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BANK STABILIZATION, RIPARIAN LAND USE AND THE DISTRIBUTION OF LARGE WOODY DEBRIS IN A REGULATED REACH OF THE UPPER MISSOURI RIVER, NORTH DAKOTA, USA

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ABSTRACT

Large woody debris (LWD) is an important component of ecosystem structure and function in large floodplain rivers. We examined associations between LWD distribution and riparian land use, bank stabilization (e.g. riprap revetment), local channel geomorphology, and distance downriver from the dam in the Garrison Reach, a regulated reach of the upper Missouri River in North Dakota, USA. We conducted a survey of shoreline-associated LWD in the reach during typical summer flow conditions. Reach-wide LWD density was 21.3 pieces km^{-1} of shoreline, of which most pieces (39%) were 'beached' between the waterline and the bankfull level, 31% of pieces had evidence of originating at their current location (anchored), 18% of pieces were in deep water (>1 m), and 13% were in shallow water. LWD density along unstabilized alluvial (sand/silt) shorelines (27.3 pieces km^{-1}) was much higher than along stabilized shorelines (7.2 pieces km^{-1}). LWD density along forested shorelines (40.1 pieces km^{-1}) was higher than along open (e.g. rangeland, crop land; 9.2 pieces km^{-1}) or developed (e.g. residential, industrial; 7.8 pieces km^{-1}) shorelines. LWD density was highest overall along unstabilized, forested shorelines (45 pieces km^{-1}) and lowest along open or developed shorelines stabilized with a blanket-rock revetment (5.5 pieces km^{-1}). Bank stabilization nearly eliminated the positive effect of riparian forest on LWD density. A predicted longitudinal increase in LWD density with distance from the dam was detected only for deep LWD (including snags) along unstabilized alluvial shorelines. Partial resurvey in the summer following the initial survey revealed a reduction in total LWD density in the reach that we attribute to an increase in summer flow between years. Changes in riparian management and land use could slow the loss of LWD-related ecosystem services. However, restoration of a natural LWD regime in the Missouri River would require naturalization of the hydrograph and modification of existing bank stabilization and channel engineering structures. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: large woody debris; snags; Missouri River ecosystem; flow regulation; bank stabilization; riparian; riprap

INTRODUCTION

The importance of large woody debris (LWD) to river ecosystem structure and function is recognized (Sedell and Froggatt, 1984; Harmon *et al.*, 1986; Bilby and Bisson, 1998; Gurnell *et al.*, 2002). In large, unstable-bed alluvial rivers like the Missouri River (USA), LWD provides otherwise rare stable substrate for macroinvertebrates (Mestle and Hesse, 1993; Hesse, 1996). Mestle and Hesse (1993) inferred that much of the historic invertebrate production in the Missouri River was associated with LWD, and partly attributed decreased invertebrate production following flow regulation to reduced delivery of LWD from the floodplain to the channel. Associations between LWD abundance and invertebrate production in sand-bed rivers have also been shown elsewhere (e.g. Cudney and Wallace, 1980; Benke *et al.*, 1984, 1985). In addition to its importance to fish food resources, LWD provides cover for Missouri River fishes (Funk and Robinson, 1974; Dryer and Sandvol, 1993; Hesse, 1996; Lehtinen *et al.*, 1997).

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LWD has a geomorphic function in rivers (Gurnell *et al.*, 2002). LWD at the channel margin or embedded in the substratum ('snags') increases the hydraulic roughness of the bed (Shields and Nunnally, 1984) and increases the retentiveness of the channel to entrained LWD and fine particulate organic matter (Gurnell *et al.*, 1995). LWD can block channels (Triska, 1984); create pools, bars and islands (Abbe and Montgomery, 1996); route sediments; and otherwise modify channel bed texture and topography (Keller and Swanson, 1979; Shields and Smith, 1992). LWD increases habitat heterogeneity at spatial scales relevant to invertebrates, fish, and other wildlife, and is an important determinant of biodiversity in river ecosystems (Maser and Sedell, 1994; Gurnell *et al.*, 1995).

Available historic information suggests that the Missouri River channel once had a high density of LWD (Bodmer, 1833; Chittenden, 1962; Funk and Robinson, 1974; Mestle and Hesse, 1993; Hanson, 2003). The source of the abundant LWD in the river was an extensive floodplain forest, of which only isolated stands remain (Johnson *et al.,* 1976). Human activity on the Missouri River has greatly altered LWD abundance and dynamics. The first manipulations of the Missouri River were snagging operations to remove LWD from the channel and river bank in order to improve navigability during the steamboat era (*c*. 1832–1892; Funk and Robinson, 1974; Hesse, 1996). The settlement of the upper Missouri River valley began in earnest with the arrival of the railroad at Bismarck, Dakota Territory, in 1872 (Chittenden, 1962). In the Garrison Reach of the upper Missouri River in North Dakota (Figure 1), 38% of the floodplain forest was cleared for agriculture between 1881 and 1938, and by 1979, 56% of the original floodplain forest was gone (Johnson, 1992). Similar changes in land use have occurred elsewhere along the Missouri River (Bragg and Tatschi, 1977; Hesse, 1996). Starting in 1937 with the completion of Fort Peck Dam

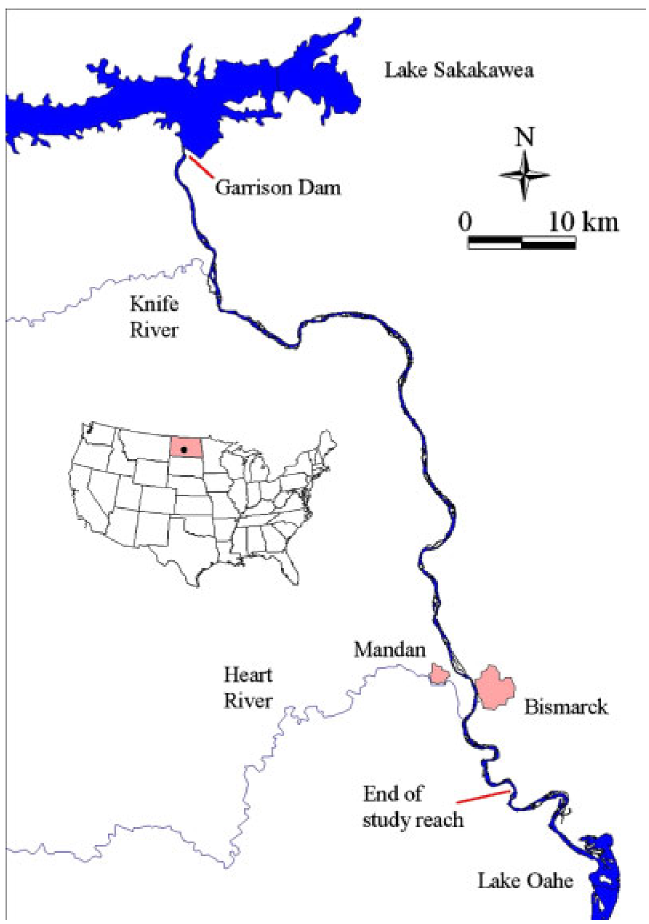

Figure 1. Map of the Garrison Reach of the Missouri River, North Dakota, between Lake Sakakawea (impounded by Garrison Dam) and Lake Oahe. Only a part of Lake Sakakawea and Lake Oahe is shown. Inset map of the contiguous United States shows the location of the Garrison Reach and North Dakota

