THE SPATIAL DISTRIBUTION OF LARGE WOODY DEBRIS AND ITS RELATIONSHIP WITH CHANNEL MORPHOLOGY IN THE BITTERROOT RIVER, MONTANA

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ABSTRACT

The spatial distribution of large woody debris (LWD) within a river channel has a complex, but influential, relationship with channel morphology. This study examines the spatial distribution of LWD, present as both jams and singular logs, and its relationship with the channel morphology of the Bitterroot River in western Montana. Using basic GIS digitising methods, the spatial distribution of LWD was assessed along a ten kilometre stretch of the river, spanning from Victor Crossing in the south to Crystal Lane in the north. The location of LWD was then evaluated in relation to certain channel features, including point bars, meander bends, midchannel bars and the flood plain. The most common area of LWD accumulations was on point bars, with 35% and 28% of jams and logs respectively, occurring here. Jams also commonly occurred on bare parts of islands; however a higher percentage of singular logs were located on the flood plain. Analysis of the size and orientation of LWD showed consistency with previous studies; the dominant orientation of individual logs was parallel to flow direction and larger LWD deposits were more likely to influence channel morphology. Based on the observed primary influence of LWD on flow deflection, sediment storage, pool formation and bank armouring, the secondary processes of stabilisation of planform morphology, meander cutoff and formation of depositional features were inferred.

1. INTRODUCTION

The transport and accumulation of large woody debris (LWD) within a river can have large impacts on hydrological, geomorphological and ecological processes (Abbe & Montgomery, 1996). As the body of research published in regards to LWD has grown, its importance in controlling river system dynamics has become increasingly understood and appreciated. LWD is generally defined as wood with a diameter greater than ten centimetres and a length greater than one metre. LWD deposits act as channel altering mechanisms, affecting the hydrology and fluid dynamics of rivers and streams. These changes can have subsequent effects on the transportation and deposition of sediment, nutrients and organic matter as well as channel and bedform morphology, which has further implications for ecology and floodplain genesis (Fetherston, Naiman & Bilby, 1995). Although many of these processes have been well studied in other North American rivers (e.g. Collins, Montgomery, Fetherson & Abbe, 2012; Fetherston et al., 1995; Keller & Swanson, 1979), there have been no published studies of this kind conducted on the Bitterroot River in western Montana.

It is likely LWD found within the Bitterroot River has come from direct input of vegetation on adjacent banks or transportation of vegetation debris from upstream sources. Processes contributing to this addition include; undercutting due to lateral channel migration or high energy flow events which causes bank erosion and the remobilisation of wood stored on the floodplain (Piégay, Thévenet & Citterio, 1999); wind throw, which is the uprooting of trees during strong winds and subsequent deposition into the river; or the destabilisation of soils and uprooting of large vegetation during landslides and floods induced by large storm events (Gurnell, Piégay, Swanson & Gregory, 2002).

The impacts of LWD deposits are not limited to the physical environment. LWD also has the ability to have large impacts upon ecological processes, in both terrestrial and aquatic environments. The presence of LWD deposits facilitates the growth of important habitats by acting as ecological refugia or leading to the formation of additional depositional sites. LWD protects sections of the river from high energy flow, resulting in the formation of calm and stable areas, providing a wider diversity of habitats,

and consequently increased biodiversity of plant and animal species. Depositional sites associated with LWD provide sites for seedling recruitment, as well as the debris itself acting as “nurse logs” on which species not suited to saturated soils can grow (Fetherston et al., 1995; Fremier, Seo & Nakamura, 2010). In this respect LWD is highly important in understanding the establishment and distribution of riparian vegetation.

This study presents a review of the spatial distribution of LWD in a section of the Bitterroot River and its relationship with channel morphology. A critical analysis of LWD observed along the Bitterroot River is undertaken using GIS and satellite imagery. The study will look at LWD present as individual logs or as jams, and its characteristics, including orientation, size and the relationship with channel dimensions will be quantitatively analysed. This will be followed by a more qualitative approach to the distribution of LWD in different parts of the river and the relationship of LWD with morphological processes including channel avulsion and meander cut off, lateral migration and formation of depositional structures.

2. STUDY AREA

The Bitterroot River, a tributary of the Columbia River, is located in the Rocky Mountains of western Montana. The river runs from south to north through a wide valley at the centre of the Bitterroot Sub-basin which is bounded by the Bitterroot Range to the south and west and the Sapphire Mountains to the east. Streams originating in these mountain ranges are the tributaries of the Bitterroot River. The river consists of a main anastomosing channel within a series of narrow and sinuous minor channels. The river is dynamic and shows evidence of lateral channel migrations, meander cutoffs, point bar accretion and avulsions; it is known to frequently experience overbank flow (Northwest Power and Conservation Council [NPCC], 2009). The river has a high bedload of sediment, especially cobbles, derived from the bordering ranges (NPCC, 2009).

Vegetation adjacent to the river consists of riparian hardwood forest, comprised predominantly of black cottonwood, ponderosa pine and quaking aspen species associated with red-osier dogwood shrubs. Sandbar willow is the dominant species established on younger depositional sites, such as point bars (NPCC, 2009).

The specific reach to be studied is approximately ten kilometres long, the southern limit of which is the Victor Crossing near the town of Victor, Ravalli County, Montana and the northern limit is an eastward continuation of Crystal Lane (Figure 1). This reach was selected for the prominence of LWD along the channel, as well as morphological features which have shown to be related to LWD accumulation in previous studies. It was also important to choose a section of the river where the observed morphology could be attributed to natural processes and is less influenced by human emplaced restrictions. This was taken into account by choosing a reach of the main channel mostly bordered by riparian communities, with only some minor sections which border directly onto cleared agricultural or residential land. The section of the river in the study reach has a catchment area of approximately 5080km^2 (United States Geological Survey [USGS], 2013a). The gradient of the middle Bitterroot River, a section within which the study reach is located is shallow, varying from 0.1 to 0.22% (NPCC, 2009).

