradient channel

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A B S T R A C T

Mobility of large woody debris (LWD) in low gradient channels is an important but often overlooked transport process. The majority of studies on LWD have focused on its role in geomorphic and ecologic river processes. When jams extend across the width of the channel, they have the potential to retain sediment and alter the channel profile. When jams obstruct only a portion of the channel, they can re-direct flow, altering patterns of scour and deposition. The boundary complexity created by LWD has a recognized role in riverine ecosystems which has led to programs of replacing LWD in-channel corridors where it was previously removed. Although LWD jams are common in rivers around the world, they have been studied most intensely in steep, forested channel reaches where they are often found to be stable channel features. It is not fully known how much of the information on LWD from steep forested channels will transfer to other channel types. Whereas it may be reasonable to assume that the ecological benefits of LWD are similar in low gradient channels, research has shown that a much higher rate of LWD transport occurs in low gradient channels, with jams mobilized on timescales of $10^3$-$10^5$ years.

This study evaluates the distribution and mobility of LWD over 72 km of the San Antonio River, a low gradient channel in southeast Texas. LWD jam locations were identified for 2003 and 2007 using a combination of aerial photography and field mapping. Each jam was cataloged according to its location in the channel cross-section and the amount of channel area blocked. During the four-year period, all the LWD jams were mobilized, including those jams extending across the channel width. Although easily mobilized, 34 jams re-form in the same locations, creating 34 channel locations with persistent LWD jams. Data from the San Antonio River are applied to two models developed to predict LWD mobility and transport distances to assess the applicability of each model to a low gradient channel. The locations of stable (or recurring) LWD jams were matched to model results where predicted LWD transport distances were equal to measured LWD jam spacing. Model results showed good agreement with the mean and median spacing of LWD jams when given input parameters specific to the channel and wood species. The ability to predict where LWD jams will persist over time in a low gradient channel has application in watershed management. Persistent LWD jams can exert a greater influence on channel morphology and may require active management.

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1. Introduction

Large woody debris (LWD) and woody debris jams have been documented in rivers over a number of continents and physiographic regions (i.e. Lisle, 1986; Gurnell et al., 2000; Haschenburger and Wilcock, 2003; Daniels and Rhoads, 2003; Faustini and Jones, 2003; Comiti and Lenzi, 2006). Woody debris has attracted the interest of researchers for its ability to enhance aquatic ecosystems, affect channel morphology, and alter channel hydraulics. It can create flow resistance and influence the formation of channel bedforms, including inducing step pool formation. Where wood jams form, upstream reaches can experience backwater effects and induce sediment deposition (Daniels, 2006). The majority of LWD studies have been conducted in forested areas where little anthropogenic influence has occurred in the form of bridge construction or channelization (i.e. Swanson et al., 1982; Wohl and Goode, 2008).

LWD and wood jams were common in American rivers prior to the 19th century. Much of this wood was removed during the 19th and 20th centuries to improve river navigation, reduce flooding, and enhance ecosystems (Montgomery et al., 2003). Many studies have focused on rivers where the detrimental impacts of wood removal on channel morphology and aquatic ecosystem health were first documented: steep channels within forested landscapes. A number of geomorphic, ecologic, and hydraulic characteristics have been tied to the presence of LWD. Research has shown a link between LWD and channel morphology (i.e. Robison and Beschta, 1990; Nakamura and Swanson, 1993; Montgomery et al., 1995; Abbe and Montgomery, 1996; Wallerstein and Thorne, 2004) ecological value through enhanced ecosystem habitat (i.e. Bilby and Likens, 1980; Smock et al., 1989; Benke and Wallace, 1990), and hydraulics in the immediate region of LWD jams (i.e. Magna and Kirchner, 2000; Manners et al., 2007). LWD is
defined as logs with either a diameter of 0.1 m or a length of 1 m. Logs are supplied to channels through riparian tree mortality, bank failure, channel incision, windthrow, and floods (Downs and Simon, 2001; Wallerstein and Thorne, 2004).

The extent of the impact of LWD on channel morphodynamics is largely a function of the residence time of the logs in the channel. Residence time measures the period of time LWD and debris jams remain stationary and is often measured by indirect means, for example as the age of young trees growing out on a stable jam (Martin, 2001). LWD and debris jams in steep channels can have residence times measured in decades and the effect on channel morphology can be significant (Wallerstein and Thorne, 1996; Webb and Erskine, 2003). In British Columbia, wood jams have been documented as stable for time periods in excess of 200 years (Keller and Tally, 1979). Rather than mobilizing during large flows, stable jams extending across the channel can develop a step pool morphology as flows over the jams scour a plunge pool downstream (Thompson, 1995; Webb and Erskine, 2003). Channel morphodynamics adjust to the presence of the wood and the channel planform is stabilized by the wood as the wood decays in place. Long residence wood is common in steep headwater channels in forested areas where channels typically have a width that is less than or equal to that of the average length of log that falls in the river. The fallen log remains in place, sometimes spanning the river width, as channel flow has a limited ability to mobilize and redistribute the wood. As a result, accumulations of LWD and jams are common in headwater channels (Keller and Swanson, 1979).