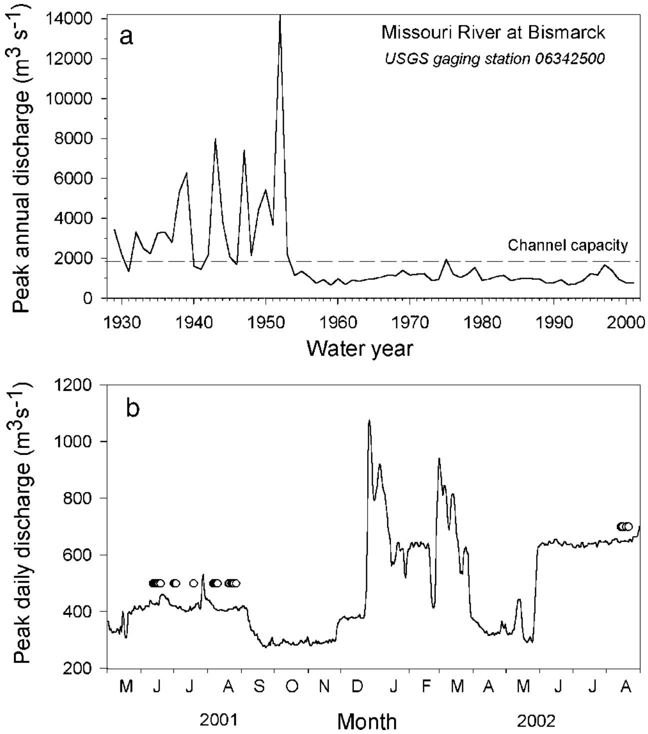

Figure 2. (a) Peak annual discharge for the Garrison Reach at Bismarck, North Dakota. Channel capacity has been estimated at 1840 $m^3 s^{-1}$ (NDGFD, 1998). Garrison Dam was closed in 1953. A water year is October–September. (b) Peak daily discharge at Bismarck during the study. Symbols show LWD survey dates. The last four sample dates on 2001 were intra-annual revisits; sample dates in August 2002 were interannual revisits

in eastern Montana, a series of six mainstem reservoirs was constructed (Schneiders, 1999) which created North America's largest reservoir storage system (NRC, 2002b). Attenuation of peak flows since Garrison Dam was completed in 1953 (Figures 1, 2a) has greatly reduced channel migration (Johnson, 1992; Shields *et al.*, 2000) and virtually eliminated overbank flows. Before flow regulation, spring and summer floods caused lateral bank erosion and channel avulsions that caused trees (mostly cottonwoods, *Populus deltoides* Marsh; Johnson *et al.*, 1976) to fall into the channel at outside bends (Chittenden, 1962). At the same time, new stands of cottonwood and willow (*Salix* spp.) seedlings colonized bare alluvial landforms including mid-channel and point bars, abandoned channels, and scoured floodplain surfaces (Johnson *et al.*, 1976; Scott *et al.*, 1997; Dykaar and Wigington, 2000). In the now highly regulated Missouri River, delivery of LWD to the channel and establishment of new riparian forest stands are both greatly reduced because the river and its floodplain are ecologically uncoupled (NRC, 2002b).

Unlike the lower river, large-scale commercial navigation on the upper Missouri River (the river in North and South Dakota and Montana) did not persist into the 20th century. Consequently, the headwater and inter-reservoir reaches of the upper river have not been channelized, and the shorelines have not been completely stabilized as has most of the lower river (Galat *et al.*, 1998). However, flow regulation has encouraged development on the floodplain along the upper river, particularly near the cities of Bismarck and Mandan, North Dakota. Since Garrison Dam was built, extensive rock revetments (riprap), rock dykes, and other shoreline protection structures have been installed to prevent erosion (USACE, 1981). Although channel migration is minimal in the Garrison Reach, some bank erosion still occurs due to mass wasting and a channel widening response to reduced sediment input (Williams and Wolman, 1984; Biedenharn *et al.*, 2001).

A recent review of the status and management of the Missouri River ecosystem (NRC, 2002b) concluded that the existing, highly modified system was not providing the broadest set of ecosystem benefits to the region. The panel recommended that a redistribution of benefits be implemented through management that is focused on restoration of ecosystem functions that support a diverse, productive, and sustainable river/floodplain ecosystem. Among the processes that characterize a functioning Missouri River ecosystem is the production of LWD and its delivery to and redistribution in the channel (NRC, 2002b). Restoration of a pre-transformation LWD abundance and distribution pattern would require major changes in how the dams are operated, and in riparian land use. These changes are not presently feasible (NDGFD, 1998). However, there may be flow-management strategies, and alternatives to how human activities on shorelines and in riparian zones are currently managed, that can restore some of the ecological benefits of a more naturalized LWD regime.

The purpose of this paper is to examine spatial variation in shoreline-associated LWD in the Garrison Reach of the upper Missouri River in North Dakota, USA. We relate LWD type (e.g. deep, beached), density, and distribution to shoreline type (e.g. sand/silt alluvium, riprap), riparian land use (e.g. forest, residential), local channel geomorphology, and distance downriver from Garrison Dam. We relate our findings to published accounts of LWD dynamics in floodplain rivers, and suggest how changes in river ecosystem management might support restoration of the ecosystem functions associated with LWD. This research is part of the US Environmental Protection Agency's Great River Ecosystems Environmental Monitoring and Assessment Program (Schweiger *et al.*, in press).

STUDY REACH AND METHODS

Study reach

The Garrison Reach of the upper Missouri River is in central North Dakota (Figure 1). The approximately 160 km long reach is defined as the free-flowing river between Garrison Dam and the headwaters of Lake Oahe (completed in 1958). Our study reach extends from the dam at rkm (river kilometres from the mouth) 2236.7, downriver to rkm 2090.9, and flows through the cities of Bismarck and Mandan. Median annual Missouri River discharge at Bismarck for the period of record was 629 $m^3 s^{-1}$ (USGS, 2003). Since completion of the dam, discharge has not exceeded the approximate channel capacity of 1840 $m^3 s^{-1}$ (NDGFD, 1998; Figure 2a). Watershed area for the reach is 482 774 km^2 at Bismarck (USGS, 2003). Two tributaries enter the reach from the west, the Knife River (rkm 2213; 4.2 $m^3 s^{-1}$ median discharge), and the Heart River (rkm 2110; 5.8 $m^3 s^{-1}$ median discharge; USGS, 2003).

The Garrison Reach lies at the boundary of the Northwestern Glaciated Great Plains and the unglaciated Northwestern Great Plains (Bryce *et al.*, 1998). The present course of the river is a late-Wisconsinan ice-margin position (Kume and Hanson, 1965). The river flows through an alluvial valley that ranges in width from <1.6 km near Garrison Dam to >11 km south of Bismarck (Johnson *et al.*, 1976). Alluvial bank materials in the reach are composed of weakly cohesive sandy silt (Berkas, 1995). Planar failure due to toe scour and fluvial bank erosion are the most common mechanisms of bank collapse (Pokrefke *et al.*, 1998). At several locations in the reach, the river channel is at the margin of the alluvial plain and has contacted the erodible Tertiary sandstone bedrock and inset glacial deposits that form the bluffs overlooking the river (Kume and Hanson, 1965). Colluvium eroded from the bluffs armours the river bank at these locations.

The meandering channel is characterized by a shifting sand substrate (bed $D_{50} = 0.92$ mm; Biedenharn *et al.*, 2001) and extensive mid-channel and lateral sand bars that vary in elevation and vegetative development. Bed degradation of 1.5 to >3 m has occurred for about 40 km below the dam (Williams and Wolman, 1984; Biedenharn *et al.*, 2001). Avulsion-formed islands in the reach are few; most islands are vegetation-stabilized sandbars. Median channel depth was 1.9 m during the typical summer flows that occurred during the study (T. R. Angradi, unpublished data). Mean bankfull width in the reach is 615 m (Biedenharn *et al.*, 2001).

