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RESEARCH ARTICLE

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The where and why of large wood occurrence in the Upper Mississippi and Illinois Rivers

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Abstract

Large wood (LW) plays important geomorphic and ecological roles in rivers and is widely used as a restoration tool. Changes to floodplain land use and historical removal have altered wood dynamics in fluvial systems globally. We know little about the distribution and dynamics of LW in great rivers (approximately >10^5 km^2) like the Upper Mississippi and Illinois Rivers despite its ecosystem importance and use in restoration projects. We assessed LW occurrence data collected by the fisheries component of the Upper Mississippi River Restoration Program's Long Term Resource Monitoring element. We analysed 25 years of data collected across six reaches of the Upper Mississippi and Illinois Rivers that represented contrasting physiographic settings, and across four aquatic area types comprising gradients of hydrology, connectivity and geomorphology. We tested hypotheses on drivers of LW occurrence using generalised linear mixed effects models, where occurrence was predicted by reach- and local-scale environmental variables. Occurrence varied significantly across reaches and aquatic area types. In general, wood occurred more frequently upriver and in side channels compared to other aquatic areas. Large wood was most strongly predicted systemically by reach identity but not local-scale variables, underscoring the importance of broad-scale physiographic gradients in defining hydrogeomorphic processes. Floodplain forests and shoreline revetment were consistently important predictors across reaches. Our findings show that the spatial variability of LW occurrence reflects the physical variability of the Upper Mississippi and Illinois Rivers. They also reveal the value in using geomorphic classifications as frameworks for understanding physical processes like LW dynamics because of their ability to contextualise site-scale conditions. The baseline understanding of LW abundance across different hydrogeomorphic gradients and scales presented here can give insight into how to more effectively target restoration efforts in great rivers and contribute to a broader understanding of LW dynamics where such studies have been lacking.

KEYWORDS
geomorphology, hydrology, large wood, Mississippi River, river, restoration, river ecology

1 | INTRODUCTION

Large wood (LW) is a critical element in river-floodplain ecosystems (Gurnell et al., 2002; Wohl et al., 2019). It is generally defined as downed, dead wood pieces greater than 10 centimeters (cm) in diameter and 1 meter (m) in length (Wohl et al., 2010), although other definitions exist (Ruiz-Villanueva et al., 2016), and is sometimes referred to as large woody debris or coarse woody debris. LW influences the ecology and geomorphology of rivers and their floodplains by interacting with flow and sediment regimes to shape habitat abundance and diversity, connectivity, and nutrient cycling across spatial and temporal scales (Wohl et al., 2019, 2023). It can also be an important dispersal vector for organisms and propagules, provide refugia, and act as a disturbance agent when mobile (Wohl et al., 2023). Because of the importance of LW in shaping river systems, understanding the distribution of LW and its recruitment, storage, and transport dynamics can inform river management practices aimed at achieving healthy, resilient ecosystems (Roni et al., 2015; Wohl et al., 2019).

Yet, how LW is distributed and the potential drivers of its spatial patterns remain poorly described for many river systems (Swanson et al., 2021; Wohl, 2017). This is particularly true for great rivers (Kramer & Wohl, 2017; Wohl, 2017). Great rivers are variously defined in the literature but generally are agreed to have very large drainage areas typically exceeding 10^5 square kilometers (km^2), high mean annual discharges greater than 3000 cubic meters per second (cms), seasonally inundated floodplains and main channels widths much wider than the typical length of LW (Angradi et al., 2009; Lewin and Ashworth, 2014; Kramer & Wohl, 2017). Great rivers are plural systems with multiple channels and interacting sub-components that tend to have high off-channel complexity and depth heterogeneity (Amoros & Bornette, 2002; Bouska et al., 2018; Lewin & Ashworth, 2014a; Wiens, 2002). The broad geographic scales and high physical complexity of great rivers make observing and monitoring LW a challenge, confounding efforts to identify important hydrogeomorphic processes (Krause et al., 2014; Ruiz-Villanueva et al., 2016). To further complicate matters, many great rivers have been heavily modified to facilitate commercial navigation, produce hydropower or control flooding. These factors have altered natural flow, sediment and large wood regimes, often with profound effects on ecological and geomorphic functions (Best, 2019). There is interest in restoring some of these functions by incorporating LW into restoration designs in some systems, such as in the Upper Mississippi (U.S. Army Corps of Engineers, 2012) and Missouri Rivers (National Research Council, 2002). Such efforts would benefit from a greater understanding of LW occurrence (presence/absence) patterns and the processes that govern them.

Recruitment, storage, and transport processes govern distributions of LW in space and time (Benda & Sias, 2003; Wohl et al., 2019). Figure 1 conceptualises how these processes may operate in a great river reach. In this model, LW at a given site within a reach may be recruited from upriver sources, tributaries, and lateral exchanges with the floodplain and local river banks through interactions among hydrology, geomorphology and characteristics of LW pieces themselves (Gurnell et al., 2002; Keller & Swanson, 1979; Kramer & Wohl, 2017; Montgomery et al., 2003; Piégay, 2003; Wohl, 2020). Recruitment of LW is predicated on the presence of forests, whose spatial positioning within the watershed and structural characteristics may affect the relative importance of upriver, tributary, floodplain and local sources of LW (refer to Wohl, 2017 for review). Recruited pieces of LW are either subsequently stored within the channel or floodplain, or transported out of the river reach, as a function of the river's flow regime; geomorphic characteristics like channel complexity and hydraulic roughness; the size, shape, and wood density of LW pieces; and interactions among all such factors (Guiney & Lininger, 2022; Kramer & Wohl, 2017; Lininger, Scamardo, & Guiney, 2021). In great rivers, storage is likely to occur along banks as water levels recede, downstream from tributary junctions, and within the channel (Kramer & Wohl, 2017; Wohl, 2020). The relative importance of various processes and their relevant scales are likely to vary throughout a great river because of physical complexity (e.g. Lewin & Ashworth, 2014a; Scown, Thoms, & De Jager, 2015), variable hydrologic connectivity (e.g. Mertes et al., 1995) and anthropogenic modifications (e.g. Skalak et al., 2013; Schenk et al., 2018). Recruitment, storage, and transport processes are expected to operate at and across different spatial and temporal scales as a reflection of the hierarchical organisation of river systems (Wohl, 2020; Wohl et al., 2019).

How and to what degree recruitment, storage, and transport processes operate at different scales to influence LW occurrence in great rivers is not well understood. However, several hypotheses emerge from observations of recruitment, transport and storage dynamics in other river systems as described above (Figure 1). For example, we expect reaches with greater contributing watershed area, more tributary junctions, and greater proportions of forested shorelines increase LW recruitment and should be associated with more frequent LW occurrence. We expect these conditions to produce more recruitment opportunities via higher discharges and more flow competence, abrupt changes in river geomorphology and transport capacity that result in depositional environments (Bull, 1977), and greater source