As the watershed area contributing to a channel increases, the size of the channel and rates of flow increase. The residence time of wood and wood jams decreases and understanding the mobility of the wood becomes increasingly important. LWD mobility focuses on how often wood moves in a given river system. It is measured through direct (tagging and surveying) and indirect (repeat aerial photography) methods (Gippel et al., 1996). The ability of the channel to transport the wood and the range of flows over which the wood moves increases as the channel width to log length ratio increases. In a small U.K. stream, 270 LWD jams changed position or character in less than 12 months during which the highest recorded discharge was near bankfull (Gregory et al., 1985). Channel spanning log jams are rarer as the channel width increases, but those jams that do form are typically larger than those found in the upstream reaches (Swanson et al., 1982). Mobility is often greater in low gradient channels which tend to have larger channel widths and a higher stream order.

Increased LWD and wood jam mobility does not necessarily correlate to reductions in the influence of wood on channel morphodynamics. Where LWD and wood jams are easily mobilized, the frequency of wood mobility and preferred deposition locations become important to understanding channel morphodynamics. When wood jams recreate in the same locations after each mobilizing flood, the effect on the channel can be similar to that of immobile jams. Low gradient channels are likely to include areas where the built environment intersects the river, making them subject to active channel and watershed management. It is important in these channels to understand how often the large wood moves and where it tends to accumulate so that management can be targeted and construction around channels can be more informed.

It is not fully known how much of the information on LWD from steep forested channels will transfer to other types of channels. Whereas it may be reasonable to assume that the ecological benefits of LWD are similar in low gradient channels, research has shown that a much higher rate of LWD transport occurs in low gradient channels, with jams mobilized on timescales of 10^2–10^3 years.

This study evaluates the distribution and mobility of LWD in a low gradient channel in southeast Texas over a four-year time span. The locations of LWD jams are documented and categorized according to type of deposition and amount of channel coverage. The purpose of the paper is to document and characterize the distribution of wood in the channel, to evaluate jam mobility, and to apply the field data of LWD mobility to models of log transport. This paper aims to fill a gap concerning wood in low gradient channels. By modeling the observed log movement, the paper evaluates the applicability of results from studies of LWD in steep channels to low gradient channels.

2. Study site

The study area encompasses 72 km along the main stem of the lower San Antonio River, from below San Antonio to the crossing of FM541 near Poth, TX (Fig. 1). This length of river has a watershed contributing area of 5473 km². The study reach begins downstream of the concrete-lined river reach within the city of San Antonio and falls entirely within the coastal plain physiographic region. Longitudinal slope in the study reach is 5.7 × 10^-4. Land use is historically dominated by ranches and agriculture outside of the city of San Antonio, where forested areas intersperse within the rangeland.

A U.S.G. gauging station, located at Elmendorf, TX (gage 08181800), coincides with the upstream end of the study reach. A continuous flow record occurs at this gage extending to 1962. For the period from 2003 to 2007 the flows measured correspond to the time of LWD transport observations (Fig. 2). The mean daily flow for this period is 9 m³/s while the range in daily flows is between 2.10 and 455.95 m³/s. Major floods occurred in the watershed in 1998 and 2002, both prior to the study time frame.

Riparian vegetation in the study reach is the source of LWD into the channel. The entirety of the reach, in the Post Oak Savannah biotic region, is characterized by grassy pastures with interspersed post oak (Quercus stellata) and blackjack oak (Quercus marilandica) (Gould, 1962). In the immediate riparian area one large tree rarely dominates, enabling a larger density of trees on the edge of the river. Texas sugarberry (Celtis laevigata) dominates the riparian zone, followed by box elder (Acer negundo), cedar elm (Ulmus crassifolia), and cottonwood (Populus deltoides). Most cottonwoods (P. deltoides) and black willows (Salix nigra) are isolated to the inner riverbank, while Texas sugarberry (C. laevigata), cedar elm (U. crassifolia), and American elm (Ulmus americana) are more evenly distributed from the inner bank to the outer bank (Bush and Van Aukem, 1984). All of these species are fast growing, and indicate that the riparian zone has adjusted to frequent disturbances by flooding (Kochel and Baker, 1982) and that LWD is supplied to the river. The tallest trees within the riparian zone are the cottonwoods and black willows, which can grow up to 30 m and 37 m, respectively, and over a meter in diameter (Preston, 1976; Brockman et al., 2001). Trees of medium height include Texas sugarberry and American elm, both of which can reach over 20 m with diameters near 2 m. Box elder remains a small tree in the study reach, rarely reaching 20 m tall and diameters of 1 m (Preston, 1976; Brockman et al., 2001).

Soils adjacent to the river channel are identified for each 2 km segment within the study reach. Soil types alternate between clay and clay loam with the clay soil type dominant (Wermund, 1996; Soil Survey Staff, 2008). Channel width and planform pattern were analyzed from historic aerial photos. Between photo years 1938 and 1948, channel width increased from an average of 25 m in 1938 to an average of 40 m in 1948. A large flood in 1940 is a probable catalyst for the observed bank failures and channel widening across the study reach during this time frame (Cawthon and Curran, 2007). Between 1948 and 2007, the channel width increased by an average of 9 m. The limited amount of channel widening over the past 60 years illustrates a stable channel width during the time period over which LWD are analyzed.