The upper Missouri River floodplain-forest overstorey was historically dominated by cottonwood, with a smaller component of American elm (*Ulnus americana* L.), box elder (*Acer negundo* L.), and green ash (*Fraxinus pennsylvanica* Marsh.) (Meriwether Lewis, 26 April 1805; cited in Thwaites, 2001). Because of flow regulation, cottonwood, a pioneer species, has declined in floristic importance in the floodplain forest (Keammerer *et al.*, 1975; Johnson *et al.*, 1976; Johnson, 1998).

Field methods

In June and July 2001, we conducted a complete survey of the Garrison Reach shoreline by boat. We recorded the location (latitude and longitude) for every piece of LWD seen on the shoreline below the bankfull level or in the

Table I. Classification schemes for LWD type, shoreline type, and riparian land use. Each piece of LWD was in only one LWD type, shoreline type, and riparian land-use category

Category	Description
LWD Type	
Anchored	LWD anchored to the shoreline above the bankfull level or exhibiting other evidence of originating at the current location; see text for details.
Deep	LWD that is not anchored to the shoreline and is at least partially in >1 m deep water. Category includes LWD embedded in the river bottom (snags) and pieces incorporated in log jams. The piece may or may not project above the water surface.
Shallow	LWD that is not anchored to the shoreline and is at least partially in water <1 m deep. The piece may or may not project above the water surface. Otherwise similar to beached LWD.
Beached	LWD that lacks evidence of having originated at its current location, is situated below the bankfull level and is not inundated. Usually oriented parallel to shoreline and often has evidence of being transported (bark, small limbs, roots, rootwads are missing).
Shoreline type	
Blanket-rock revetment	Boulder- to cobble-sized rock, piled on the bank extending from below the water line to (or near to) the bankfull level. Also called riprap. Revetments may be haphazard or highly engineered.
Toe-fill revetment	Rock piled on the bank but not extending >1 m above the waterline.
Rock-dyke revetment	Rock- or earth-core jetty extending into the channel. Dyke may be revetted with rock on upriver or both sides. The length of the structure is more than twice the width at the base (also called wing dyke).
Hard point	Same as dyke revetment except that length of the structure is less than twice the width at the base.
Wall revetment	A concrete wall usually associated with industrial sites.
Windrow revetment	Rock piled or buried in a trench on the top of the bank at or near the bankfull bankline. The rock is intended to fall into a functioning position at the wetted shoreline as the bank erodes.
Trash revetment	Concrete slabs, construction debris, etc., piled on the bank extending from below the water line to (or near to) the bankfull level.
Car-body revetment	A type of trash revetment.
Tributary mouth	Self-explanatory.
Gravel/cobble	Natural colluvium on the shoreline in reaches where the river channel contacts the bluffs at the floodplain margin.
Sand/silt	Unstabilized alluvial shorelines without any of the above features.
Riparian land use	
Closed forest	Closed canopy of usually mature trees, including cottonwoods.
Open forest	Patchy forest. Mature cottonwoods are uncommon.
Open land	Includes rangeland and shrubland.
Crop land	Includes row crops and hay fields.
Industrial	Includes commercial and industrial uses, transportation infrastructure, and animal feedlots.
Residential	Includes suburban and urban residential areas, and recreational infrastructure (e.g. parks, ramps).
Dyke	Areas where the 'land' behind the dyke-created shoreline is actually a backwater.
Inside bend	Aggraded land where the shoreline is not the historic floodplain margin.
Tributary mouth	Self-explanatory

river within 10 m of the shoreline. We also recorded the location of the downriver end and upriver end of every shoreline feature (e.g. revetment, dyke; Table I). LWD was defined as pieces >5 m long and >0.3 m in diameter at the large end. This definition of LWD is larger than has been used elsewhere (Gurnell *et al.*, 2002). We used this definition so our data would be comparable to data collected using standardized methods (USEPA, 2000) for an ecological assessment of the Garrison Reach (Schweiger *et al.*, in press). Also, restricting the survey to large pieces was necessary to make the survey feasible.

Each piece of LWD was classified as anchored, deep, shallow, or beached; definitions are in Table I. Evidence of a local origin for an anchored piece of LWD included: (i) an attached rootwad above the bankfull level; (ii) the presence of soil or fine roots in the rootwad if the rootwad is at the water's edge; (iii) orientation orthogonal to the shoreline; (iv) attachment of a dead stem to the stump; or (v) projection of a broken stem above the bankline higher than it could be carried by high flows (which indicated that a top had fallen out of a large tree). The determination of LWD type was partly subjective; mitigating this source of error was crew uniformity during the survey. For each piece of LWD, we noted the apparent riparian land-use category (Table I) in a zone extending 20 m landward from the bankline.

Our study is based on LWD density (number of pieces km^{-1} of shoreline) rather than on LWD volume or mass because our goal of relating shoreline type and riparian land use to LWD distribution required a complete survey, precluding the very labour-intensive measurement of LWD volume. LWD density and volume are doubtless correlated in our study, especially since we counted only large pieces of LWD.

We restricted our LWD survey to pieces on the shore or in the river within 10 m of the shoreline because most Garrison Reach LWD is in that zone (T. Angradi, personal observation), and because we were primarily interested in the influence of bank stabilization and riparian land use on local LWD distribution. In extremely shallow water (<0.25 m) we had to position the boat >10 m from the shoreline; otherwise we held the boat within 10 m of the shoreline. Latitude and longitude for each piece of LWD and shoreline feature were acquired using a Garmin® model GPSmap76 hand-held global positioning system (GPS) receiver. Re-acquisition of fixed points in the river channel produced waypoint groups with a maximum separation of <4 m. Plotting waypoint coordinates for readily identifiable fixed points (e.g. the tip of a dyke) on high resolution photo-imagery (described below) showed that positional accuracy was within 10 m. We considered this precision and accuracy within the data quality needs for this study.

The river channel is now isolated from the pre-dam floodplain by a 2–3 m high bank. The isolation is due to channel bed degradation (Williams and Wolman, 1984) and the elimination of bankfull flows (Figure 1). The interface between the pre-dam floodplain and the existing active channel zone was the target shoreline that we surveyed in our study. We attempted to use the boat for as much of the survey as possible, but where the navigable channel diverged from the target shoreline, we counted LWD on foot. We restricted our survey to the pre-dam floodplain margin because that is where bank stabilization and riparian development occur. For some inside-bend complexes with multiple secondary channels, multiple low terraces, or wetlands, we could not always effectively identify and survey the target shoreline and we omitted these shorelines from the analysis.

Intra- and interannual variation in LWD density

In late August 2001, we revisited four segments of forested shoreline distributed through the Garrison Reach (5 km total) and recounted LWD to assess intra-annual variation. In August 2002, we recounted LWD on 17 shoreline segments distributed through the Garrison Reach (27 km total) to assess interannual variation associated with LWD transport and recruitment in the intervening year. Summer peak flows were 50% higher in 2002 than in 2001 (Figure 2b). At these higher flows, which caused an increase in river stage of about 0.6 m at Bismarck, some LWD pieces would have changed type (e.g. some shallow pieces became deep pieces; some beached pieces became shallow pieces).