The U.S. Geological Survey has four gauge stations located on the Bitterroot River; Bitterroot River near Conner, Bitterroot River near Darby, Bitterroot River at Bell Crossing near Victor and Bitterroot River near Missoula (Figure 1). The Bell Crossing near Victor station is the only one of the four which lies in the study reach. Figure 2 shows that, as expected, the rate of discharge of the Bitterroot River increases downstream. The Bell Crossing site, near the midpoint of the study reach, had a 2011 seasonal average discharge (averaged over the period of March to September) of approximately 90 cubic meters per second (USGS, 2013a). Figure 3 shows the gauge height of the Bitterroot River measured at the USGS stations upstream and downstream of the study area. The timing and magnitude of flood events at the upstream and downstream gauge stations are consistent, indicating floods flow through the study area without any irregularities.

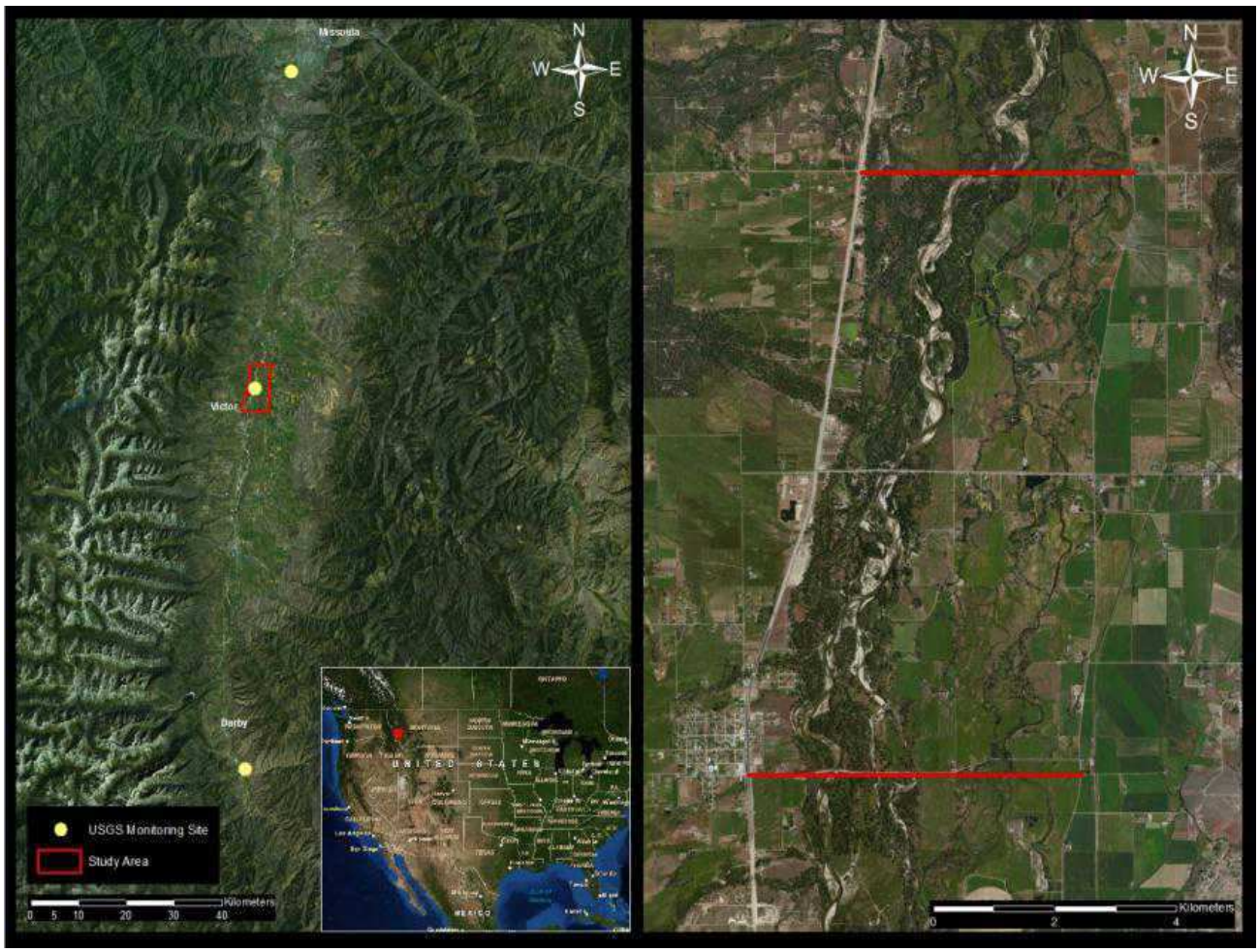


Fig 1: Study location along the free-meandering reach of the Biterrroot River in Montana, US