3. Results: field

LWD jams are composed of multiple pieces of wood of different lengths. Log jams form when pieces of LWD accumulate into a stable
structure. An initial log deposits when an obstacle in the channel precludes continued downstream transport or the depth of flow reduces to the point at which the log no longer floats. This log then acts as a jam 'key member' and stabilizes the smaller 'racked members' that comprise the majority of the jam (Abbe and Montgomery, 2003). A requirement in the definition used in the field during this research was that the jam must appear stable in the channel (Fig. 3). Many locations exist where small wood accumulated on the water surface in a defined area but did not include a stabilizing key member (Fig. 4). These accumulations of wood create areas of congested wood transport but do not represent stable LWD jams and were not included in mapping as LWD jams. The focus of the research is on the ability of LWD jams to influence channel morphodynamics in low gradient channels and wood accumulations in the absence of a key member are unlikely to exert a significant influence on the channel.

LWD jams present in the study reach were field mapped using GPS over the timeframe from November 2006 to February 2007. The percent lateral surface channel coverage and channel cross-sectional location were recorded for each jam (Table 1). Lateral channel coverage was estimated and those jams extending over 90% of the channel width were considered complete jams. LWD jam in-channel locations are described as river left, river right, or mid-channel. A total of 142 jams were identified, and of these 95 extended over more than 5% of the channel area. Jam spacing was measured between each set of adjacent jams. The average and median measured spacing between jams was 430 m and 230 m, respectively. LWD jams present on December 7, 2003, were mapped from 30 cm resolution, low-level aerial photos (San Antonio River Authority, 2004). From these images a total of 73 jams were identified with mean and median jam spacing of 840 m and 500 m, respectively.

Jam locations from 2003 are compared to locations mapped in the field in 2007. The mean flow on Dec. 7, 2003 at the Elmendorf USGS gage was 9.65 m$^3$/s with a depth 4.04 m. The mean recorded flow during the field mapping was 8.28 m$^3$/s with mean water depth of 3.56 m. Approximately twice as many LWD jams were identified in 2007 when compared to 2003, and the density of jams increased from 1.0 jam/km in 2003 to 2.1 jams/km in 2007. The lower total number of jams and larger jam spacing in 2003 when compared to 2007 may partially result from the different methods used to locate and identify jams. Whereas individual jams spaced within 1 m of each other can be distinguished in the field where the river was surveyed longitudinally by boat, on aerial photos these same jams can appear merged as a single large jam. It is also easier to identify LWD jams that span 0–5% of the lateral channel area when in field situation, and these smaller jams may have been present in 2003 but not identifiable from aerial photos.
Variations and patterns in jam density in the study reach are consistent between 2003 and 2007. Between river km 43 and river km 60, the LWD jam density increases dramatically with an increase in river sinuosity. The channel sinuosity between river km 43 and 60 is 2.6 while outside this segment the average sinuosity is 1.86. In 2003, the jam density increases from 0.9 jams/km outside of river km 43–60 to 1.6 jams/km within the 17 km segment. In 2007, the pattern repeats such that outside of river km 43–60 jam density is 1.6 and within the segment between km 43 and 60, jam density is 4.1 jams/km. The consistent pattern of LWD jam density indicates a source of wood and an increase of wood storage in jams between river km 43 and river km 60. The confluence of the Seguin River with the San Antonio River occurs at km 32, increasing the total drainage area by 49 km$^2$ and providing LWD to the channel. More importantly, the channel planform between 43 and 60 km has a tortuous meander pattern and sinuosity ratio of 2.6 rather than the gentler bends and lower sinuosity elsewhere in the study reach. LWD jam locations are compared to estimate the overall LWD jam mobility. Tracking devices were not used to monitor the movement of individual logs, so it is not possible to distinguish with certainty whether a jam identified in 2003 and 2007 remained stationary or re-formed in the same location. Field observations do not indicate that the logs comprising the debris jams had been exposed to the weather for a long period of time. Of the 73 LWD jams located on photos from 2003, 41 had mobilized and transported downstream by 2007. Neither a significant increase in the size of LWD jams between 2003 and 2007 nor an increase in downed wood in the riparian area was observed, indicating that the wood from these 41 jams traveled out of the study reach. Whereas tributaries to the San Antonio River are often cleared of wood accumulation on the San Antonio River, but not a LWD jam (Cawthon, 2007).
woody debris, the main stem of the river is not. Thus, the wood can be assumed to have moved through the study reach, implying that the other 32 LWD jams identified on the 2003 photos were also mobile.