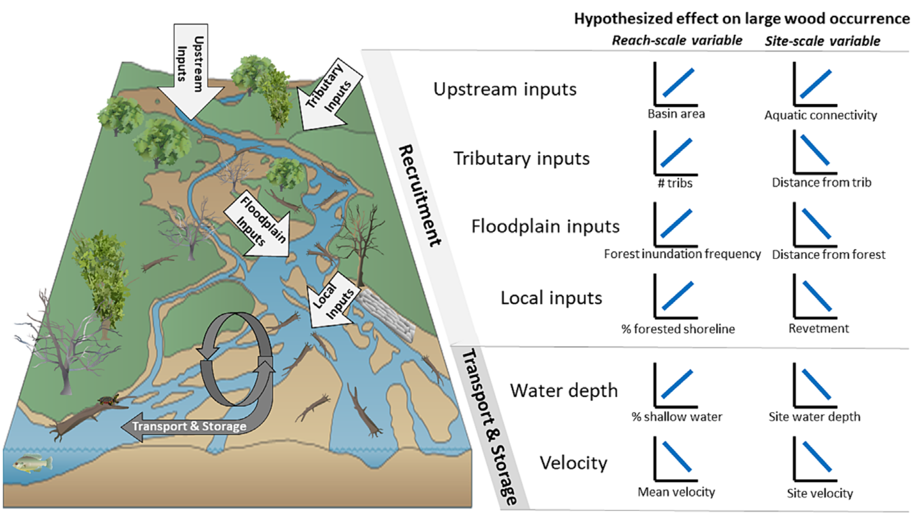

FIGURE 1 Conceptual model of large wood dynamics in great river systems like the Upper Mississippi River System as they relate to potential drivers of large wood recruitment (upstream, tributary, floodplain, and local inputs) and transport and storage (water depth, velocity). The hypothesized relationships of reach- and site-scale variables describing recruitment, transport, and storage with large wood occurrence at a given site are depicted graphically; variables are further described in Table 1. Graphics were sourced from the Integration and Application Network (ian.umces.edu/media-library). [Color figure can be viewed at wileyonlinelibrary.com]

area of wood pieces. In addition, reaches with more shallow aquatic areas and slower velocities are expected to increase retention through trapping and storing wood pieces, thereby increasing LW occurrence. At the site scale, however, different factors may control LW recruitment and retention. For example, LW occurrence may be positively related to hydrologic connections to other aquatic areas, which could increase opportunities for recruitment to a site via fluvial transport. We expect that occurrence should be negatively related to a site's distance from a tributary junction and forested shoreline because of limitations in transport and fewer opportunities for recruitment. Recruitment and retention at the local scale may also both be affected by the presence of revetments that can limit LW abundance through tree removal during installation, reductions in shoreline erosion that would otherwise undermine trees, increased hydraulic smoothness of the shoreline surface, and further shoreline development and deforestation (Angradi et al., 2004). Like the reach scale, LW occurrence is also hypothesised to occur more frequently at sites with shallow water depths and slower velocities, as these factors can enhance trapping and limit transport capacity. Testing hypotheses about the relationships between LW occurrence and potential drivers of LW recruitment, storage, and transport at multiple spatial scales may therefore help understand important processes governing LW distributions in great rivers.

The Upper Mississippi and Illinois Rivers, together referred to as the Upper Mississippi River System (UMRS), are great rivers with a combined drainage area of 1.8 million km^2. LW likely plays important ecological and geomorphic roles in the UMRS (Angradi et al., 2010; Ickes et al., 2014; Lehtinen, Mundahl, & Madejczyk, 1997), yet very limited information exists on its spatial distribution and the importance of various governing processes on LW occurrence. The UMRS is an intriguing system in which to evaluate LW dynamics given it spans extensive gradients in the factors hypothesised to govern spatial patterns and controls on LW occurrence. Specifically, it is characterised by a complex mosaic of hydrogeomorphic conditions (De Jager & Rohweder, 2012; Scown, Thoms, & De Jager, 2015; Van Appledorn, De Jager, & Rohweder, 2021) nested within broader longitudinal gradients of hydrology, geomorphology and land cover (Bouska et al., 2019; De Jager et al., 2018; Houser, 2022). The UMRS also comprises anthropogenic modifications that support commercial navigation including locks, low-head dams, river training structures like wing and closing dams, and shoreline armouring that likely affect LW occurrence. LW was removed from the main channel for navigation purposes prior to the installation of the current lock and dam system (Dobney, 1978; Fremling, 2004; Tweet, 1975). Previous work documenting current LW abundance in the main channel of the UMRS has demonstrated a strong relationship between LW density (number of pieces per length of shoreline) and shoreline forest cover (e.g. Angradi et al., 2004, 2010), indicating an important role of natural shorelines.

The UMRS also includes a diverse array of aquatic habitats that range from a fast-flowing main channel artificially maintained for navigation, to off-channel areas such as secondary and tertiary channels, backwater lakes, and tributary junctions (De Jager et al., 2018). To date, LW distributions have not been quantified in areas outside the main channel despite the importance of such areas to UMRS biota and ecosystem resilience (Bouska et al., 2019; De Jager et al., 2018). Additionally, potential drivers of spatial patterns of LW occurrence have not been assessed across the diversity of hydrogeomorphic conditions found across the broader longitudinal gradients of the UMRS. These gaps are important to address not only because of interest in the use of LW in restoration designs in the UMRS (U.S. Army Corps of Engineers, 2012) but also to fill a broader need to understand LW dynamics in great river systems (Kramer & Wohl, 2017).

The overall aim of this study was to provide fundamental information about the spatial patterns of LW and the recruitment, transport, and storage processes that may govern them in a complex, large river-floodplain ecosystem. First, we leveraged a long-term monitoring dataset comprising six reaches of the UMRS to describe the spatial patterns of LW occurrence across various levels of river organisation (system, reach and aquatic area type). Second, we tested hypotheses about potential drivers of LW occurrence (Figure 1) by modelling relationships between LW occurrence and potential reach- and site-scale variables that characterise LW recruitment, transport, and storage processes.

2 | METHODOLOGY AND METHODS

We analysed LW presence/absence data from six study reaches of the UMRS to describe distribution patterns within and among the reaches. The sampling design, described below, allowed inference about how LW occurrence may relate to broad-scale, longitudinal gradients of river conditions and finer-scale hydrogeomorphic conditions. We tested our hypotheses (Figure 1) on environmental controls of LW occurrence using logistic mixed effects models. These models related LW presence/absence to variables developed from empirical observations and geospatial analyses to characterise LW recruitment, transport, and storage drivers at reach and local scales.

2.1 | The UMRS and Upper Mississippi River Restoration (UMRR) Program

The UMRS comprises approximately 1853 river kilometers and adjacent floodplain lands of commercially navigable waters of the Upper Mississippi and Illinois Rivers (Water Resources Development Act of 1986, 33 U.S.C section 652). Water levels upstream from river kilometer 327 of the Upper Mississippi River, as well as the Illinois River, are regulated with a series of low-head dams to maintain sufficient water depths for navigation during low-flow conditions; the dams do not influence high flows. River stretches between sequential sets of locks and dams are referred to as 'navigation pools' and comprise lentic and lotic habitats. Downstream from river kilometer 327 (approximately St. Louis, Missouri), the Upper Mississippi River is free flowing (i.e., it lacks locks and dams) and has a flow regime influenced by the Missouri River. The Upper Mississippi River has a predominantly sand-bed main channel that distinctly coarsens downstream from Pool 20, below the confluence with the Des Moines River; the Illinois River's main channel comprises variable grain sizes (silt to gravel) with no regular coarsening (WEST Consultants, Inc., 2000).

The federally funded Upper Mississippi River Restoration (UMRR) Program was established by Congress in 1986 and reauthorised in 1999 under the Water Resources Development Act. The UMRR was tasked with restoring and enhancing habitat for the diverse biota of the UMRS including birds, fish, mussels and other wildlife that was altered by the construction of the locks and dams. The UMRR's Long Term Resource Monitoring (LTRM) element provides environmental data on the condition of the river and its biota that complement and inform restoration efforts. LTRM uses standardised protocols to collect water quality, aquatic vegetation and fisheries data in six study reaches of the UMRS (Figure 2; Ratcliff et al., 2014): Pools 4, 8, 13 and 26 are in the impounded stretch of the Upper Mississippi River, the La Grange Pool is in the Illinois River, and the Open River Reach is on an unimpounded stretch of the Upper Mississippi River south of St. Louis, near Jackson, Missouri. The reaches encompass the rivers and their floodplains.