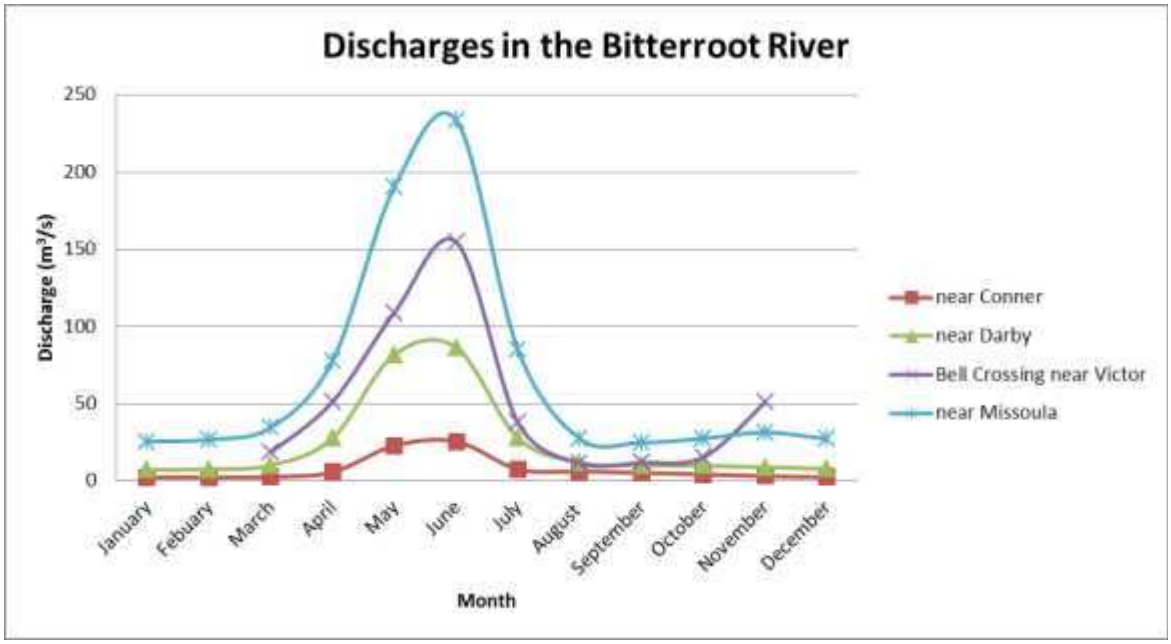
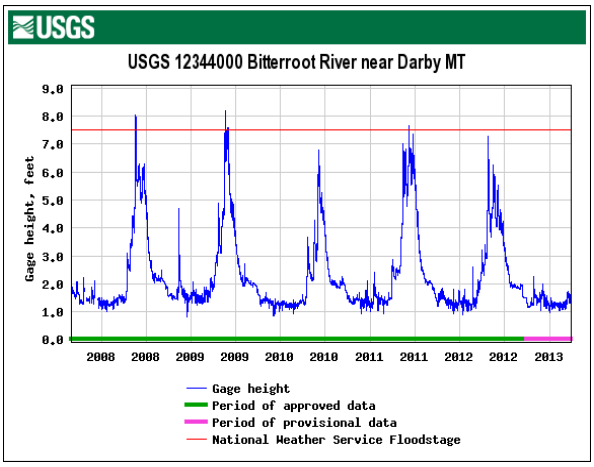
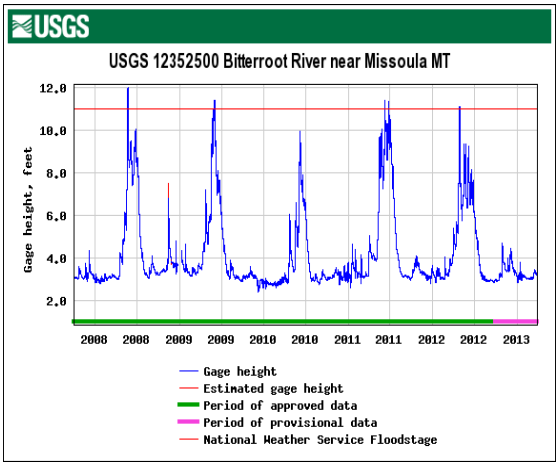


Fig 2: Monthly average discharge (1937-2013) at four sites along the Bitterroot River (USGS, 2013b).



(a)



(b)

Figure 3: Gauge heights at two USGS sites on the Bitterroot River with the red line indicating the flood level; (a) Bitterroot River near Darby station (upstream of the study reach) and (b) Bitterroot River near Missoula (downstream of the study reach) (USGS, 2013b).

3. METHODOLOGY

ArcGIS 10.1 and satellite imagery were used to map the spatial distribution of LWD and its relationship with channel morphology. Satellite imagery was accessed through Bing Maps. Digitisation of the active and wet channel was conducted using Bing Maps and simple digitising techniques. The extent of the digitised active channel defined which of the minor channels would be included in the analysis. The boundaries of the active channel were based on the distribution of temporary riparian vegetation. A 30 metre buffer around the active channel was created using the proximity analysis tool 'Buffer'. Creation of the buffer zone allowed consistent definition of the floodplain location during spatial analysis of LWD along the full ten kilometre study reach.

Digitisation of LWD location was conducted as best as possible given the resolution of the images. Two categories were used: 1) polylines representing the location of individual logs; 2) points representing the location of jams. Due to the limitations of purely GIS-based analysis the location, orientation and exact number of individual logs within a jam could not be accurately determined and therefore were not accounted for. The size of each jam was approximated into three categories of small 2-5, medium 6-24 and large ≥25 logs. The length of singular logs was determined in ArcGIS using the calculate geometry function.

Measurements were made to determine a value for the bankfull width of the river within the study reach. Due to the presence of multiple channels and numerous islands, there were several options for defining and measuring bankfull width. For our purposes only the span of the most prominent channel was used. This means that where an island was at least in part higher than bankfull flow, as determined by the establishment of weak vegetation, the width was only measured on one side of the island from whichever channel was dominant. Nineteen measurements were taken on an approximate interval of five hundred metres

The spatial distribution of LWD was assessed by defining zones representative of the entire study area and classifying each individual log or jam into one of these locations. The categories and their descriptions are provided in Table 1.

Following a similar technique used in Baillie, Garrett and Evanson (2008) the direct influence of LWD on morphology was determined by tallying the relationship of individual logs and jams withthe following processes: sediment storage, pool formation, flow deflection and bank armouring (Fig.2).