Wood mobility is closely tied to the rates and depths of flow in the channel. Mobility of wood and LWD jams in the study reach is 100% over the four-year period. During this time, the largest flow in the river on November 23, 2004 was 456 m$^3$/s, which represents a flood with a 10% probability of exceedence. The discharge rate and channel depth were large enough to float and mobilize the LWD, including the complete jams. LWD jams may also mobilize at flows lower as evidenced upon inspection of aerial photos from June 2, 2004, which were available for limited portions of the study reach. When photos pairs from December, 2003 and June, 2004 were compared, a channel spanning jam documented in 2003 was found to have mobilized by June, 2004. During this period, the largest flow was 153 m$^3$/s, with a 94% exceedence, indicating that LWD and jams are easily mobilized in the lower San Antonio River.

The comparison of 2003 and 2007 data identified 32 preferential LWD deposition and jam formation locations (Fig. 5; Table 2). The jams form in bends and straight reaches, but the majority is associated with channel meanders. The most common repeat locations for LWD jams are the outside of meander bends where the key member is a large tree fallen into the channel as the meander bend eroded outward (Table 1). Although the average channel width over the study area increased by only 9 m between 1948 and 2007, the majority of the widening occurred on the outside of meanders to enlarge channel bends (Cawthon and Curran, 2007). The fallen tree acts as the key member and traps smaller wood being transported downstream to form a jam. The fewest persistent jams are associated with the inside of meander bends, which build after a key member deposits on a point bar. Mid-channel bars create an obstruction to continued LWD transport at low flows and are also a persistent location for LWD jams. The bed of the San Antonio River is primarily sand with small gravel where bedforms and mid-channel bars are easily built. Similar to the increase in LWD jam density downstream of km 34, the number of repeat jam locations increases in the lower part of the study reach. Complete channel jams repeatedly form at two locations, one of which is a bridge.

4. Models

Two models, developed to predict the circumstances under which LWD is mobilized, transported, and deposited, are applied to the San Antonio River data. These models were developed from flume work and designed around small, steep gradient, forested channels. Data from the San Antonio River will be used to assess the applicability of each model to a low gradient channel where LWD mobility is frequent. A short summary of each model is provided here with the details behind model development available through the referenced literature.

The first model, developed in Braudrick et al. (1997) and Braudrick and Grant (2000), is referred to here as the Braudrick and Grant model. It was developed from flume experiments where the mobility of wooden dowels, with and without disks attached to simulate rootwads, was measured over a sand bed. Movements of dowels, including rolling, sliding, and rotating, were documented along with rates of transport and preferential deposition locations. Movement of dowels was a function of the ability of the wood to float and, hence, a function of the type of wood. In the lab, the measured physical characteristics of the wood were calibrated to field measurements to develop models that could be applied to the field (Table 2).
dowels included wood species, specific gravity, and moisture content. For the San Antonio River, moisture contents are assumed to be between either 20 and 40% or 30 and 60%, depending on tree species. At these levels of saturation, all of the species have specific gravities above 500 kg m\(^{-3}\). At moisture contents above 60%, the log density becomes greater than water density and causes the log to sink (Simpson and TenWolde, 1999). Given the physical characteristics of the wood, the critical depth for flotation can be calculated using Eq. (1) (re-arranged from Eq. (3) in Braudrick et al., 1997).

\[
d_c = r + r^2 \left[ \frac{\pi \left( \frac{d^2}{4} - \frac{1}{2} \right) - \sin^{-1} \left( \frac{d-r}{2r} \right)}{\sqrt{2d_r - d^2}} \right]
\]  

where \( r \) is the log radius (m), \( d_c \) is the critical depth for flotation (m), \( \rho_{\text{log}} \) is the density of the log (kg m\(^{-3}\)), and \( \rho_w \) is the density of water (kg m\(^{-3}\)). Dowels floated when the water depth was a minimum of half the dowel diameter, which was expressed as the dimensionless ratio of dowel diameter to water depth. This ratio was the primary determinant of mobility for dowels with and without a simulated rootwad.

Exceeding the floating threshold for an individual log will not necessarily transport that log because channel morphology is an important feature in determining log mobility. A limitation of the Braudrick and Grant model is that it was designed around shallow channels and not tested in deep rivers. In all the experiments, the depth of the water was less than the diameter of the dowels. This is often the case in steep channels, where the critical depth criteria works well (Wohl and Goode, 2008). When the water depth is low in large, low gradient rivers, this is likely because of channel bar formation. Instances of locally reduced water depth can be considered in the model through inclusion of spatially varying depths of flow and channel bar the bathymetry when applying the model criteria of \( d_{\text{log}}/d_r < 0.5 \) for flotation. Channel bars act as preferential deposition locations in the San Antonio River, and the Braudrick and Grant model can be used to predict log transport off the bars. Secondary importance in determining log mobility but still a controlling factor over log transport is the dimensionless ratio, log length to channel width. By using both ratios, log mobility is predicted as a function of channel morphology. For a wide channel, such as the San Antonio River, the ratio must be greater than 0.5 for individual logs to move. The \( D_{\text{log}}/d_r \) criterion has been shown to be a useful predictor of log mobility in shallow, steep gradient rivers (Haga et al., 2002).