Data summary

GPS coordinates for LWD and shoreline features were plotted in a geographic information system (GIS) onto a digital photo-mosaic (0.3-m pixel resolution) colour-infrared aerial photographs of the reach taken in August 2000. In the GIS, we moved the coordinates for the downriver and upriver ends of shoreline features orthogonally from the GPS receiver position to the shoreline. We created shoreline segments connecting the upriver and downriver ends of each feature (e.g. a section of riprap). We also created shoreline segments attributed with riparian land use based on the field notes (the land-use assignment for each piece of LWD) and classification of the aerial photographs. Thus, we created two continuous lines for each shoreline: one with shoreline type attributes, and one with riparian land-use attributes. In the GIS we extracted the total length of shoreline and LWD present for each shoreline type, riparian land- use category and each shoreline type–land use combination. We created an additional line representation for each shoreline attributed (from aerial photographs) as either having the target shoreline adjacent to an active (flowing) channel or having the target shoreline isolated from the channel by a well-developed sandbar, usually a point bar. Finally, we created template one-dimensional shorelines that we split into non-overlapping 1 km segments of shoreline that we then attributed with the LWD locations, shoreline type and riparian land-use characteristics. We used the data partitioned into 1 km segments only to examine the effect of shoreline distance from Garrison Dam on LWD density.

Statistical tests of independence between categorical attributes of LWD (i.e. LWD type, riparian land-use category, shoreline type, channel location, visit number) were based on the chi-square statistic calculated for total LWD counts. Comparisons of LWD abundance between inter- and intra-annual visits were made using paired *t*-tests. LWD density along right and left shorelines was similar: we counted 575 more pieces ($4\,km^{-1}$) along the right shoreline than along the left shoreline. Preliminary analysis revealed little difference in the distribution of LWD types or shoreline types. Therefore, data from right and left shorelines were combined unless otherwise indicated.

PREDICTIONS

We assumed that no LWD has been exported to the Garrison Reach from upriver since the completion of Garrison Dam in 1953. Tributaries contribute <2% of flow in the reach and are not heavily forested. The largest flow on record for the Garrison Reach ($14\,160\,m^3s^{-2}$ in April 1952; Figure 2a) occurred just before the dam was completed. We assumed that much of the LWD in the Garrison Reach channel at the time of the flood was exported downriver or deposited on the floodplain. Some large pieces of wood (snags) may have been exported into the reach from upriver during the 1952 flood and may still be in the reach. However, the distribution of most of the LWD in the reach probably represents processes in the regulated river, with some unknown historical influence. We predicted that local LWD density would be reduced by local decoupling of the channel from the floodplain forest by reduced alluviation, elimination of floods, bank stabilization, and floodplain development. Therefore, we expected higher LWD density along unstabilized alluvial shorelines than along stabilized shorelines, higher LWD density along forested shorelines than along open or developed shorelines, and higher LWD density where the target shoreline was adjacent to an active channel than where it is distant from a channel. We predicted that the relative abundance of each LWD type would vary among shoreline types and among riparian land-use categories according to the origin and relative transportability of each type. Because no LWD is presently imported to the reach from upriver on the mainstem, we predicted that downriver accumulation of LWD mobilized during post-regulation high flows (e.g. July 1975; July 1997; Figure 2a) would skew the LWD distribution downriver, and the effect would be greatest for the most LWD-retentive shorelines (forested and unstabilized) and for the putatively most readily transported LWD types (shallow and beached).

RESULTS

LWD density and type

We counted 6085 pieces of LWD along 286 km of shoreline (right and left shorelines combined). Overall LWD density in the reach was 21.3 pieces km^{-1}. Beached (39%) and anchored (31%) LWD were the dominant types, followed by deep (18%) and shallow LWD (13%). We excluded 15.7 km of shoreline (5.4% of the total) for which we considered the data unreliable (see 'Field methods' section). LWD density along these excluded shorelines was only 2.7 pieces km^{-1}; removing them from the analysis did not affect our conclusions.

Effects of shoreline type and riparian land use on LWD density and type

LWD density was highest along alluvial sand/silt shorelines (27.3 pieces km^{-1}) and lowest along shorelines protected by a blanket-rock revetment or a rock dyke (<7 pieces km^{-1}; Table II). Alluvial sand/silt shorelines had about 1.6 times as much LWD per kilometre as shorelines armoured with natural gravel/cobble colluvium eroded from the river bluffs. Overall, LWD density along unstabilized shorelines was 3.6 times higher than along stabilized shorelines.

LWD density along forested shorelines (53.6 and 29.7 pieces km^{-1}, for closed and open forest, respectively; Table III) was four to five times higher than along open or developed shorelines. Although riparian residential areas in the Garrison Reach are often wooded, residential shorelines had lower overall LWD density than crop land or other open land because most residential shoreline is protected by some type of rock revetment. Open land (e.g. shrubland, rangeland, crop land) was the dominant riparian land use in the reach (44%); 40% of shoreline was forested; 16% was developed.

Table II. LWD abundance, density, and percentage of total length for each shoreline type in the Garrison Reach of the Missouri River in North Dakota. Estimates of LWD density for rare shoreline types ($\leq 3\%$ by length) are less reliable than estimates for more extensive shoreline types. Other revetments include hard points, toe fills, trash revetment, wall revetment, windrow revetment, and car body revetment (see Table I)

Shoreline type	Number	Density (number km^{-1})	Length (%)
Alluvial sand/silt	5137	27.3	66
Colluvial gravel/cobble	425	17.0	9
Blanket-rock revetment	388	6.8	20
Rock-dyke revetment	55	6.0	3
Other revetment	77	14.0	2
Tributary mouth	3	2.9	<1
Unstabilized shorelines	5565	26.0	75
Stabilized shorelines	520	7.2	25
All shorelines	6085	21.3	

Table III. LWD abundance, density, and percentage of total length for each riparian land-use type and shoreline location in the Garrison Reach of the Missouri River in North Dakota. Riparian land-use categories are defined in Table I. Open shorelines include open land, crop land, and inside bends; developed shorelines include residential, industrial, and dyke

Riparian land-use/channel location	Number	Density (Number km^{-1})	Length (%)
Closed forest	2664	53.6	17
Open forest	1916	29.7	23
Open land	871	10.4	29
Crop land	207	8.9	8
Residential	211	7.2	10
Industrial	74	11.8	2
Dyke	70	7.0	4
Inside bend	69	3.9	6
Tributary mouth	3	2.8	<1
Forested shorelines	4580	40.1	40
Open shorelines	1147	9.2	44
Developed shorelines	355	7.8	16
Distant shorelines	634	9.1	24
Adjacent shorelines	5451	25.2	76
All shorelines	6085	21.3	

Compared with alluvial sand/silt shorelines, colluvial gravel/cobble shorelines had relatively more beached LWD and less of other LWD types ($\chi^2 = 303.9$, $p < 0.01$; Figure 3). Unstabilized shorelines had relatively more anchored LWD and less beached LWD ($\chi^2 = 80.9$, $p < 0.01$) than stabilized shorelines. Proportions of shallow and deep LWD were about the same along unstabilized and stabilized shorelines.

Open shorelines ($\chi^2 = 427.6$, $p < 0.01$) and developed shorelines ($\chi^2 = 151.9$, $p < 0.01$) had relatively less anchored and more beached LWD than forested shorelines (Figure 3). Open forest, in which the dominant tree species (green ash, box elder) tend to be relatively small, had relatively less deep LWD, including snags, than closed forest which typically retains a significant mature cottonwood component ($\chi^2 = 22.4$, $p < 0.01$). Open and developed shorelines had similar relative frequencies of each LWD type ($\chi^2 = 7.2$, $p = 0.07$).