Table 1: Description of the LWD location categories

Category	Description of LWD Location
Wet channel	Suspended in the current flow or snagged on a shallow section of the current channel.
Point bar	On a point bar on the inside bend of a meander. Some point bars now appear as islands as they have been cutoff from the floodplain by a minor channel. “Point bar” is still the most representative term for this location and has therefore been used instead of “island” in these circumstances.
Cutbank/outside of meander bend	On the margin of the channel; specifically on the outside bend of a meander.
Midchannel bar	On a completely unvegetated bar within the active channel.
Island - Vegetated - Bare	An island within the active channel is distinct from a midchannel bar as it contains some form of vegetation. The island setting has been divided into vegetated and bare to reflect that although an island must be at least partly vegetated it may have young, bare sections which are less stable.
Margin	Snagged on or overhanging the bank of the active channel excluding the meander margins.
Floodplain	On the floodplain within 30 metres of the active channel.

Table 2: Description of how LWD influence on channel morphology was observed

Category	Observable Feature
Sediment storage	LWD is located on or adjacent to a depositional site.
Pool formation	A deep area, which can be determined by the dark colour of the water, occurs adjacent to LWD.
Flow deflection	Flow direction changes as a result of deflection around LWD or complete obstruction of flow.
Bank armouring	LWD occurs on the banks of the active channel or an island and appears to protect these banks from erosion.

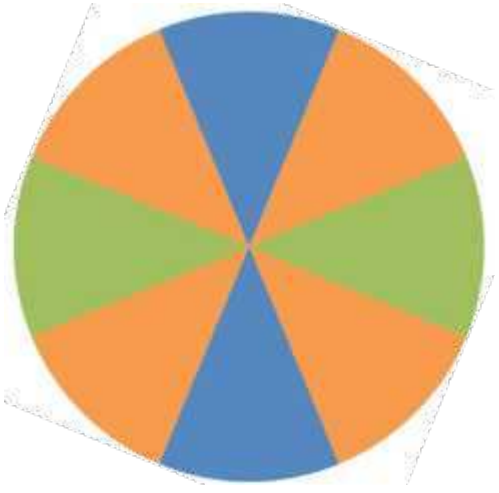
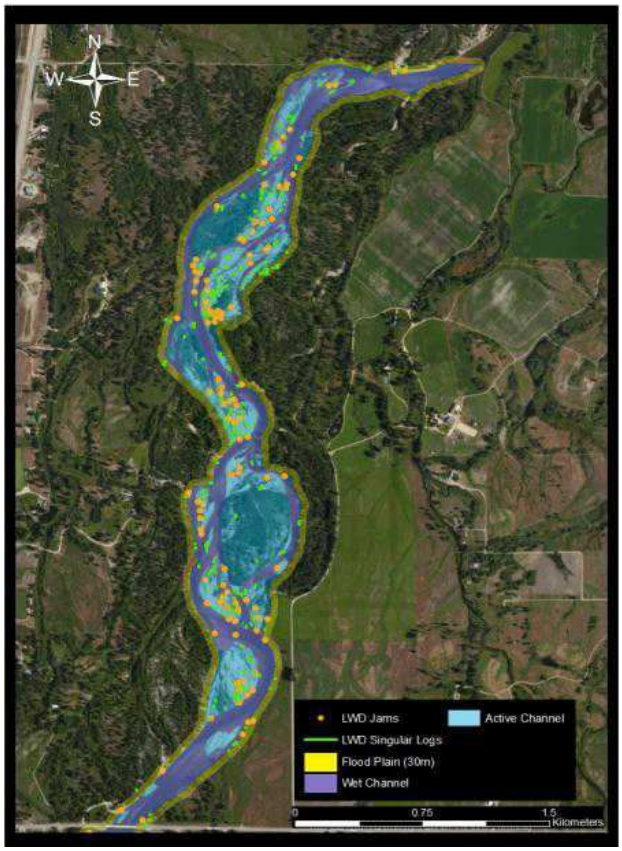


Figure 4: Orientation categories of individual logs.

4.RESULTS

4.1. Spatial Distribution of LWD

There were a total of 637 individual logs and 239 jams observed within the study reach. The most common location for both LWD jams and individual logs was point bars; 35% and 28% of jams and individual logs respectively occurred on these structures. The floodplain produced the most notable difference between the distribution of logs and jams. Less than 1% of jams occurred on the floodplain, but it was the second most common location of individual logs, holding 21% of the total number. In contrast, the second most common location for jams was the bare parts of islands which held 18% of jams and 12% of individual logs. Comparable proportions of jams and individual logs were found on the margins, outside of meander bends, vegetated parts of islands, midchannel bars and in the wet channel. The relative distribution of individual logs and jams across the all locations in the system can be observed in Figures 5 and 6.



4.2. Characteristics

4.2.1. *Size*

The size of LWD deposits should be considered in relation to the size of the river. The average width of the river along the study reach was measured as 132 metres. The average length of individual logs was 9.46 metres. The maximum length of an individual log was approximately 35 metres; the minimum observed length of 1.5 metres is a reflection of our definition of LWD as longer than one metre and the resolution of the imagery. The distribution of log length is shown in Figure 5(a). The most common jam size was the medium category of 6 to 24 logs, closely followed by jams classified as small with between two and five logs. The jam size distribution is shown in Figure 5(b). When examining the relationship between LWD size and influence on morphology, it was observed that larger individual logs and jams were more likely to exert influence on channel morphology than smaller deposits.