The second model examined, the Bocchiola, Rulli, and Rosso model, comes from two manuscripts of Bocchiola et al. (2006, 2008), and examines the transport and deposition of large woody debris in the presence of obstacles. It is referred to here as the Bocchiola model. The analytical model is derived from flume experiments where dowels were fixed into the channel bed to create obstacles to transport. As loose dowels were added to the flume channel, the depositional locations and the influence of obstacles on transport were documented. The Bocchiola model extends the Braudrick and Grant model by including explicit predictions of log movement by sliding or rolling on the channel bed as a function of flow velocity, bed slope, log length, and the angle of friction of the dowels on the bed. The criterion for LWD floating is adjusted in the Bocchiola model to account for the effect of the dowel on the local depth of water. The threshold for floating is given by \( Y^* \), which includes the buoyancy of the dowel and the density of the wood (Eq. (2); from Eq. (2) in Bocchiola et al., 2006).

\[
Y^* = \frac{\rho_w d_r}{\rho_{\text{log}} D_{\text{log}}} = \frac{1.26}{1 + 2.48X_{ce}^0.5} \tag{2}
\]  

where \( X_{ce} \) accounts for the force balance causing a dowel to move by rolling \( (X_s) \) or sliding \( (X_c) \), \( D_{\text{log}} \) is the diameter of the log (m), \( d_r \) is the water depth (m), \( \rho_{\text{log}} \) is the density of the log (kg m\(^{-3}\)), and \( \rho_w \) is the density of water (kg m\(^{-3}\)). When \( Y^* > 1.26 \), the wood will float, and below that value it may move by sliding or rolling on the channel bed, determined as a function of the friction angle of the log on the bed, log length, and log diameter. Once the forces acting on the wood are great enough to surpass the threshold necessary to float the log, the model predicts the probability of LWD deposition in the presence of obstacles. The model assumes that the distance traveled by a log is a function of the dimensionless log length, \( L_T = L_T/L_0 \), and the excess force acting on the log, \( X^*_e \) (Eq. (3), from Eqs. (4) and (7) in Bocchiola et al., 2006).

\[
X^*_e = \frac{1}{2gD_{\text{log}} \tan\alpha - \sin\delta} \left( \frac{1.26}{Y^* - 1} \right) / 1.26 \tag{3}
\]

where \( L_T \) is the length of log travel (m), \( L_0 \) is the spacing between obstacles in the channel (m), \( U_w \) is the average water velocity (ms\(^{-1}\)), \( \alpha \) is the bed slope, \( \delta \) is the friction angle of the log when rolling, and \( g \) is gravity (ms\(^{-2}\)). The distance each dowel traveled during the flume experiments was documented as well as the number of pieces depositing to form jams in the channel. The results were used to develop a probabilistic model of log movement, deposition rate, and deposition location as a function of log Froude number, where \( F_{\text{log}} = U_w/(gD_{\text{log}})^{0.5} \). The normalized dimensionless length traveled by the dowels and number of dowels in each jam were fit to gamma distributions. For each value of \( L_T \) (where \( L_T = L_T/L_0 \)), the average dimensionless distance traveled by a single piece of wood or jam can be predicted as a function of the \( F_{\text{log}} \). Combining the average distance between obstacles in the river with the probability of travel distance, the probable distance traveled by each log and LWD jam can be predicted.

5. Results: modeling

Channel morphology and flow hydraulics are most influenced by LWD in locations where LWD jams persistently form. Data from the San Antonio River are applied to the Braudrick and Grant and Bocchiola models to evaluate each model’s ability to predict persistent jam locations and spacing. For each wood type, three different moisture contents are modeled to simulate wood of different residence times in the river. The rates of flow applied in the models correspond to the minimum, mean, and median flows over the time period of the fieldwork (2006–2007), the time period of the study (2003–2007), and the long term gage record (1962–2007).

The Braudrick and Grant model was used to calculate the minimum depth \( (d_c) \) required to float LWD in the San Antonio River (Table 3). Calculated \( d_c \) values are all much lower than the measured depths in the study reach, which range from 3.0 to 14.24 m over the period of study, indicating that the wood is able to be mobilized at all flows. If this were the only factor governing LWD presence, the river would not retain any LWD. The spatial variability in the bathymetry of the channel bed is, however, not accounted for in the model. Where channel bars occur, the local depth will be shallower than that measured at the Elmendorf gage. LWD may accumulate locally on in-channel bedforms although the measured gage flows indicate that it should float and transport.

Log characteristics are important to modeling mobility. Measured depths of flow from the USGS gage are used to calculate the \( D_{\text{log}}/d_r \) ratio in the river. This ratio must be less than 0.5 for the log to transport downstream (Fig. 6). As this ratio decreases below the 0.5 threshold, the logs will transition from sliding and rolling to floating. LWD from Cottonwoods plots closest to the threshold line and at the lowest flows depths, plots above the threshold. Thus, Cottonwood is the most likely species of LWD to find in the river as it is the least mobile overall. Mobility is a function of the critical water depth required for flotation and the ratio of log length to channel width. When the \( L_{\text{log}}/W_e \) ratio is
greater than 0.5, logs are expected to lodge in the channel where they can act as key pieces in jam formation. The average channel width of 15.24 m was used to calculate the \( \frac{L_{\log}}{W_c} \) ratio for each tree species. Although the channel width can vary locally, the standard deviation across the study reach is 3.4 m. At the average width, the longest LWD from cottonwoods and willows will lodge in the channel, with \( \frac{L_{\log}}{W_c} \) ratios of 1.43 and 0.58 respectively. Willows were often recorded at lengths less than the maximum possible and the \( \frac{L_{\log}}{W_c} \) reduced.