2.2 | LTRM dataset

In this study, we used wood presence/absence data from 1993 to 2017 collected by LTRM fisheries component that samples fish communities and their relevant habitat characteristics, including LW, in all six study reaches. Although this monitoring component was not designed specifically to quantify the abundance and distribution of LW, it now has generated a unique 25 + year dataset of LW occurrence across major longitudinal and lateral extents of a great river. Fish and habitat characteristics were sampled using a spatially stratified random design across strata that approximate major aquatic habitats (Ratcliff et al., 2014) in every reach. We refer to these strata as 'aquatic area types.' The aquatic area types are based on enduring geomorphic features described by Wilcox (1993) and include the main channel, side channels, impounded areas and backwaters. These features are not unique to the UMRS and may be found in other great river systems (see Lewin & Ashworth, 2014a, 2014b for reviews). We used data from four aquatic area types in our analysis: main channel border – unstructured (hereafter, 'main channel border' [MCB]), side channel border (SCB), backwater contiguous shoreline (BWC), and impounded areas (IMP) (Figure S1). MCBs are located at the margins of the navigation channel and the nearest natural shoreline area, including islands and mainland; shorelines with and without revetment are sampled. SCBs are along secondary or tertiary channels

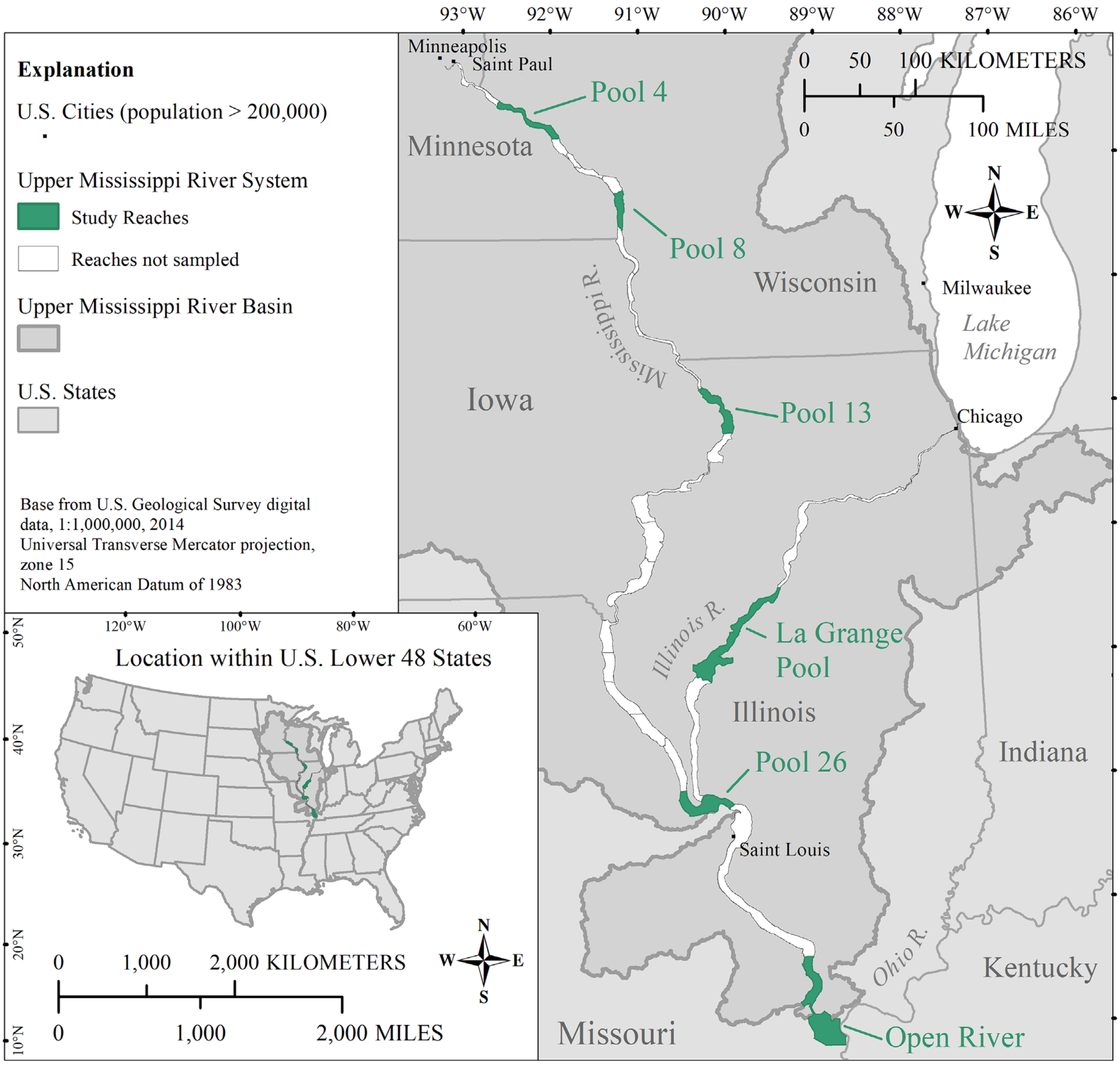

FIGURE 2 Location of long-term monitoring program study reaches within the Upper Mississippi River System. The reaches comprise the river channels and their floodplains. [Color figure can be viewed at wileyonlinelibrary.com]

(Wilcox, 1993) that have terrestrial margins and measurable velocities at normal water elevations. Backwater contiguous shorelines (BWC) are aquatic areas that have some hydrologic link to the main navigation channel but are separated from the main channel by a terrestrial area; sampling occurs in BWC within 50 m of the nearest shoreline. Impounded areas (IMP) are usually large, mostly open-water areas located immediately upriver from locks and dams; sampling occurs within 50 m of the nearest shoreline. Pools 8, 13 and 26 comprised all four aquatic area types. Pool 4 and La Grange lacked IMP, and Open River lacked IMP and BWC.

Field teams used a variety of gear types (e.g., nets and electrofishing) to monitor fish populations (Ratcliff et al., 2014). Here, we used data from only daytime electrofishing efforts because sampling occurred in a transect adjacent to shorelines with a standardised area (200 $\times$ 30 m; 6000 m^2) and across all four aquatic area types (MCB, SCB, BWC, and IMP). Daytime electrofishing transect locations (hereafter, 'sites') were selected annually with statistical randomisation to represent the four aquatic area types described above; sampling was not repeated at any site either within or across years. Field teams recorded a suite of relevant habitat characteristics while electrofishing at each site in water typically 0.5 to 3.0 m deep. Characteristics include average site water depth, velocity, substrate type, presence of shoreline revetment and LW presence/absence (Ratcliff et al., 2014). Land cover nearest to the site was not reported. Field teams made a visual assessment of the presence/absence of LW within the site, which could include exposed or visible pieces immediately below the water surface or partially submerged pieces along shorelines within the site. Although there were no explicit guidelines for what constitutes a minimum size for indicating LW presence, LW was counted as present if at least one piece was interpreted as providing relatively stable habitat for fish. As such, pieces were assumed to be semi-permanent features (i.e., not actively being transported by the river) and of sizes large enough to provide cover for fish. We presumed this definition met and likely exceeded the minimum criteria of conventional LW definitions (e.g. 0.1-m diameter and 1-m length; Wohl et al., 2010). The detection probability of LW in any given year did not appear to be a function of discharge for impounded study reaches but was greater at higher discharges in the Open River reach (Figure S2). Data are served online after a rigorous quality assurance and control process by field and programme staff (https://umesc.usgs.gov/data_library/fisheries/fish1_query.shtml). Our final dataset consisted of 10, 958 observations of LW presence/absence. These were distributed across all four aquatic area types, from 1993 to 2017, for the six study reaches (Figure 3; Table S1; Figures S3–S7) with some temporal variation in the sampling effort to accommodate field logistics and environmental conditions (Table S2).

2.3 | Environmental variables

We used a suite of environmental variables (Table 1 and Figure 1) to characterise the potential drivers of LW occurrence in the UMRS related to recruitment (upstream, tributary, floodplain and local inputs) and transport and storage (water depth and velocity) dynamics to test our hypotheses in Figure 1. The variables were developed for each sample site and summarised at two spatial scales, reach- and site-scale, as described below.