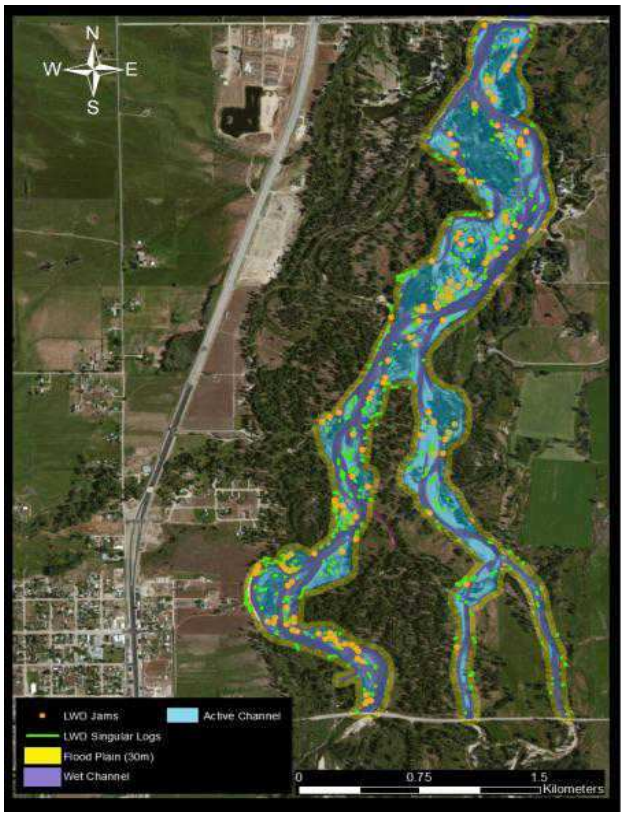


Fig. 5: Distribution of size of identified LWD; (a) distribution of the length of logs and (b) distribution of jam size.

4.2.2. *Orientation*

Analyses of the orientation of individual logs, as shown in Figure 6, shows that across the whole system 48% are oriented parallel and 41% are oriented oblique to the direction of flow. Very few individual logs were perpendicular to flow, only 11%. The only locations within the system which showed differing orientations to this overall trend were the floodplain and outside of a meander bend; these locations had a much higher proportion of logs oriented perpendicular to flow than other locations.

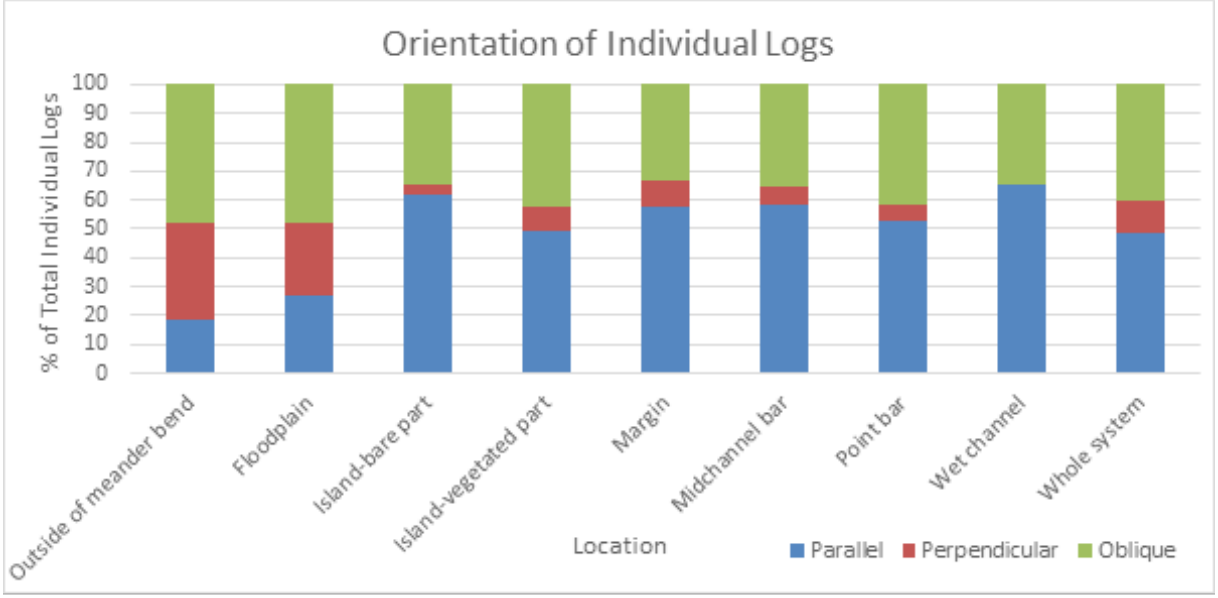


Fig. 6: Orientation of individual logs at different locations of the study reach and across the whole system.

4.3. Influence on morphology

The vast majority of individual logs, 70%, were observed to have no influence on sediment storage, pool formation, bank armouring or flow deflection, compared to only 38% of jams. This suggests that jams were much more likely to influence channel morphological processes than individual logs. Of the LWD which did exhibit some influence, the trends were consistent between individual logs and jams; flow deflection was the dominant process, followed by sediment storage and bank armouring with pool formation being the least common process associated with LWD. Flow deflection occurred with 19% of individual logs and 45% of jams. 10% of individual logs and 34% of jams were associated with sediment storage.

5. DISCUSSION

5.1. Spatial Distribution of LWD

LWD located on the floodplain, not in contact with the active channel, is likely to be the result of deposition during a high energy, overbank flow event. Such an event would transport a large amount of LWD which has become entrained during this event, been redistributed from further upstream or remobilized from disintegrating jams (Marcus, Marston, Colvard & Gray, 2002). As high flows recede they abruptly deposit LWD onto the floodplain. Sudden deposition of these logs due to flooding is supported by the apparently random orientation of the logs in this location, compared with other parts of the river where logs are most commonly oriented parallel to the channel. Although there was a high amount of LWD on the floodplain, it was almost entirely in the form of individual logs rather than jams. Whereas the distribution of individual logs can be a result of one off deposition events like flooding, the formation of jams is the outcome of long term, constant build-up of individual pieces under stable flow conditions. This is why there were very few occurrences of jams on the floodplain.