Characteristics of the San Antonio River are used in the Bocchiola model to evaluate predicted log transport distances against field identified persistent LWD jam locations. The \( Y^* \) value was calculated to be between 1.83 and 18.36 for all combinations of wood species and flow rates, which is above the 1.26 threshold value necessary to float and transport LWD. The relationship between Fr_{log} and the average distance traveled by LWD in the presence of obstacles that is part of the Bocchiola model is extended here to predict the distance traveled by LWD in the San Antonio River. Obstacles to downstream transport in the San Antonio River include in-channel bars, channel bends, tree falls, and bridges. Channel bends are the most prevalent and permanent obstacles to continued downstream transport of LWD, and three values are modeled: 500 m to represent the tightly meandering section in the study reach between river km 43 and 60, 1000 m to represent the average spacing between meander bends throughout the study reach; 2500 m to represent the straight sections in the study reach. The frequency function for the average distance traveled by LWD was held constant at 50%.

Model results show an increase in travel distance as discharge and obstacle spacing increase (Fig. 7; Table 4), illustrating a correlation between persistent jam locations and the presence of obstacles in the channel. To evaluate the correlation between model results and measured LWD jam spacing, groupings are identified by eye on the graphs where model results cluster near a field measured value. Despite scatter in the model results, groupings are identifiable (Fig. 7). When the obstacle spacing in the Bocchiola model is set at 500 m to simulate the tight meander bends, the modeled LWD travel distances cluster around 400 and 950 m. The cluster at 950 m closely matches the median persistent jam spacing across the study reach (980 m) and the mean persistent jam spacing between river km 43 and 60 (930 m). The predicted cluster of LWD deposition around 400 m is more representative of the spacing of the temporary LWD in the channel, jams that were mapped but did not persist in the same location over time. When all LWD locations, temporary and persistent, are considered, the median jam spacing between 43 and 60 m in 2003 was 300 m and in 2007, the total mean spacing was 430 m. When the obstacle spacing was set to 1000 m in the Bocchiola model, the model predicts preferred LWD deposition after travel distances of 1000 m and 1900 m. These predictions replicate the mean and median spacing of all persistent LWD jams as well as the median jam spacing when only those jams outside the sinuous segment are considered (Table 4).

The 1000 m spacing prediction also agrees well with the measured mean spacing for all jams, temporary and persistent, in 2003. The largest obstacle spacing used with the model, 2500 m, represents the least sinuous segments of the study reach. Model results using a

<table>
<thead>
<tr>
<th>Species</th>
<th>Moisture content (%)</th>
<th>( D_{\log} ) (kgm(^{-1}))</th>
<th>( d_o ) (m)</th>
<th>( L_{\log} ) (m)</th>
<th>( \frac{L_{\log}}{W_c} )</th>
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<tr>
<td>Cottonwood</td>
<td>20</td>
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<td>0.87</td>
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<td>8.8</td>
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<tr>
<td>Willow</td>
<td>25</td>
<td>813</td>
<td>0.25</td>
<td>8.8</td>
<td>0.58</td>
</tr>
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<td>0.31</td>
<td>8.8</td>
<td>0.58</td>
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<tr>
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<td>5.5</td>
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</tr>
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<tr>
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<td>5.5</td>
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<tr>
<td>Sugarberry</td>
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<td>708</td>
<td>0.30</td>
<td>7.3</td>
<td>0.48</td>
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<td>813</td>
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<td>888</td>
<td>0.44</td>
<td>7.3</td>
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</tbody>
</table>

Table 3
Details of San Antonio data for use with the Braudrick and Grant model.

Fig. 6. Results of Braudrick and Grant model applied to data from the San Antonio River. Discharges and flow depths correspond to the minimum, mean, and median flows over the time period of the fieldwork, study period, and long term record at the USGS gage at Elmendorf, Texas. The dashed line represents the value of the \( D_{\log}/d_o \) ratio that is an upper bound on log transport.

Fig. 7. Results of Bocchiola, Rulli, and Russo model applied to data from the San Antonio River. Discharges and flow depths correspond to the minimum, mean, and median flows over the time period of the fieldwork, study period, and long term record at the USGS gage at Elmendorf, Texas. (A) has the obstacle spacing set at 500 m to replicate the spacing of channel bends between river km 43 and 60. (B) has the obstacle spacing set at 1000 m to replicate the spacing of the more gentle meanders in the study reach. (C) has the obstacle spacing set at 2500 m to replicate the spacing of the straight sections in the study reach. Groupings of LWD transport distances that correspond to measured LWD spacing are marked with circles on each graph. Please note the change in scale on the \( y \)-axis of the graphs.
Table 4
LWD jam spacing from 2003 and 2007.