2.3.1 | Environmental variables related to recruitment processes

Upstream inputs were characterised at the reach scale using the basin area at the nearest U.S. Geological Survey (USGS) gage (Table S17) to test the hypothesis that greater discharges had the potential to deliver more LW to a given reach. Basin area is correlated with discharge; we used basin area instead of discharge because it is a single value rather than a statistical summary of hydrologic variability. Upstream inputs of LW were characterised at the site scale as the percentage of a given area that is bordered by another aquatic area, as defined by the LTRM Aquatic Areas Level III dataset (U.S. Army Corps of Engineers' Upper Mississippi River Restoration (UMRR) Program Long Term Resource Monitoring (LTRM) element, 2018). We refer to this site-scale measure of upstream inputs as 'aquatic connectivity'.

Tributary inputs were characterised at the reach scale as the total number of large tributaries entering the reach. We defined 'large tributaries' as those rivers sufficiently large enough to transport wood as a function of river discharge based on equations from Kramer and Wohl (2017). In our case, only tributaries that exceeded a mean monthly discharge threshold of 19.8 cms for at least 1 month of the year were included. We specified that a single month above that threshold discharge was required because of the episodic nature and cumulative influence of multi-year flow history on wood transport in river systems (Jochner et al., 2015; Kramer et al., 2017; Kramer & Wohl, 2017). Discharges for all tributaries were extracted from the National Hydrography Dataset Plus High Resolution which provides estimated monthly discharge summarised from 1971 to 2000 (U.S. Geological Survey, 2019). This resulted in two to five tributaries per reach (Table S3). Tributary inputs were characterised at the site scale by computing a distance from the *XY* coordinates of the sampling site to the nearest upstream tributary junction (Figure S1).

Median inundation frequency of all forested areas within each study reach was used to characterise floodplain inputs at the reach scale. We derived median inundation frequency from the UMRS Floodplain Inundation Attribute Rasters (Van Appledorn, De Jager, & Rohweder, 2018). At the site scale, floodplain inputs were characterised by computing a distance from the *XY* coordinates of the sampling location to the nearest upriver or lateral forest patch indicated in the UMRR Land Cover dataset (U.S. Army Corps of Engineers, 2017) (Figure S1).

Local inputs of LW were computed at the reach scale as the proportion of shorelines that were forested according to the UMRR Land Cover dataset (U.S. Army Corps of Engineers, 2017) as a measure of local sources of LW. Local inputs of LW were characterised at the site scale using the presence/absence information on shoreline revetment in the LTRM Fisheries Database.

2.3.2 | Environmental variables related to transport and storage processes

Water depth was quantified at the reach scale by computing the proportion of water depths <= 1 m during the 75% annual exceedance discharge for all aquatic areas in the reach based on bathymetric maps that were developed using data collected in 1989–1992, 1995–1998, and 2003–2009 (Rogala, 2019a, 2019b). Although geomorphic changes have occurred over the duration of the LW sampling period (e.g., Van

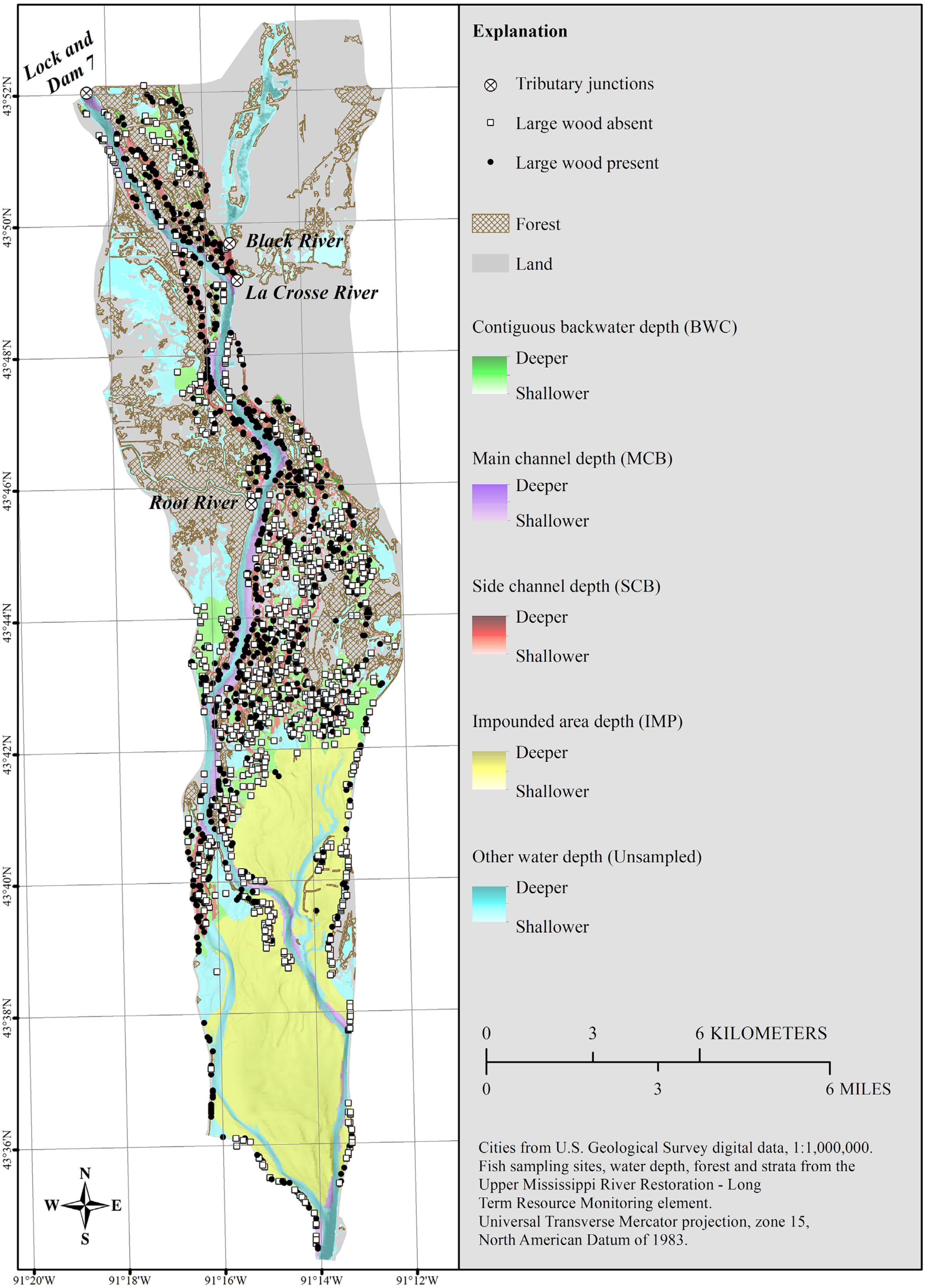

FIGURE 3 Large wood presence (black circles) and absence (white squares) at sampling sites in the Pool 8 study reach. All years of data are shown. Depth of four aquatic area types with associated sampling strata noted in parentheses (BWC = backwater contiguous shoreline, MCB = main channel border, SCB = side channel border, IMP = impounded area) and unsampled aquatic areas. Major tributary junctions and upriver lock and dam are labelled by name. Flow direction is from the top to bottom of the panel. Refer to Figures S2–S6 for similar maps of other study reaches. [Color figure can be viewed at wileyonlinelibrary.com]

Appledorn & Rogala, 2022), the magnitude of such changes is unlikely to affect persistent, among-reach patterns in the distribution of shallow areas that this variable intended to capture. We used *in situ* measurements of water depth recorded by the LTRM fish sampling teams as the site-level variable, which represents the average water depth observed across the electrofishing transect (Ratcliff et al., 2014).

TABLE 1 Reach- and site-scale environmental variables used to characterise potential drivers of large wood occurrence in the Upper Mississippi River System related to large wood recruitment (upstream, tributary, floodplain, and local inputs) and transport and storage (water depth and velocity).