Total LWD density was highest along forested alluvial sand/silt shorelines (45 pieces km^{-1}; Figure 4) and lowest along open and developed shorelines stabilized with blanket-rock revetments (<6 pieces km^{-1}). Land-use and shoreline type were not independent ($\chi^2 = 1065.9$, $p < 0.01$). Although LWD density along forested shorelines stabilized with blanket-rock revetments (10.5 pieces km^{-1}) was higher than LWD density along open or developed shorelines with blanket-rock revetments, the land-use effect on LWD density along revetted shorelines was less

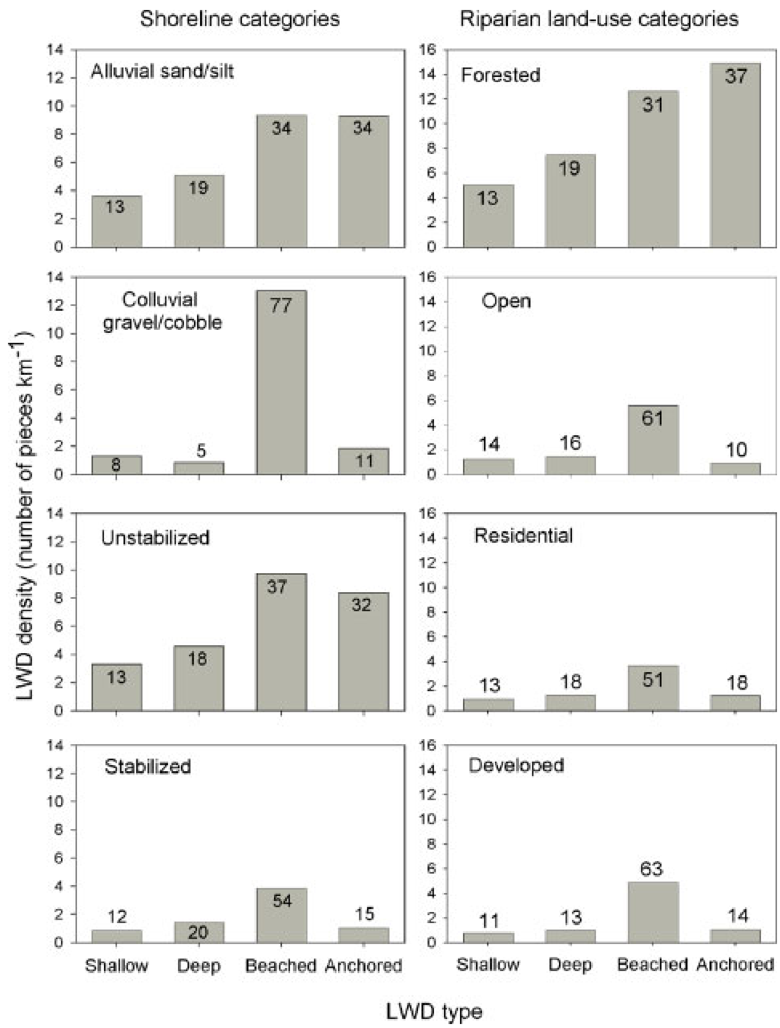

Figure 3. Reach-scale LWD density by LWD type for selected shoreline types (left column of plots) and riparian land-use categories (right column of plots). Bars represent reach totals expressed as a density based on total shoreline length. Values on bars are percentage of the total. Total LWD abundance given in Tables II and III. A total of 15.7 km of shoreline was excluded from the analysis (see text for details)

than the land-use effect along sand/silt shorelines. In other words, bank stabilization greatly reduced the positive effect of shoreline forest on LWD density. Bank stabilization nearly cancelled out the effect of shoreline forest for anchored LWD, which is the LWD type most directly related to land use (Figure 3). On forested shorelines, the effect of shoreline revetment was least for deep LWD (Figure 4).

Effects of channel location on LWD density and type

LWD density at shoreline locations where the target shoreline was adjacent to an active channel (25.2 pieces km^{-1}) was 2.7 times higher than at distant shoreline locations (9.2 pieces km^{-1}; Table III). Distant shoreline locations had relatively more beached LWD than adjacent shoreline locations ($\chi^2 = 86.9$, $p < 0.01$; Figure 5). Rare instances of shallow or deep LWD along distant shoreline (<0.7 pieces km^{-1}) were due to classification of shorelines based on photographs of the river at flow conditions different from those during the survey. Based on the aerial photos, 75% of the shoreline was adjacent to an active channel and 25% was distant from an active channel.

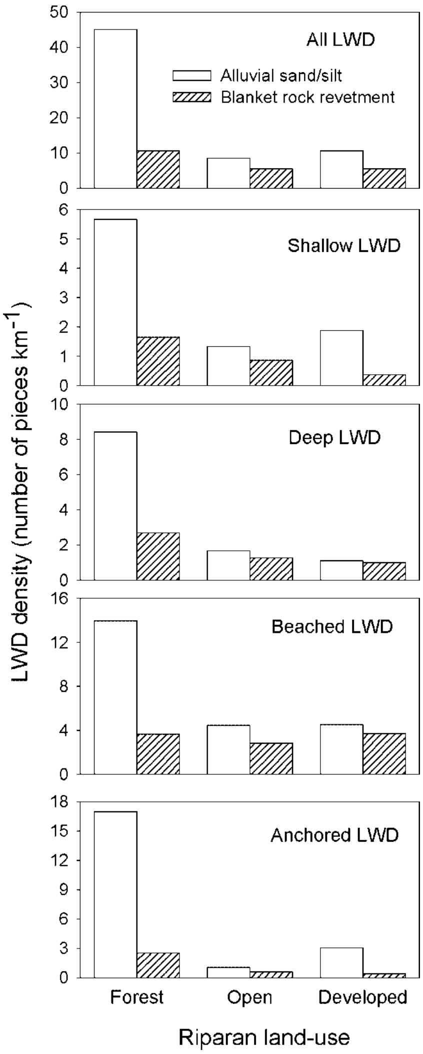

Figure 4. Reach-scale LWD density for dominant shoreline types and riparian land uses. Bars represent reach totals expressed as a density based on total shoreline length. Percentages of shoreline in each shoreline type and riparian land-use category are given in Tables II and III

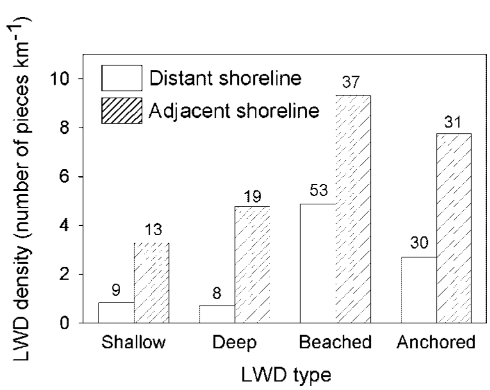

Figure 5. Reach-scale LWD density by shoreline position and LWD type. On adjacent shorelines, the target shoreline was adjacent to an active river channel; on distant shorelines, the river channel was isolated from the target bankline by a sandbar. Bars represent reach totals expressed as a density based on total shoreline length. Values above bars are percentage of the total

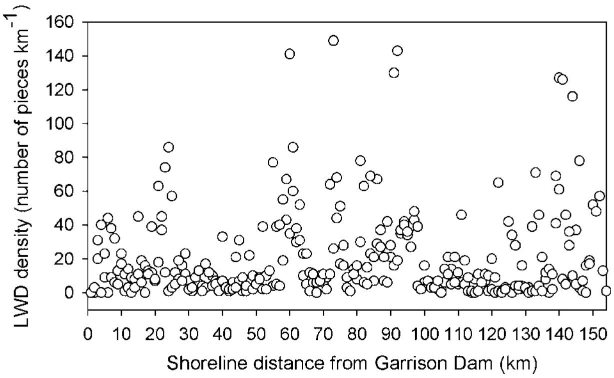

Figure 6. Variation in LWD density with shoreline distance downriver from the dam. Each value is for a non-overlapping 1 km segment of shoreline

Longitudinal variation

LWD density was highly variable through the Garrison Reach (Figure 6). Maximum density was 149 pieces km^{-1}, and several other segments had a LWD density >100 pieces km^{-1}. Segments with no LWD were very common. There was no consistent upriver or downriver gradient in LWD density (Figure 6) for all shoreline types combined. The same data, separated by LWD type for the two dominant shoreline types, reveal a longitudinal increase in the maximum density of deep LWD along alluvial sand/silt shorelines (Figure 7). The large number of segments in which there was no deep LWD obscures the downriver pattern, but for segments with deep LWD, there was a weak but significant increase in density of deep LWD with distance from the dam ($r = 0.47$, $p < 0.01$). The effect was not due to the distribution of shoreline forest or adjacent channel locations in the reach, which exhibited no longitudinal pattern.