The falling stage of overbank flow events would also contribute to the deposition of individual logs onto the upper parts of point bars and islands (Gurnell et al., 2002). Like on the floodplain this type of deposition results in random orientation, and would account for the

perpendicular and oblique logs in these locations. However, because these environments are part of the active channel and regularly in contact with the river, LWD can also accumulate here during regular flow conditions. A high proportion of LWD within the study reach was located on point bars and islands. The most common orientation of logs on point bars and islands was parallel, which supports deposition by catching on the banks of these structures during regular flow. As the banks of an island and point bar accrete the LWD formerly deposited at the edges of these, structures will come to be located an increasing distance from the channel. Over time, as the point bar or island builds, this leads to parallel LWD accumulation across the entire width of the structure, despite deposition mainly occurring at the edges. The constant contact with flow on the edges of bars and islands also allows for the formation of jams, especially at the upstream tip of these structures. As well as providing similar depositional environments, point bars and islands are strongly related in the Bitterroot River, as a number of islands appear to have once been point bars that have become isolated from the floodplain due to channel avulsion.

The relatively low abundance of LWD on the cutbank or outside of a meander bend is because of the high velocity of this zone. These conditions favour erosion rather than deposition of LWD. The logs which were found in this setting showed the highest propensity for orientation perpendicular to flow. This can be attributed to undercutting during lateral channel migration being the primary source of wood at these sites. As the bank beneath these trees erodes they collapse sideways into the channel; their orientation is unrelated to flow direction so doesn't show the usual parallel tendency (Marcus et al., 2002). These individual logs have the potential to act as key pieces, initiating the formation of a jam by snagging passing logs.

The low proportion of individual logs located on midchannel bars, compared to jams, is most likely a reflection of the tendency for multiple pieces to build up on these structures. Because midchannel bars are constantly in the direct path of flow, often in the fastest section of the river, they are more likely to trap multiple logs to form a jam than marginal locations.

5.2 Characteristics of LWD

5.2.1 *Size*

The influence LWD has on channel morphology is limited by the size of the individual log or jam. The larger the size of either the individual log or jam, the greater the likelihood it will influence flow conditions and therefore channel morphology. These findings are supported by Baillie et al. (2008), who found that LWD accumulations that effect channel morphology are generally larger. Gurnell et al. (2002), also found that the greater the size of the log, the more likely it is to become lodged in the river. However, the effect of LWD on channel morphology is largely determined by the size of the river. Gurnell et al. (2002) placed so much importance on the relationship between LWD and river morphology that they based a classification scheme for river size on the comparison of a river's width with size of LWD present in the river. Under this scheme the Bitterroot River within the study reach would be classified as large, as the width of the river is greater than the length of all LWD found within it. In previous studies jams have proven to have a stronger effect on channel morphology than a single log, this trend is also evident in the results of this study (Keller & Swanson, 1979; Fetherston et al., 1995). Size plays a key role in the ability of LWD to influence morphology as it defines both how much of the flow can be affected and how easily LWD can become lodged.

5.2.2 *Orientation*

The dominant orientation of individual pieces of LWD within the study reach was parallel to bankfull flow. This is consistent with Abbe and Montgomery (2003) who suggest that as river size increases, LWD becomes increasingly oriented parallel to flow. The orientation of LWD is important as it influences its ability to change standard flow conditions. If LWD becomes lodged parallel to flow, it has less potential to change flow conditions compared to that of obliquely or perpendicularly lodged LWD (Costigans & Daniels, 2013). A log which is anchored perpendicular to flow has higher potential to form a jam. A recent study found that in 75% of jams, the key piece that initiated jam formation was lodged perpendicular to flow (Baillie et al., 2008). Despite the relatively low

percentage of perpendicular LWD found in the study area, orientation still plays a key role in modifying the effect of LWD on channel morphology. Further field investigations of the jams would likely find that many of the jams are formed with a perpendicular LWD as their key piece.

5.3 Influence on Morphology

The difficulty in determining what influence LWD has on river morphology is that morphology also has a strong control on the distribution of LWD. Have existing structures led to the deposition of LWD or has the emplacement of LWD contributed to the formation of the structures they are now associated with? In order to break down this problem we have considered both the primary and secondary influence of LWD; the primary effects being directly observable and attributable to LWD, for example sediment storage, and the secondary, larger scale effects being inferable based on the primary processes, for example meander cutoff.

Jams showed a much higher likelihood of influencing primary morphological processes than individual logs, the majority of which had no effect. Based on this it can also be inferred that jams would be more likely to affect secondary morphological processes than individual logs. This can be attributed to two factors; the differences between spatial distribution of individual logs and jams and their differing size. Only those LWD deposits in contact with the current channel could be recorded as having an influence on morphology. A significant proportion of individual logs were located on the floodplain or upper parts of islands or bars where they had no interaction with the current channel. Almost all LWD on the floodplain or on islands were therefore classified as having no influence. In contrast, the proportion of jams located on the floodplain was very small, so overall jams were better placed to directly influence morphological processes. As it is known that the Bitterroot River often experiences overbank flow, it is important to consider that although LWD not in contact with the current channel has no influence on morphology under the current regime, it would have an influence during higher flow periods and overbank flow events. The degree of influence LWD has on channel morphology is strongly related to its size relative to the width of the channel (Gurnell et al., 2002). As jams consist of a number of logs, they are going to be comparatively larger than one single log, which increases their likelihood of influencing morphological processes.