	Driver	Scale	Environmental variable	Description and data sources
Recruitment	Upstream inputs	Reach	Basin area	Basin area in square kilometers based on nearest U.S. Geological Survey gage location (Table S17)
		Site	Aquatic connectivity	Percent of site's aquatic area perimeter that is adjacent to other aquatic areas. Source: U.S. Army Corps of Engineers' Upper Mississippi River Restoration (UMRR) Program Long Term Resource Monitoring (LTRM) element (2018)
	Tributary inputs	Reach	Number of tributaries	Total number of large tributaries entering each reach; large is defined as rivers with mean monthly flow > 19.8 cubic meters per second (cms) for at least 1 month per year (Kramer & Wohl, 2017)
		Site	Distance from tributary	Least-cost path distance from a site to the nearest large upriver tributary (Figure S1); large is defined as rivers with mean monthly flow > 19.8 cms for at least 1 month per year (Kramer & Wohl, 2017)
	Floodplain inputs	Reach	Forest inundation frequency	Median inundation frequency of forested floodplain areas in a reach. Sources: U.S. Army Corps of Engineers (2017) and Van Appledorn, De Jager, & Rohweder (2018)
		Site	Distance from forest	Least-cost path distance from a site to the nearest upriver or lateral forest patch (Figure S1). Source: U.S. Army Corps of Engineers (2017)
	Local inputs	Reach	% forested shoreline	Proportion of forested shoreline within a reach. Sources: U.S. Army Corps of Engineers' Upper Mississippi River Restoration (UMRR) Program Long Term Resource Monitoring (LTRM) element (2018), U.S. Army Corps of Engineers (2017)
		Site	Revetment	Presence of shoreline protection (revetment) at a site. Source: LTRM Fish Database (https://umesc.usgs.gov/data_library/fisheries/fish1_query.shtml)
Transport and storage	Water depth	Reach	% shallow water	Proportion of a reach's aquatic areas that are less than 1 m deep. Sources: U.S. Army Corps of Engineers' Upper Mississippi River Restoration (UMRR) Program Long Term Resource Monitoring (LTRM) element (2018), Rogala (2019a, 2019b)
		Site	Site water depth	Average water depth (m) at sampling site. Source: LTRM Fish Database (https://umesc.usgs.gov/data_library/fisheries/fish1_query.shtml)
	Velocity	Reach	Mean velocity	Average velocity across all sites within a reach. Values were corrected to account for discharge (Appendix B). Source: LTRM Fish Database (https://umesc.usgs.gov/data_library/fisheries/fish1_query.shtml)
		Site	Site velocity	Empirical measure of velocity reported at each site on the day of sampling. Values were corrected to account for discharge (Appendix B). Source: LTRM Fish Database (https://umesc.usgs.gov/data_library/fisheries/fish1_query.shtml)

Note: Hypotheses about each variable's effect on large wood occurrence are shown in Figure 1.

We based both reach- and site-scale characterisations of water velocity on empirical velocity measurements from the LTRM Fish Database. Because discharge exhibits substantial down-river increases across the study reaches, we scaled empirical velocity measurements by fitting generalised additive models that related velocity to discharge at the nearest USGS gaging location on the day of sampling and used residuals from those models as the site-scale predictive variable in the environmental models. Refer to Appendix B of the Supplementary Information for a full description of the development of the models. Model residuals were averaged across all sites and all years within each study reach to compute the reach-scale environmental variable.

All environmental variables were standardised using *Z*-scores prior to inclusion in subsequent models by subtracting the population mean from each value and dividing the difference by the population's standard deviation. This accounted for different scales and allowed us to compare effect sizes. All geospatial processes were completed using Esri ArcMap version 10.8.1.

2.4 | Statistical analyses

We described spatial distributions of LW by calculating the proportion of sites with LW detections for each year of sampling (i.e. annual occurrence frequency). We summarised the annual occurrence frequency across all years (1993–2017) for multiple levels of river organisation: universally across all six study reaches, within each study reach, universally across the four aquatic area types, and across the four aquatic area types within each study reach. We tested for significant differences in LW occurrence among study reaches and aquatic area types using Kruskal–Wallis multiple comparison tests and Dunn post-hoc pairwise comparisons with Bonferroni adjustments, assuming an alpha level of 0.05. We further tested whether LW occurrence varied within Pool 4 above and below Lake Pepin, a large riverine lake in the centre of Pool 4 (Figure S3) that has high sediment retention rates (Maurer et al., 1995; Wasley, 2010), which results in significant upstream-downstream differences in physical and ecological conditions (Burdis et al., 2020; Jankowski, 2022), using a Wilcoxon rank-sum test.

We fit generalised linear mixed effects models (GLMMs) using the *lme4* package in *R* (Bates et al., 2015) to test our hypotheses on environmental controls on LW occurrence. We fit two types of models: a system model that predicted LW presence/absence across all study reaches by accounting for both site- and reach-scale environmental variables and their interactions, and reach-specific models predicting LW presence/absence within individual reaches only using site-scale environmental predictors. This combination of models allowed us to understand how the importance of various environmental controls on LW may differ across spatial scales and levels of river organisation.

We used modelled LW occurrence as presence/absence using a binomial distribution for all GLMMs. We also included a random effect of 'year' on the intercept in the system and reach-specific models to account for annual variability. For the system model, we used observations from all six study reaches. We included site-scale variables as fixed effects to capture non-random local effects of the variables on LW occurrence. We used 'reach' as a random effect on the intercept to capture statistical variability that may occur among reaches in the model. After fitting the system model, we evaluated the potential drivers of the regional variation in the system using simple linear regressions. Here, we predicted reach-specific values of the random effect (i.e., each reach's deviation from full model intercept) using reach-level environmental variables. We evaluated reach-scale effects this way because we only had a single value of each reach-level environmental variable per reach and including them as regular, fixed effects in the model would have caused pseudo-replication. Therefore, we exploited the reach-level information from the random effect (i.e., each reach's deviation from the mean) which allowed us to evaluate specific hypotheses of controls on reach-scale variation while also accounting for site-level variation. For the reach-specific models, we fit a GLMM for each individual reach for observations within a given reach using only site-scale variables as predictors.

We evaluated the performance of all models using predictive accuracy and coefficient of determination (R^2) values. We assessed predictive accuracy by training a model on a subset of the data (70%) and then evaluating its performance on the remaining data. Training and testing datasets were selected randomly using the *rsample* package (Frick et al., 2022). We then assessed the model with a confusion matrix using the *caret* package (Kuhn, Wing, & Weston, 2023) and Receiver Operator Characteristics – Area Under the Curve (AUC) metric using the *ROCR* package (Sing et al., 2020). For the confusion matrix, we established a probability threshold of 0.5 for LW presence, whereby modelled probabilities of occurrence ≥ 0.5 were considered LW presences and probabilities < 0.5 were considered absences. The appropriateness of this threshold was evaluated by also assessing model performance with the AUC metric, which evaluates several thresholds for making the distinction between presence and absence in the modelled probabilities. AUC ranges from 0 to 1, with a value of 1 meaning perfect differentiation between classes, 0.5 meaning no ability to differentiate classes and 0 meaning that the model predicts the classes inversely (i.e., 1 predicted as a 0). Finally, we generated R^2 values for all models using the *MuMIn* package in *R* (Barton, 2022), which generates pseudo-R^2 values that account for the variance explained by the fixed effects only ($R^2_{marginal}$) and the entire model ($R^2_{conditional}$).

We performed all computations using *R* statistical software (R Core Team, 2023).

3 | RESULTS

3.1 | Spatial patterns of LW occurrence

LW was annually detected in 53.8% of all sampling sites on average. Yearly LW occurrence varied significantly across study reaches ($X^2 = 64.22$, $df = 5$, $p < 0.001$; Table S4; Figure 4a). The greatest average annual LW occurrence rates were detected in Pools 4 and 13 where LW was found in over 68% of sampling sites. There were no statistically significant differences in annual LW occurrence upstream or downstream from Lake Pepin in Pool 4 ($W = 371$, $p = 0.260$; Figure S8). Pools 8 and 26 had the next highest levels of annual LW occurrence with 50.4% in both. LW was least likely to be detected in the Open River (36.3% of sampling sites) compared to all other study reaches.