Urbanization and Garrison Reach shorelines

Composition of shorelines in the 19 km of the Garrison Reach that flows through the Bismarck/Mandan urban area was different from upriver and downriver rural shorelines (Figure 8). Through Bismarck/Mandan, 55% of shorelines were stabilized compared to 21% of rural shorelines. Seventy per cent of rural shorelines had alluvial sand/silt substrates compared with 37% of the urban shorelines. Only 17% of Bismarck/Mandan shorelines were forested, compared with 43% of rural shorelines (Figure 8). Shorelines through Bismarck/Mandan were 59% developed, primarily residential land use (47%); 11% of rural shorelines were developed.

Intra- and interannual variation

Shoreline segments revisited in August 2001 (Figure 2b) had 10% more LWD pieces than in the original survey (intra-annual variation; Figure 9). This change in total abundance between visits was not significant for any LWD type or for all LWD types combined (for all tests, $t \leq 2.1$, $p \geq 0.12$, $n = 4$). However, there was relatively more anchored LWD during the second visit ($\chi^2 = 7.9$, $p < 0.05$). The percentage of LWD that was anchored increased by 10% between visits, possibly because of our increased experience at detecting evidence of a local origin (the criteria for being anchored).

Shoreline segments revisited in 2002 had 35% less LWD than in 2001 (Figure 9). There was significantly less beached ($t = 4.1$, $p < 0.01$, $n = 17$) and anchored LWD ($t = 2.8$, $p < 0.05$, $n = 17$) and less of all types combined ($t = 3.9$, $p < 0.01$, $n = 17$) in the second visit. The relative frequency of LWD types changed between visits ($\chi^2 = 67.6$, $p < 0.01$). The percentage of the total comprising beached LWD decreased by 16%, while the percentage comprising shallow and deep LWD increased by 5% and 8%, respectively. The interannual variation we observed cannot be explained by a 10% error in total count or a 10% error in the proportion of anchored LWD (from intra-annual variation; Figure 9). Apparently, beached and anchored LWD was exported from the shorelines we revisited. There was no relationship between change in LWD density between years and distance from the dam for any LWD type or for all types combined ($r < 0.41$ and $p > 0.1$ in all cases).

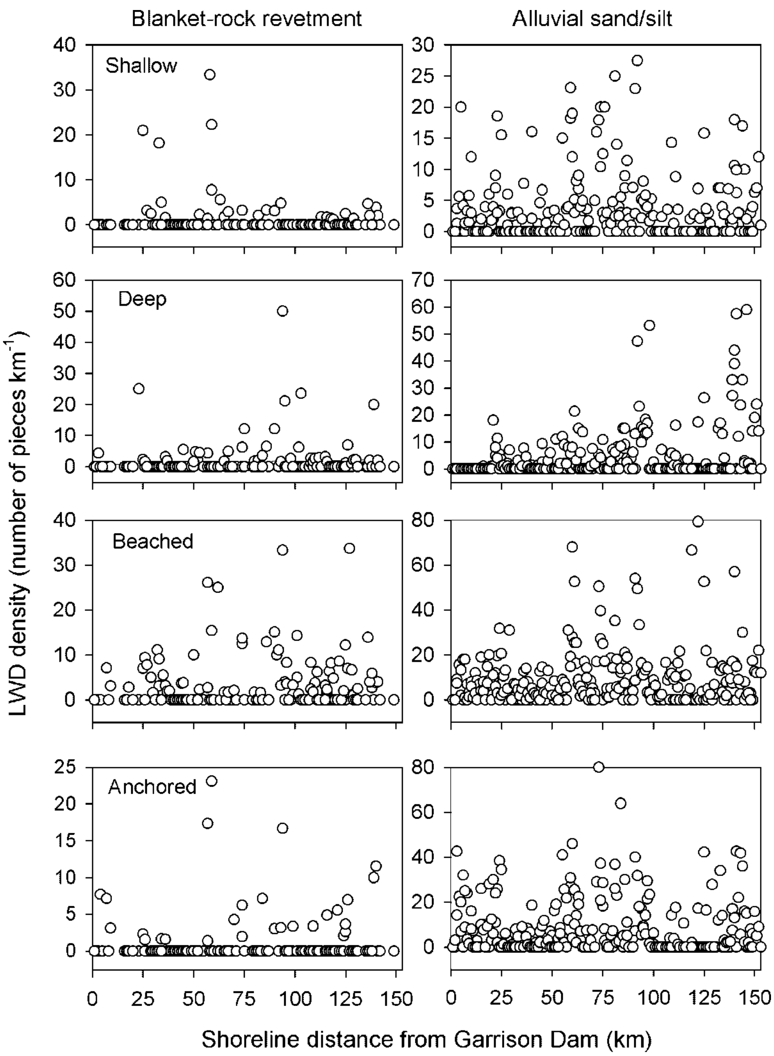

Figure 7. Variation in LWD density with shoreline distance downriver from the dam by LWD type for shorelines stabilized with blanket revetments and unstabilized sand/silt shorelines. Values are for that proportion of each 1 km segment of shoreline that is alluvial sand/silt or blanket revetment

DISCUSSION

Predictions

Our general prediction was supported: the decoupling of the floodplain and the river channel by bank stabilization and riparian development reduced the local density of shoreline-associated LWD. Overall, LWD density was about 3.5 times higher along unstabilized shorelines than along stabilized shorelines, and four to five times higher along forested shorelines than along open or developed shorelines. A key finding of this study is that the highest density of LWD occurred along unstabilized forested shorelines, and that there was an interaction between riparian land-use and bank stabilization: the positive effect of forest on LWD density was nearly eliminated by stabilization (Figure 4). Stabilized, forested shorelines had only about as much wood as unstabilized open or developed shorelines. This effect applies for both anchored and beached LWD, suggesting that bank stabilization decreased local LWD density by decreasing retention of entrained LWD *and* by decreasing the rate at which LWD falls into the channel. The second effect is due both to the elimination of bank erosion on stabilized shorelines, and to the increased distance between riparian forest and the river caused by the interposition of often massive rock revetment