5.3.1 Primary Effects

Flow deflection was the dominant primary morphological effect of LWD observed in the study reach. The dominant control on whether a log or jam caused flow deflection was its location; LWD located on the floodplain or upper parts of islands and bars did not cause deflection under the current flow regime as it was not in contact with the current channel. Location also controls the pattern of flow deflection. For example, a LWD deposit within the wet channel causes flow to diverge upstream of the deposit and eventually converge again on the downstream side which results in a complex 3D velocity and stress profile around the obstruction (Abbe & Montgomery, 1996). Whereas LWD located on the margin of the active channel or on the bank of an island or bar has a different effect, deflecting flow away in predominantly one direction. The location of an LWD deposit is therefore a major controlling factor on if and how an LWD deposit will influence river morphology. Size and orientation are important factors in controlling the amount of deflection caused by LWD, but field based studies are required to quantify this effect. The changes to a river's velocity and stress profile resulting from flow deflection may lead to the subsequent processes of sediment storage, pool formation or bank armouring (Abbe & Montgomery, 1996).

Sediment storage was commonly associated with LWD deposits in contact with the current channel within the study reach. This can be partially attributed to LWD providing a trap for suspended sediment by creating zones of reduced velocity around the obstructions (Skalak & Pizuto, 2009). However, the association of LWD with depositional features is also due to the existing sediment structures within a river acting as obstacles themselves and causing the deposition of LWD. In addition to initiating deposition, sediment also helps secure the LWD in place by complete or partial burial, which creates a more stable jam or individual log than if they were left exposed (Gurnell et al., 2002). It has been noted that sediment storage directly related to LWD deposits is a significant contributor to the annual sediment load of a river (Skalak & Pizuto, 2009). When large wood accumulations are removed from river channels, there is consequently a significant increase in

sediment transport (Gurnell et al., 2002). As sediment storage associated with LWD is a result of flow deflection the controls on where and how much sediment storage occurs are the same as those controlling flow deflection; size, orientation and location of LWD deposit.

LWD has the potential to facilitate pool formation by obstructing flow. This initiates a scouring effect in front of the deposit which deepens the riverbed. Previous studies have shown that the ideal conditions under which this will take place are for LWD to be large relative to the channel, be stably anchored in place, located in high flow zones and orientated perpendicularly or obliquely to the flow (Magilligan et al., 2008). The results from the Bitterroot River study reach indicate that jams are more likely to influence pool formation than individual logs, which is consistent with the known importance of size and stability. In contradiction to what would be expected, our results show that the majority of individual logs which had some influence on pool formation were orientated parallel to flow. This is unexpected because these logs offer less of an obstruction than those perpendicular or oblique to flow. However, this relationship may be explained due to the secondary variable of size; this set of logs oriented parallel to flow were approximately twice the average length of individual logs, thus their size compensated for their unsuitable orientation. Piégay et al., (1999) observed that jams which effect the formation of pools tend to be located on the tops or edges of bars. The results above align with this, as a significant portion of the LWD showing some influence on pool formation was located on the edges of point bars, midchannel bars and islands. However, in addition to these locations, the logs located in the wet channel of the Bitterroot River were commonly observed to influence pool formation. As these logs permanently obstruct flow and occur in high energy zones in the central part of the channel, they have a high ability to impede flow and therefore aid pool formation.

Bank armouring occurs when LWD snagged on the banks of islands or the active channel reduces bank erosion. This occurs because LWD increases the channel roughness of the bank, which dissipates the force of the river and deflects high energy flow away from the bank (Keller & Swanson, 1979). LWD deposits have the same effect which artificially deposited boulders, or riprap, have in the prevention of bank erosion. The amount of protection a particular LWD deposit can offer is controlled largely by its size and orientation. Individual pieces and jams oriented parallel to the bank will protect the greatest area, however LWD oriented perpendicular or oblique to the bank will still have some protecting effect in a zone downstream of the deposit. With increasing size of LWD deposit, there is increased flow deflection and the area of bank sheltered from erosive forces is increased. LWD located on the edges of the channel can also cause bank instability in some places where the deflected flow moves across onto the opposite bank and causes erosion there (Keller & Swanson, 1979).

5.3.2 Secondary Effects

A potential secondary effect of LWD deposits is the stabilisation of the planform morphology of a river. This is achieved where flow deflection and bank armouring prevent the erosion of the banks of islands and river margins. A key location where LWD may have a great effect on planform stabilisation is the outside bend of a meander where erosive forces are especially strong. Daniels and Rhoads (2003) showed that the three dimensional dynamics of a river were altered by the presence of an LWD obstruction on the outside of a meander bend. The overall result was a reduction of near bank velocity on the outside of the meander and limiting of the high velocity zone to the centre of the channel. These changes would reduce erosion of the outer bend, ultimately resulting in the inhibition of lateral migration. There were occurrences observed within the study reach of the Bitterroot River where the presence of LWD appeared to be preventing bank erosion, two examples are shown in Figure 7.

(a)

(b)

Figure 7: (a) Individual logs and jams within the blue circle on the outside of a meander bend deflecting flow away from the bank and inhibiting lateral channel migration; (b) a collection of individual logs and jams in a favourable position to prevent bank erosion within the blue circle. Red lines indicate individual logs, yellow circles indicate jams, blue circles indicate the area of interest and white arrows point downstream.