The annual occurrence frequency of LW varied significantly across aquatic area types ($X^2 = 63.93$, df $= 3$, $p < 0.001$; Table S5; Figure S9). LW was detected most frequently in MCB (55.0% of sampling sites) and SCB (68.5% of sites); it was least likely to be detected in IMP and BWC (48.4% of sites), which were statistically indistinct from each other (Table S5).

LW also varied significantly across aquatic area types within individual study reaches (Tables S6 and S7). LW was consistently most likely to be found in SCB than any other aquatic area type (Figure 4b). In Pools 4, 8 and 13, LW was also frequently observed in MCB (62.6–82.1% of sampling sites). However, in Pool 26, LW was more likely to be found in BWC than in MCB (52.6% versus 42.4%, respectively), and in the La Grange reach of the Illinois River, there was no statistical difference in the occurrence of LW in BWC (36.2%) versus MCB (36.4%) (Table S7). The Open River comprises only two of the four aquatic area types, but patterns of LW occurrence mirrored patterns in other study reaches: LW was significantly more common in SCB than MCB (47.2% versus 30.9% of sampling sites; $X^2 = 8.99$, $p < 0.001$).

3.2 | Associations between LW occurrence and environmental variables

The system model had a predictive accuracy of 63% (AUC = 0.72), with a slightly stronger accuracy in predicting LW presence (71%) than

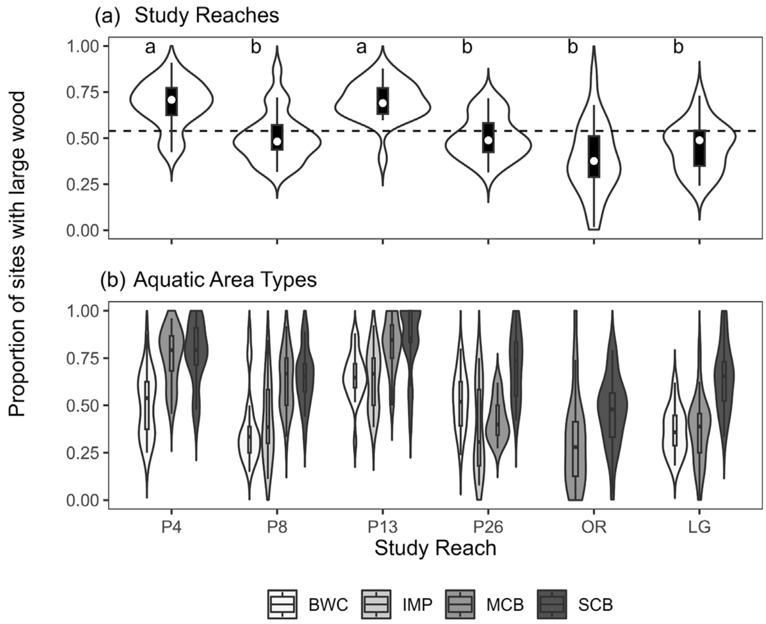

FIGURE 4 Violin plots of the annual proportion of sampling sites with large wood across study reaches (Panel A; P4 = Pool 4, P8 = Pool 8, P13 = Pool 13, P26 = Pool 26, OR = Open River, LG = La Grange) and by aquatic area type within study reaches (Panel B; MCB = main channel border, SCB = side channel border, IMP = impounded shoreline, BWC = contiguous backwaters). Dashed horizontal line in Panel A indicates mean value across all observations. Width of the violin plots reflects a kernel density estimate of the number of observations. Medians are shown as white points (panel A) or horizontal black lines (panel B); interquartile ranges (IQRs) shown as black (panel A) or open (panel B) rectangles with whiskers extending to 1.5 times the IQRs. Letters shared by study reaches in Panel A indicate statistically insignificant differences between distributions based on alpha = 0.05. Letters are not shown in Panel B; refer to Table S7 for tests of statistical significance across aquatic area types by study reach.

absence (61%). The R^2 value indicated that more of the variation in the data was explained by the reach-scale versus the site-scale effects (conditional R^2 [full model] = 0.22 versus marginal R^2 [fixed effects only] = 0.06; Table S8). Together, this indicates that reach identity explained more variation in LW occurrence across the study area than site-level environmental variables, and that our ability to explain LW occurrence across all reaches with only local environmental variables was limited.

In the system model, all site-level predictors of LW occurrence were statistically significant except for water depth (Figure 5a). However, site-level predictors explained very little variation overall ($R^2 = 0.05$; Table S8), suggesting that significance may be driven by large sample size. The direction of the relationships between most significant predictors and LW occurrence matched our hypotheses in Figure 1 despite their low explanatory power. For example, distance from tributary, distance from forest, revetments and site velocity were all negatively associated with LW occurrence in the system model, agreeing with expectations.

We regressed reach-specific random effect sizes against each reach-level predictor individually to evaluate some of the potential drivers of the regional variation in the system model (Figure S10 and Table S9). We did not find a strong statistical association with any of the reach-scale variables that we included, likely due in part to the small sample size ($n = 6$ reaches). This was the case even for basin area, which had the potential to over-predict the discharge effect in more downriver reaches relative to upriver reaches because of the nonlinear relationship between discharge and contributing area (Knighton, 1998). However, the direction of the associations agreed with our hypotheses: there were positive associations with forest inundation frequency (floodplain inputs) and percent shallow water (storage and transport) and a negative effect of mean velocity (storage and transport).

We observed both similarities and differences among reaches when we evaluated the effects of environmental variables on LW occurrence using reach-specific models. Inputs from floodplain forests and local sources were most consistently significant across all reach models (Figure 5b; Tables S10–S15). LW was negatively related to distance from forest in all reach models except Pool 13, and negatively related to presence of revetment in all reaches except Pool 8. In fact, the modelled effect of revetment on LW occurrence was the strongest of all environmental variables in every reach where it was statistically significant except for Open River where site-level upstream inputs had the strongest effect (Table S14). There was some variations among reaches in the other drivers that were important, however, indicating that factors controlling wood distribution are not consistent across a great river. Aquatic connectivity (upstream inputs) was a significant driver of LW only in the lower three reaches (Pool 26, Open River, and La Grange) where it consistently had a negative association with LW occurrence. Greater aquatic connectivity was associated with lower frequencies of LW in those reaches, indicating that higher connectivity may have been more related to transport out than delivery to the lower portion of the UMRS. Distance from tributaries (tributary inputs) were only significant in Pool 4, Pool 8, and La Grange and were always negatively related to LW occurrence. This relationship implied that LW was more likely to be observed near tributary junctions than farther away. Finally, transport and storage related variables (site water depth and site velocity) were only significant in Pool 26. Models for individual reaches had R^2 values ranging from 0.135 in Pool 8 to 0.371 in the Open River (Tables S10–S15) and were consistently better at predicting the presence rather than absence of LW (Table S16).

4 | DISCUSSION

LW occurrence varied across multiple levels of river organisation in the UMRS in ways that reflected the hydrogeomorphic complexity of the ecosystem. Large wood was more frequently encountered in two of the three upriver reaches compared to the two lower reaches in the Mississippi River and the La Grange Reach on the Illinois River. There were also differences in occurrence across aquatic area types, where LW was most frequently observed in side channels. This