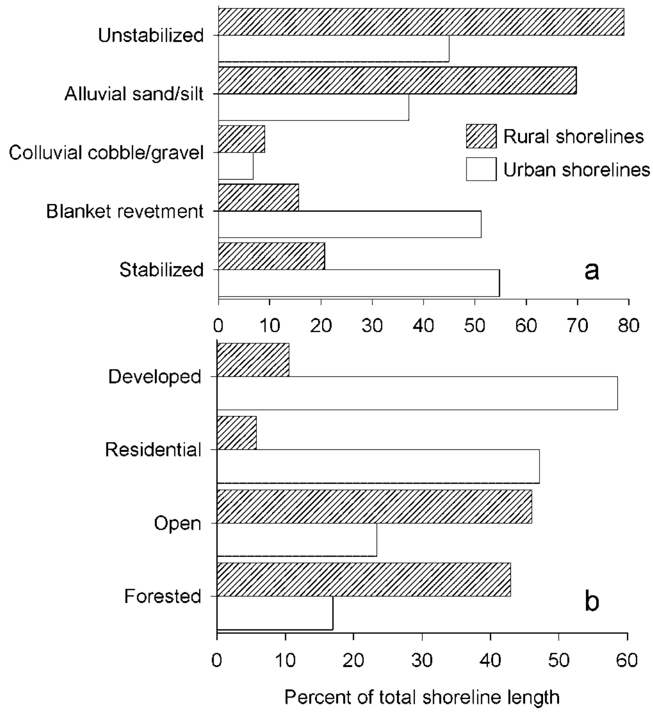

Figure 8. Relative length of selected shoreline types (a) and riparian land-use categories (b) for Bismarck/Mandan (urban) shorelines (rkm 2109.4 to 2128.5) and for the rural shorelines upriver and downriver from Bismarck/Mandan. Percentages by type for the entire Garrison Reach are in Table III. Unstabilized shorelines includes alluvial sand/silt and colluvial cobble/gravel shorelines. Stabilized shorelines includes blanket, hard point, rock dyke, toe fill, trash, wall, windrow, and car-body revetment. Developed shorelines includes residential, industrial, and dyked shorelines. Forested shorelines include closed and open forest shorelines. Open shorelines include rangeland, shrubland, and crop land. Total length of shoreline through Bismarck/Mandan was 35.6 km (4.6 km excluded from the analysis); total length of rural shorelines was 250.4 km (11.2 km excluded from the analysis)

structures. At these sites, trees that fall naturally toward the river have to fall farther to reach the river. Also, riparian zones were often cleared of trees when revetments were installed to permit access with heavy equipment. Attempts to reforest these cleared zones have mostly failed (W. Bicknell, US Fish and Wildlife Service, Bismarck, North Dakota, personal communication).

The dominant type of LWD in the reach was beached. This is not surprising since this LWD category included any piece on the shore large enough to qualify as LWD, including tree limbs, tops, and small stems of any species. In contrast, snags (i.e. most deep LWD) are restricted to massive cottonwood stems with the rootwad attached. A 19th century account of the origin and character of Missouri River snags still applies: 'Trees that line the river bank are undermined [during the spring and summer flood] and fall into the stream. They are borne along by the current until they become anchored in the bottom, where they remain with one end sticking up and pointing downstream, sometimes above and sometimes below the surface . . . They are called snags or sawyers' (Chittenden, 1962).

Compared with unstabilized sand/silt or forested shorelines, stabilized and developed shorelines had relatively more beached LWD and a less anchored LWD. Although modified shorelines were less retentive overall than natural shorelines (i.e. they had a lower density of beached LWD), because the local floodplain LWD source has been removed or at least isolated from the channel, most of the LWD along these shorelines has necessarily been transported there by the river, which accounts for the higher proportion of beached LWD.

As predicted, adjacent shorelines had higher density of LWD than distant shorelines for all LWD categories. Including both adjacent and distant shorelines in the analysis confounds the effect of shoreline type because the LWD-poor distant shorelines were virtually all unstabilized shorelines. The density of LWD on just the adjacent unstabilized shorelines (34 pieces km^{-1}) was higher than the density of LWD on all unstabilized shorelines combined (26 km^{-1}, Table II), which strengthens our conclusions about the negative effect of shoreline stabilization on

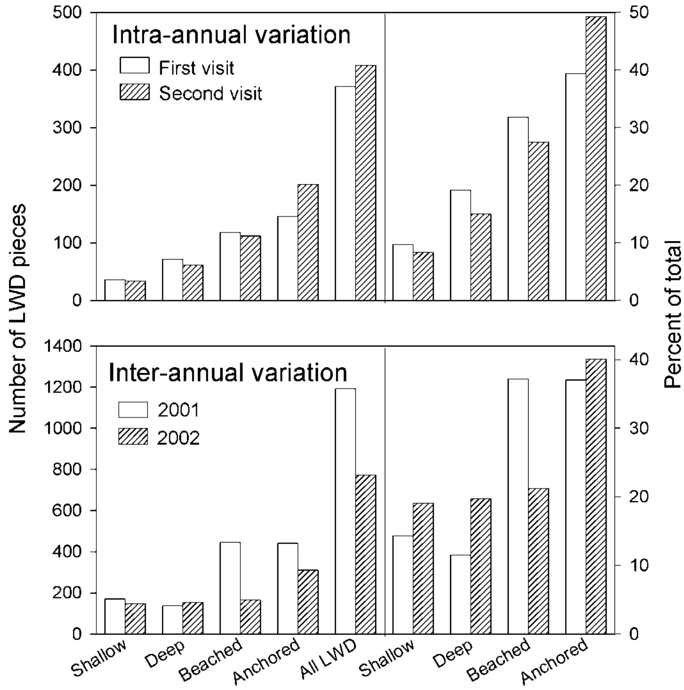

Figure 9. Intra- and interannual variation in LWD abundance (to left of vertical line) and proportional composition by LWD type (to right of vertical line). Intraannual results are based on four shoreline segments with a total length of 5 km visited twice in 2001. Interannual results are based on 17 shoreline segments with a total length of 27 km revisited in 2002. Sample dates are shown in Figure 2b

LWD. However, our findings are based on the combined analysis because we sought reach-scale estimates of LWD density, because riparian development occurs along adjacent and distant shorelines and because our channel classification was subjective and applies only to the flow conditions during the study.

Colluvial gravel/cobble shoreline are naturally protected from erosion by coarse particles eroded from bluffs and by bedrock outcrops in some locations. They necessarily occur on outside bends (otherwise they would be alluvial shorelines), but they tend to be quite shallow because the coarse bed material prevents scour. Because they are generally unforested shorelines, they have little anchored LWD; because they are so shallow (often <1 m deep many metres out from the shoreline) deep LWD is, by definition, rare; and because of the coarse bed material, snags do not readily embed themselves in the river bottom.

Not well supported was our prediction that LWD density would increase downriver from the dam due to progressive export without replacement by LWD imported from upriver. Any reach-scale longitudinal distribution pattern (Figure 6) was masked by local effects of shoreline type, land use, and local post-regulation channel geomorphology. Only density of deep LWD along alluvial sand/silt shorelines increased with distance from the dam (Figure 7). This result was unexpected because we assumed that since it its more readily transported, beached or shallow wood would exhibit more longitudinal variation than deep LWD, which is mostly massive pieces embedded in the river bottom. Density of deep LWD was highest on outside bend shorelines bordering mature cottonwood forest in two tight meanders in the lower study reach (>135 shoreline km from the dam; Figure 1). We speculate that the continuous resupply of LWD from the floodplain between high flow events prevents a downriver accrual pattern for beached and shallow LWD.

Because we lack data on the pre-regulation distribution of LWD in the Garrison Reach, we cannot rule out the possibility that the current distribution, particularly of snags, partly reflects pre-dam LWD input and transport patterns. However, there was a strong influence of bank stabilization on LWD density of all types (e.g. Table II, and Figures 3 and 4), and virtually all Garrison Reach bank stabilization projects were installed after the completion of Garrison Dam (USACE, 1981)—strong circumstantial evidence that the current LWD distribution reflects post-dam input and transport patterns.