<table>
<thead>
<tr>
<th>Both persistent and temporary LWD jams</th>
<th>Mean spacing (m)</th>
<th>Median spacing (m)</th>
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<tr>
<td>2003</td>
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<tr>
<td>Total</td>
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<tr>
<td>km 43–60</td>
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<tr>
<td>Outside km 43–60</td>
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<tr>
<td>Total</td>
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<td>Total</td>
<td>1700</td>
<td>980</td>
</tr>
<tr>
<td>km 43–60</td>
<td>930</td>
<td>730</td>
</tr>
<tr>
<td>Outside km 43–60</td>
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<td>1840</td>
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</table>

2500 m obstacle spacing agreed with the measured mean and median persistent LWD jams spacing outside of the sinuous region.

6. Discussion

Studies of LWD mobility where individual pieces of wood are tagged and tracked over a range of flow rates have produced direct measurements of LWD movement and a range of LWD residence times (Diez et al., 2001; Haga et al., 2002; Wohl and Goode, 2008). Recent temporal studies of the longitudinal distribution of LWD in rivers have allowed for process linkages to begin to be made between LWD movement and channel morphology. In an evaluation of 11 years of data tracking LWD and LWD jam movement in the Colorado Rocky Mountains, Wohl and Goode (2008) found that the dimensionless variables \( L_{\text{dlog}} \) (where \( L_{\text{dlog}} = L_{\text{dlog}}(W/L) \) and \( D_{\text{dlog}} = D_{\text{dlog}}(D_{\text{dlog}}) \)) exert the greatest influence over LWD mobility. This is in agreement with observations and results from other field and flume research, including the models employed in this research (Braudrick et al., 1997; Hilderbrand et al., 1998; Andreoli et al., 2007; Bocchiola et al., 2008).

All of the LWD and LWD jams identified from 2003 aerial photos over a 72 km stretch of the San Antonio River had mobilized by 2007, when field mapping was conducted. Upon further inspection of the data, it was found that 32 of the LWD jams identified in 2007 were in the same channel locations as jams were in 2003. When the jams reform in the same channel locations, a greater influence by the LWD exists on local channel hydraulics and morphology. The combination of LWD and a mobile sediment bed can create a reinforcing pattern where wood deposited on the channel bed increases sediment deposition around it. Then, as more sediment deposits around the wood, a mid-channel bar develops which acts as a preferential deposition location for more wood. The wood helps stabilize the channel bar, increasing flow resistance and deflecting flow around the bedform. If flow is diverted toward channel banks, local bank scour occurs and the channel widens to flow around the wood jam and bar (Keller and Swanson, 1979). Alternatively, the LWD may accumulate along the channel boundary and act as a deterrent to increased bank erosion, deflecting flow away from the bank. Because of the potential interaction between LWD, channel form, and channel hydraulics, it is useful to be able to predict stable or recurrent LWD jam locations.

Two models that were designed to predict LWD mobility were explored with the San Antonio data in an attempt to model the persistent LWD jam spacing and the flows that would mobilize these jams. Both models were developed from flume research that examined the mobility of individual logs. Conflicting evidence exists of whether or not the rate of change of LWD movement occurs when the logs are part of the jam. Field evidence has shown both that single pieces of LWD have the same mobility as logs in groups (Hilderbrand et al., 1997) and that jams can increase the residence time of LWD in a channel by as much as 25% (Wohl and Goode, 2008). This research focuses on the jams because they could be confidently identified on aerial photos. Mobility predicted by the models is applied to the persistent LWD jams in the San Antonio River.

The Braudrick and Grant model predicts wood mobility as a function of channel depth. The model can be applied to predict jam formation on in-channel bars where a detailed river bathymetry is known. This project did not include a high-resolution map of the channel bed, therefore, the model was most useful in predicting the trees most likely to act as a key member in jam formation. Using the physical characteristics of the different tree species in the San Antonio River, Cottonwoods were predicted to be the least mobile species in the channel and, therefore, the most likely to be found in a LWD jam. Field observations confirmed that the Cottonwoods, while not the most prevalent species in the riparian zone, were common as the key member in a LWD jam. The implication of this result is that riparian areas with a large amount of Cottonwood trees can act as a source of LWD to a channel indicate a region where a higher number of jams may be expected.