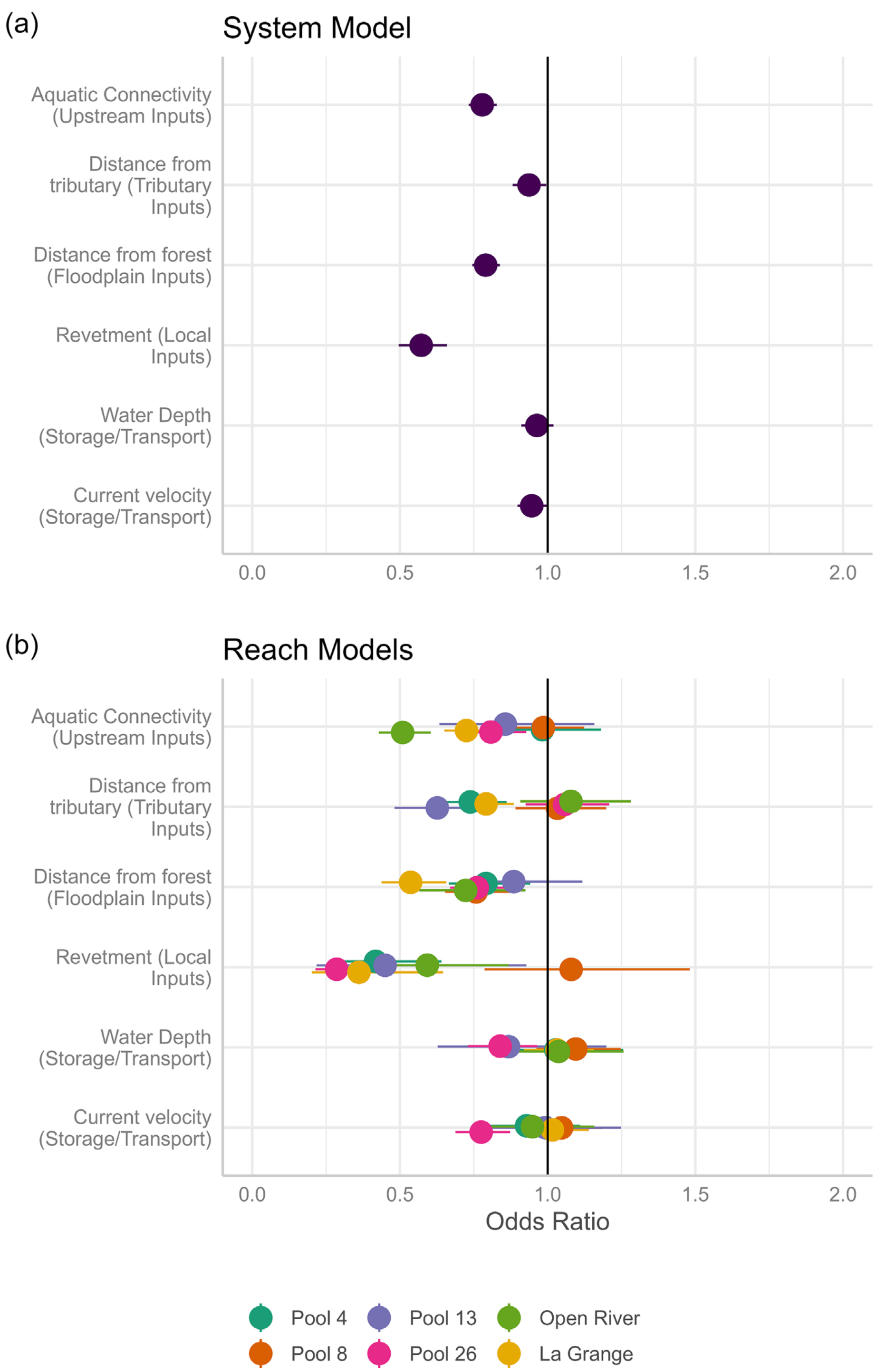

FIGURE 5 Effects of predictors of large wood (LW) occurrence reported as odds ratios for system-wide logistic mixed effects model (Panel A) and separate models for individual study reaches (Panel B). All predictors shown are site-level variables. Odds ratio values greater than 1.0 indicate a positive effect of the driver on LW occurrence; values less than 1.0 indicate a negative effect of the driver on LW occurrence. Error bars represent the 95% confidence interval (CI) of the odds ratio estimate. Estimates in which error bars cross 1.0 are considered non-significant. Category of potential drivers is listed behind measured environmental variable names in parentheses. [Color figure can be viewed at wileyonlinelibrary.com]

pattern was mirrored within individual study reaches: annual occurrence was highest in SCB for all six study reaches, although it was statistically similar to the MCB for the three upriver reaches. Statistical model results indicated that controls on LW occurrences were scale dependent. Environmental variables measured at the site-scale were poor predictors of LW occurrence across the system on their own but were relevant within the context of the river reaches. There was evidence that important processes governing LW occurrence varied by reach. By documenting LW patterns across multiple habitats in the UMRS and testing a conceptual model of their governing processes, our study addresses important knowledge gaps in understanding LW dynamics and provides a foundation for future, more detailed investigations about LW dynamics in great rivers.

4.1 | Spatial patterns of LW occurrence in the UMRS

LW was detected in just over half of the sampling sites across our study area annually, which is likely much less than what may have been present historically (Wohl, 2014). The UMRS has experienced changes that can affect the sourcing, transport and storage of LW since European settlement: floodplain forest cover has declined (De Jager & Rohweder, 2022; Theiling et al., 2000), levees have reduced river-floodplain connectivity (Bouska et al., 2019) and shoreline revetments are a common management tool (U.S. Army Corps of Engineers, 2012). Active removal of snags, log jams and LW pieces from the UMRS was also practiced historically to improve navigation

(Dobney, 1978; Fremling, 2004; Tweet, 1975); some removal efforts still occur but on a very limited scale, such as removing wood pieces from dam roller gates. However, there is a renewed interest in incorporating LW into engineering designs in the UMRS because of its ecological value (U.S. Army Corps of Engineers, 2012). Our analysis can serve as a baseline for comparing the current prevalence of LW in the UMRS to future conditions, whether LW is naturally sourced or part of restoration projects.

The distribution of LW varied across study reaches in ways that reflected broad-scale gradients of hydrology and land cover. Large wood occurred more frequently in upper reaches, especially Pools 4 and 13, than in lower reaches of the UMRS (Pool 26, Open River and La Grange reach). The upper reaches may have had more opportunities for wood recruitment due to frequent and longer lasting flood events (Van Appledorn, De Jager, & Rohweder, 2021) and greater proportions of floodplain as forest (De Jager et al., 2018), as well as more potentially greater retention in lentic shallow areas and lentic areas with wooded shoreline (De Jager et al., 2018). Low occurrence of LW in the Open River may be because of lack of river complexity that reduces retention and limited forested borders which limits inputs (De Jager et al., 2018). Low occurrence also may be related to the ability to detect LW in low-flow years, as LW detection probability appeared to be positively related to discharge (Figure S2). The Open River also experiences some of the greatest stage fluctuations (Bouska et al., 2019; De Jager et al., 2018) and inundation depths (Van Appledorn, De Jager, & Rohweder, 2021) of any study reaches. These dynamics could result in LW deposits at locations outside the wetted channel (Kramer & Wohl, 2017) where our sampling methods would not detect it, particularly at low flows. These areas may include the floodplain, bars and other shoreline areas exposed during low-flow conditions that are inaccessible to electrofishing field crews.

Across aquatic area types, LW occurrence was highest in SCBs and MCBs compared to other aquatic area types, and consistently highest in SCBs across study reaches. This finding is consistent with Gutreuter, Vallazza, and Knights (2006) who also observed that LW was encountered much more in secondary channels than the navigation channel during fish surveys conducted in the UMRS from 2001 to 2003. Other studies comparing distributions of LW across habitat types in large rivers have likewise found more wood associated with side channels or anchored to main channel banks (Triska, 1984); increased wood storage at channel margins like on concave banks, island edges, and borders of secondary channels (Gurnell et al., 2002); and wood deposited in geomorphically complex areas (Piégay, 2003; Schenk et al., 2018). In the UMRS, SCBs may represent a suite of conditions more favourable to LW storage than other aquatic habitats because of their intermediate flow velocities, potential for meandering and bank erosion, greater ratios of wood size to channel width compared to other aquatic area types, and shallower depths compared to MCBs (Bilby & Ward, 1989; Gurnell et al., 2002; Piégay, 2003). In addition, river-training structures like wing dams or closing dams that concentrate main-channel flow by narrowing the channel and limiting flows to off-channel areas, respectively, are more common in SCB and MCB than in BWC or IMP areas. It is possible that such structures could be an important influence on LW retention (Elliot & Jacobson, 2006), although our study did not test this idea.