Two other mechanisms, decay and ice jamming, could have a role in the distribution of LWD in the Garrison Reach. Published information on submerged LWD depletion rates due to fragmentation or mineralization is scarce (Harmon *et al.*, 1986). Available data (e.g. Hodgkinson, 1975) suggest that hundred of years would be required for submerged snags to be lost to decay. Historically, ice jamming or 'gorging' probably influenced the distribution of LWD in the channel: 'When the ice "breaks" and begins to "run," it is liable to strand like a steamboat on the shallow bars . . . These ice "gorges" develop a power that nothing can withstand, and the amount of property destroyed by them in the history of the river has been very great . . . '(Chittenden, 1962).

In the modern, regulated Garrison Reach, winter water releases are carefully managed to avoid serious ice jamming (L. Murphy, US Army Corps of Engineers, Omaha, Nebraska, personal communication), and the influence of ice on LWD is probably minimal.

Intra- and interannual variation

The 35% decrease in total LWD abundance detected by the interannual recount was surprising because of the relatively low flows throughout the study (compared with other post-regulation flows). However, most of the change in abundance and relative abundance of LWD was for beached pieces (Figure 9) which are presumably most susceptible to being re-transported because they are not waterlogged, not anchored in the bank, usually are less massive than other LWD types, and they rarely have a rootwad—all the reasons they were transported in the first place (Braudrick and Grant, 2000). We hypothesize that low-lying, beached LWD was exported from shorelines (at least the ones we revisited) during the abrupt 140% increase in flow in late May 2002. Higher 2001–2002 winter flows (Figure 2b) had the potential to transport LWD, but these higher flows occur when the shoreline is largely icebound and probably do not much affect beached LWD. The fate of the 'missing' LWD is uncertain. However, we observed more LWD in transport and retained on shallow mid-channel bars than in previous summers; some missing wood may have floated out of the study reach.

LWD in floodplain rivers

Studies of LWD in large floodplain rivers are rare compared with studies in woodland streams and higher gradient rivers (Gurnell *et al.*, 2002, van der Nat *et al.*, 2003); studies that examine the effects of flow regulation and other management on LWD in large rivers are rarer still. Hesse (1996) observed that since the completion of the lowest mainstem dam on the Missouri River (Gavin's Point Dam, 1955), elimination of floods and human encroachment on the floodplain have prevented the appearance of new snags in the middle reaches of the Missouri River. Shields *et al.* (1995) noticed that in several large rivers (the Arkansas, Willamette, Missouri, and Mississippi rivers), LWD was more common along eroding banks than along riprap revetments. An unleveed Puget Sound river with a migrating channel and a mature riparian conifer forest had 8–21 times more LWD than nearby leveed rivers with little riparian forest (Collins *et al.*, 2002). In western Europe, intense management of the riparian zone, flow regulation, channelization, and channel cleaning have, for hundreds of years in some cases, constrained the influence of LWD on ecosystem function in large meandering rivers (Petts, 1989; Piégay and Gurnell, 1997). Many floodplain rivers in France have young riparian forests of small trees (Piégay, 1993; Piégay *et al.*, 1999). Even compared to the regulated upper Missouri, inputs of massive, snag-caliber LWD are apparently rare in western European rivers; most wood that falls into the river is deposited downriver on bars or on the floodplain, rather than retained as snags in the channel (Piégay and Gurnell, 1997).

The current density and distribution of LWD in the Garrison Reach reflect the highly regulated condition of the system, and are similar to the typology presented by Gurnell *et al.* (2002) for low-energy, meandering lowland or tropical rivers with relatively low LWD input rates and weak LWD transport capability. In these systems, LWD is mostly deposited as single pieces along the shoreline; snags in the channel are common. In the Garrison Reach, as in other low gradient rivers (Keller and Swanson, 1979; Wallace and Benke, 1984), LWD mostly originates from erosion of concave banks and many pieces remain anchored to the bank. In the Garrison Reach, the highest density of snags was along outside bend shorelines in meanders where LWD tends to accumulate, but also where riparian forest stands tend to be most mature (because new floodplain forest stands generally originate on point bars/inside bends).

Large debris jams, and bar, floodplain, and backwater wood deposits that are characteristic of higher-energy braided rivers and 'piedmont' floodplain rivers (Gurnell *et al.*, 2002) are virtually absent from the regulated (i.e.

low energy) Garrison Reach. Writing about 19th century navigation on the upper river, Hanson (2003) stated that '[steam] boats had to depend for their fuel chiefly upon the chance accumulation of driftwood, called "rack heaps," piled up by the current on the sandbars in seasons of high water'. Although now virtually absent from the upper river, large deposits still occur occasionally in the lower reaches of the Missouri River following high flows (R. Jacobson, US Geological Survey, Columbia Environmental Research, Center Columbia, Missouri). These reaches are hundreds of kilometres from the last mainstem reservoir and receive the flow from several large tributaries; they therefore have a much larger LWD source area and a more naturalized hydrograph than the upper river.

LWD and river ecosystem management

Altered LWD dynamics in the upper Missouri are a consequence of the disconnection of biotic and hydrologic interactions between the river channel and the floodplain. Flow regulation eliminates fluvial delivery from upriver (of the dam), and greatly reduces LWD inputs from the floodplain due to reduced channel migration, and leads, invariably, to changes in land use. In the Missouri River, elimination of flooding encouraged floodplain development and land clearing for agriculture (Schneiders, 1999), both of which decrease LWD inputs. Increases in public infrastructure and private property values on the floodplain encourage bank stabilization (NDGFD, 1998), which encourages still more encroachment on the riparian zone. The current scarcity of bare alluvial substrates that historically resulted from overbank flows and channel alluviation, hampers the success of cottonwood regeneration in the regulated Missouri River (Johnson *et al.*, 1976; Rood and Mahoney, 1990). Forest succession without the formation of new cottonwood stands will lead to a riparian forest dominated by smaller tree species (e.g. green ash; Johnson, 1992). Thus, the LWD of the future may have a different character from the historic pattern.

Local changes in riparian land use (e.g. development setbacks and conservation easements) could slow the rate of river–floodplain decoupling in the Garrison Reach. New bank stabilization projects, if unavoidable, could be designed, installed, and revegetated so that LWD inputs and fluvial retention functions are maintained. Unstabilized, forested shorelines, particularly those with large cottonwoods, should be preserved whenever possible (i.e. they should remain uncleared and unstabilized); they approximate the historic condition, and have a disproportionate influence on river ecosystem function. For example, delivery to the channel of snag-caliber LWD pieces with attached rootwads is far greater from these shorelines than elsewhere in the Garrison Reach. Unfortunately, forested shorelines with mature trees are highly desirable for residential development (NDGFD, 1998), and as we have shown (Table III), residential land use was associated with the lowest LWD density among common non-forest riparian land uses.

Local conservation can slow the loss of LWD-related ecosystem services provided by the river. However, restoration of Missouri River ecosystem function would require modification or removal of existing bank stabilization works, riparian reforestation (Johnson, 1992), and, most important, changes in how water is released from mainstem reservoirs (NRC, 2002a,b). Adaptive management of flow in the Missouri River (NRC, 2002b) could help restore the benefits of a naturalized LWD dynamic. For example, experimental flow regimes designed to create sandbar nesting habitat for the endangered interior least tern (*Sterna antillarum*) could increase bank erosion, which could temporarily increase the rate of delivery of LWD to the channel. Higher flows could also create the bare alluvial substrates and other conditions necessary for successful cottonwood seedling recruitment—the LWD of the future.

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