LWD accumulations have the ability to affect the formation and preservation of depositional features including point bars, midchannel bars and islands. A LWD deposit's ability to facilitate sediment storage may accelerate the early stages of bar and island formation. This is because midchannel bars often form where a LWD deposit, located within the central part of the channel, causes upstream or downstream sediment storage (Abbe & Montgomery, 1996; Keller & Swanson, 1979). If a LWD deposit is stable and causes sufficient sediment deposition, a single midchannel bar may evolve into an island where vegetation can establish. Alternatively, a patchwork of small midchannel bars, each associated with a LWD deposit, may coalesce due to sediment deposition and eventually form an island. Once an island is in place the dominant role of the LWD is likely to switch from sediment storage to bank armouring, as stable LWD deposits act as hard point jams which prevent erosion of islands (Collins et al., 2012). These stable islands can be especially important in laterally migrating rivers, as they provide more permanent and stable riparian habitats than the transient river margins. Islands protected by hard point jams therefore provide settings where forests can reach maturity and add to future LWD stocks in the river (Collins et al., 2012). The study reach contains examples of the various stages of formation of depositional structures, as shown in Figure 8. Although in each example we cannot determine the initiating cause of bar or island formation, we can at least infer that since its emplacement LWD has facilitated sediment storage and stabilisation.

Meander cutoff or avulsion may be initiated or accelerated where one jam, or a collection of jams and individual logs, span the entire width of a channel. In this situation flow can become sufficiently blocked by the LWD itself, or sediment associated with the LWD, to form a plug and induce the backwater effect, diverting the flow of the river into another channel (Keller & Swanson, 1979). We observed at least one such meander cutoff within the study reach where several logs and jams appear to have facilitated avulsion (Figure 9). Although we cannot confirm the relative timing of avulsion and LWD deposition at this site, the LWD deposits were observed to cause flow deflection and sediment storage which would be contributing to the avulsion process.

(a,b,c)

Figure 8: (a) Within the blue circles there are two examples of sediment storage and early midchannel bar formation, one associated with an individual log and one with a jam; (b) jams at the apex and on the edges of a midchannel bar causing sediment storage and preventing erosion of the bar; (c) a jam at the upstream apex of an island acting as a hard point and preventing erosion of the island; (d) a collection of small midchannel bars and small islands within the blue circle in the process of coalescing to form a larger island because of LWD induced sediment storage. Red lines indicate individual logs, yellow circles indicate jams, blue circles indicate the area of interest and white arrows point downstream.

Figure 9: Sediment storage facilitated by LWD deposits within the blue circle has formed a plug which is in the process of causing channel avulsion and meander cutoff; red lines indicate individual logs, yellow circles are jams and the white arrow points downstream.

5.4 Limitations and Improvements

It is important to note the limitations of the methods used to record the spatial distribution and characteristics of LWD. The most likely contributor to error and inaccuracy is variation in human judgement, due to the subjectivity of some of the work. Despite the relatively high resolution of the Bing Maps images used for analysis in GIS, the resolution was not always sufficient to distinguish LWD from discolouring or other structures in the water or sediment. It was also difficult to accurately distinguish individual logs from jams, for example two touching logs forming a jam may be confused with one branching log. Similarly, determining the influence of LWD on morphological processes was sometimes quite subjective. Measuring the width of the channel also required human judgement, since it was ambiguous in some places as to what the bankfull width actually was. This was especially the case with islands located in the channel. Generally the islands were included in the bankfull width, however if there was a significantly vegetated or sized island in relation to the channel it was not included. In order to maintain consistency, and minimise error as much as possible, there was collaboration and continual checking of the work for consistency.

Because the identification of logs and jams was limited to only those visible on the Bing Maps image, our analysis would have excluded any LWD which was not clearly visible as it was submerged or hidden by tree cover. It is therefore likely that there is more LWD present in the study area than what has been identified in this study. Another limitation was not being able to record the characteristics of individual logs within jams, for example to confirm that the key pieces were generally large logs oriented perpendicular to flow direction. There were two assumptions used in order to measure the length of logs. Both were necessary, but limit the accuracy of these values. Firstly, the measuring technique assumes that all logs are lying completely flat, however in reality some will not be horizontal and therefore their length will actually be longer than what was recorded. Secondly, it was assumed the full length of all logs was observable, but it is likely that some parts of logs were submerged and could not be included in the digitisation of log length.

The overall reliability of this study would be greatly improved if combined with field observations to confirm or deny some of the assumptions made during GIS analysis. Field work would also allow more detailed and wider analysis of the characteristics, spatial distribution and influence of LWD on the Bitterroot River. As there has been no previous work published on LWD in the Bitterroot River, there is room for further study into other aspects of this topic at this location. Despite the limitations of this study, if used in combination with field work GIS has the potential to be a valuable tool in future research of LWD.

6. CONCLUSION

Throughout this study LWD has been found to influence the morphology of the Bitterroot River. The LWD characteristics of size and orientation have been shown to control the degree to which LWD influences the morphology of the river through sediment storage, pool formation, flow deflection and bank armouring. It has been found that the larger the LWD the greater the influence it will have on the morphology of the river. This can be seen through the distribution of large scale jams, primarily influencing flow deflection and sediment storage, distributed along the point bars and islands of the river. Individual logs have only a minor influence on the morphology of the Bitterroot River. However, they can act as key members contributing to the formation of a potential jam site. It has been highlighted that the dynamics and storage of wood is dependent upon the fluvial processes and dimensions of the river. Hydrological data confirms the proposed modes of transport and deposition, which include constant deposition during regular flow conditions and peak deposition events during seasonal flooding and overbank flow.

A comprehensive analysis of LWD has been achieved within the study reach, concluding that LWD enhances and facilitates the formation of river structures in this section of the Bitterroot River. However, further field investigation is required to validate the conclusions for the entire river. Understanding the effects that LWD has on shaping the morphology of large scale rivers is becoming increasingly important and a priority for stream management. The information gained through this study has the potential to influence river management practices and wildlife conservation efforts in the Bitterroot Valley.

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