The Bocchiola model predicts LWD transport distances in the presence of obstacles. The spacing of the repeated LWD jams in the San Antonio was used to evaluate the ability of the model to predict jam locations. Required input to the model includes the spacing of obstacles in the channel that prevent continued downstream transport of LWD. The San Antonio River is meandering, with sinuosity ratios between 1.86 and 2.60. Channel meanders are recognized areas of preferential wood deposition and jam formation (Piegay and Gurnell, 1997). The obstacle spacing used for the model was set to represent the distance between channel bends. Where the meanders are close together, the model simulated the spacing of the persistent LWD jams well. Jams had an average measured spacing of 930 m and the model predicted a group of LWD deposition locations after 950 m of transport. In the areas of the study reach with greater distance between channel bends, the model again performed well in predicting persistent LWD jam spacing. Modeling results predict a group of LWD travel distances near 1900 m while the field measured median LWD jam spacing was 1940 m. The model also predicted LWD with a shorter travel distance and, therefore, a shorter spacing. Two possible explanations exist for the extra model predictions and the scatter in the modeled results. First, more LWD jams occur in the channel than accounted for by the persistent jams. These jams are more mobile, do not necessarily re-form between flows, and have a shorter average spacing. Second, only the meander bends were considered in setting the distance between obstacles. In the field, channel bends were one of many potential obstacles that served as deposition locations and sites of jam formation. Channel bars, bedforms, and localized bank erosion can all be considered obstacles to transport but were not included as part of the model input. Inclusion would likely have improved the model predictions, particularly in areas where channel bends are less likely to be the dominant obstacle to log transport.

The balance of forces acting on LWD has come under scrutiny as a means for predicting LWD movement in a channel. When hydrodynamic forces acting on the LWD are greater than resisting forces, LWD will move by rolling, sliding, or floating. The variables required to predict the initiation of log movement include wood density, angle of the log with respect to the channel, channel slope, friction between channel bed and log, and the drag coefficient of the log (Haga et al., 2002). The apparent drag acting on an individual log is a function of the depth of submergence of the log (Hygelund and Manga, 2003). Forces acting on LWD are, in turn, related to how the LWD affects the hydrodynamics of a river reach. Some amount of the total shear stress in a channel flow will be attributable to LWD and LWD jams (Hygelund and Manga, 2003; Daniels and Rhoads, 2003; Manners et al., 2007). Where logs and jams are stable in the channel or persistently form in the same locations, the LWD will have more effect on shear stresses in the channel which in turn influence the channel morphology and decisions related to channel management.
7. Conclusion

Once wood has been input into a channel, it either remains in place or is transported downstream. When LWD accumulates and develops into stable jams, it has the potential to affect the channel morphology and sediment transport processes (Daniels, 2006). Transport of wood is dependent on physical properties of the wood, the quantity of supplied wood, channel hydraulics, and channel shape (Gurnell et al., 2002). LWD physical characteristics that influence transport include wood length, density, diameter, orientation relative to flow, and the presence/absence of a rootwat. The two most important parameters are ratios of log length to channel width, and channel depth to log diameter. A log floats when the moisture content and wood species combine for a wood density less than water. When a floating log is shorter than the channel width and has a diameter less than half the channel depth, it is likely to transport downstream. Logs and jams that transport easily downstream are unlikely to exert influence over channel morphodynamics. Those jams that have long residence times in a channel or re-form at the same location in the channel have the potential to alter channel hydraulics and morphology.

This project demonstrates the applicability of two models designed around steep, forested channels to low gradient, wide channels. The distribution and mobility of LWD over 72 km of the San Antonio River, a low gradient channel in southeast Texas, were evaluated through fieldwork, aerial photography, and predicted from mobility models. LWD jam locations were identified for 2003 and 2007. During the four-year period, all the LWD jams were mobilized, including those extending across the channel width. Although easily mobilized, 34 LWD jams re-formed in the same locations. Data from the San Antonio River are applied to the models of Braudrick and Grant and Bocchiola, which were developed to predict LWD mobility and transport distances. The results indicate that the Braudrick and Grant model was most useful in predicting the trees most likely to act as a key member in jam formation. When combined with information on the tree distribution of the riparian and source areas for LWD, the approximate locations of increased wood loading in the river could be predicted. The Bocchiola model uses obstacle spacing to predict the transport distance of logs in the channel, which corresponds to locations of persistent LWD jams within the area of the study reach. Obstacle spacing was set to mimic the distance between channel bends, which assumes that meander bends are the dominant obstacle to log transport. When model results were compared to the measured spacing of LWD jams not in repeat locations, the results agreed less closely with the measured LWD jam spacing. This can be at least partially attributed to the temporary nature of these jams and the lack of information on the spacing of obstacles other than channel bends. Results indicate the Bocchiola model can predict the locations of stable (or recurring) LWD jams when the spacing of obstructions impeding transport is known.

Locating stable and recurring LWD jams is important in low gradient channels, which are common in agricultural and urban areas. These channels are often actively managed and the built environment intersects the river through roads and bridges. Studies of LWD loading and jam distribution within channels can inform channel restoration projects where LWD are added to a stream to improve or restore aquatic habitat. The ability to identify reaches where LWD jams are more likely to form naturally will result in successful projects that simulate natural conditions. If natural distribution in relation to stream width, depth, and gradient is not taken into account, then LWD could be placed in a reach of the channel where retention and habitat formation (Richmond and Fausch, 1995) will not be successful.

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References

Gould, F.W., 1962. Texas Plants: a Checklist and Ecological Summary. Texas Agricultural Experiment Station, College Station, TX.