4.2 | Processes governing LW occurrence in the UMRS

Overall, results from the predictive modelling generally agreed with our hypotheses about wood recruitment, transport, and storage in the UMRS rivers (Figure 1). They are also generally consistent with principles of LW dynamics and their governing processes in other river systems (Gurnell et al., 2002; Wohl et al., 2019). We found that some environmental variables were consistently important across all reaches and that the importance of others could vary from reach to reach. These findings highlight the importance of cross-scale comparisons in great rivers to elucidate constraints on LW dynamics. Compared to smaller, single-threaded rivers, large river-floodplain ecosystems are plural systems with multiple channels and interacting sub-components that tend to have high off-channel complexity and depth heterogeneity (Amoros & Bornette, 2002; Lewin & Ashworth, 2014a; Wiens, 2002). The differences in controls on wood supply we observed at different scales of analysis imply that management strategies for LW retention and restoration may differ across large and complex river systems such as the UMRS.

We found that reach identity explained more variation in LW occurrence than site-level environmental variables in our system model. This result was somewhat unexpected given the degree of fine-scale heterogeneity within the river system that could influence LW occurrence at a given site (De Jager & Rohweder, 2022). However, our result is consistent with conceptual models of rivers' hierarchical organisations (Parsons & Thoms, 2007; Petts & Amoros, 1996; Thoms, 2003) and observations of physical complexities of great river systems (Lewin & Ashworth, 2014a, 2014b). The reaches analysed in our study represent different geomorphic settings and thus experience different physiographic constraints on hydrologic and sediment regimes (WEST Consultants, Inc., 2000), and presumably, their interactions with LW. Additional studies examining LW recruitment, transport and storage processes in a more detailed and dynamic way than is possible with the dataset we analysed may be helpful in further understanding the relationship between reach-scale and site-scale drivers of LW occurrence. Nonetheless, our analysis revealed the value in using existing geomorphic classifications of the UMRS as frameworks for understanding physical processes like LW dynamics because of their ability to contextualise site-level conditions.

4.2.1 | Local and floodplain inputs were consistently important drivers of LW occurrence across reaches

The most consistent and important drivers across the system were local inputs (as characterised by revetment presence) and floodplain inputs (as characterised by distance from forest). The direction of these relationships matched our expectations (Figure 1). The presence of revetments had a negative effect on the probability of observing LW both at the system scale and in all individual reaches except one. This result agrees with previous work in the UMRS showing a lower LW abundance associated with shoreline revetments (Angradi et al., 2010). Installing revetments is a common practice in the UMRS to reduce lateral erosion (Theiling, Janvrin, & Hendrickson, 2015), but our results indicate that natural shorelines are important in maintaining aspects of a natural wood regime even in working rivers like the UMRS.

Floodplain inputs, measured as distance from upstream forest, was the second most important driver of LW occurrence at the system scale and was a significant driver in all reaches except one. The consistently important role of distance from floodplain forests agrees with previous work in the UMRS (Angradi et al., 2010) and in other large rivers (Schenk et al., 2018), and indicates that floodplain forests have been a critical source of wood to the river across the system. Contributions from floodplain forests reflect the importance of source areas of LW as well as the river's flow regime (an important driver of LW dynamics in great river systems; Gurnell et al., 2002). Floodplain inundation can reduce wood load in some river systems through out-of-channel storage (MacVicar & Piégay, 2012; Pettit et al., 2005; Piégay & Gurnell, 1997; Wohl, 2013), which is believed to be a function of river corridor morphology and floodplain forest structure (Guiney & Lininger, 2022; Lininger, Scamardo, & Guiney, 2021). Floodplain inundation has also been shown to recruit a substantial proportion of in-channel wood in other large rivers like the Missouri River (Schenk et al., 2018) as well as smaller systems (Comiti, Lucía, & Rickenmann, 2016). The positive effect of floodplain inputs on LW occurrence in our results indicates that, like the Missouri River, forested floodplains likely serve as a net source of wood pieces in the UMRS during high-flow events. A more detailed examination of LW source-sink dynamics in floodplains and their relationship to aquatic areas is warranted. Nonetheless, our results underscore the importance of maintaining forested floodplains for sustaining wood budgets in great rivers.

4.2.2 | The importance of some environmental variables differed by reach

Some environmental variables—aquatic connectivity, distance from tributaries, water depth and velocity—were more important in certain parts of the study area than others. Which variables were important in any given reach reflected broader physiographic constraints and land cover distributions that vary throughout the UMRS. For example, aquatic connectivity was only significant in the lower study reaches of the Mississippi River (Pool 26, Open River) and the Illinois River (La Grange) and had an opposite effect on LW occurrence than we expected. These reaches are larger and faster flowing than other study reaches, which can mean that their off-channel areas can experience greater velocities compared to off-channel areas in upper reaches with the same index of aquatic connectivity. The greater aquatic connectivity found in the lower reaches likely facilitated more LW transport, with more connected areas being more subject to faster flows that mobilise LW.

Another predictor of LW occurrence, tributary inputs, was significant only in Pools 4 and 13 and the La Grange reach of the Illinois River. This variation is likely related to the land use of the contributing tributaries and their riparian corridors, their storage and transport capacity, as well as the hydrogeomorphology of the main-stem river at the tributary junctions. Tributary junctions are often places of active aggradation and delta formation in the UMRS (Van Appledorn & Rogala, 2022). Thus, we expected them to be areas of greater LW occurrence, all else being equal, but this does not appear to be the case for some reaches. Our measure of tributary inputs may be a relatively coarse indicator of the potential for wood delivery across basins with diverse land cover, and understanding the mechanisms behind our findings needs further study.

Finally, we found that site-level storage and transport variables were not significant predictors of LW occurrence in any reach except for one (Pool 26). The generally low importance of these variables is not in conflict with our findings of greater LW occurrence in reaches with more shallow areas and lower velocities and in aquatic area types characterised by lower water depths and velocities. This is because the empirical site water depth or velocity measurements do not capture the full range of variability across the reach or aquatic area scales. Electrofishing surveys are restricted to areas of 3-m deep or shallower (Ratcliff et al., 2014); thus, the deepest portions of an aquatic area or reach are not captured by site water depth measures. Similarly, areas of greatest velocity like the main channel centerline are not sampled. It is possible, therefore, to observe similar ranges of site velocity and water depths across all aquatic area types and reaches. Our collective findings suggest that further investigation into hierarchical processes that consider reach-, aquatic area type-, and site-scale effects and their interactions may improve predictive models of LW occurrence.

The results of our analysis were generally consistent with our conceptual model of LW occurrence in great river systems like the UMRS. Our findings added nuance to the model, however, by showing how the relative importance of the hypothesised drivers varied across the system. Our results demonstrated that local and floodplain inputs of LW played consistent and strong roles in occurrence patterns throughout the river system, which aligns with our general understanding of LW dynamics in rivers. The relative importance of other variables, such as delivery from tributaries and aquatic connectivity, differed across reaches, however. These patterns highlighted the importance of investigating the consistency of controls at multiple scales within great rivers to clarify how processes interact in these highly complex systems. Additional process-based studies on LW occurrence (and dynamics over time) in great rivers would be useful in improving our conceptualisation of LW regimes (sensu Wohl et al., 2019) in these systems. Given that many of the world's largest rivers and their basins are highly modified (Best, 2019), it is important to understand the relative importance of natural versus anthropogenic controls of LW occurrence. Toward this end, conceptual models of such systems could incorporate additional factors such as river training structures and other infrastructure, restoration efforts and wood introductions, the role of the wider river network in wood supply and transport, and historical wood removal.

4.3 | Ecological and restoration implications

Habitat restoration planning in the UMRS and other great rivers would benefit from understanding where LW is abundant and where it is not, and how LW occurrence relates to hydrogeomorphic constraints, floodplain forest cover, and shoreline protection efforts. Large wood is incorporated into restoration designs as part of the UMRR Program to protect shorelines, enhance habitat and increase elevation diversity (U.S. Army Corps of Engineers, 2012). Current practices could be improved by considering the broader systemic distribution of LW when planning projects. Our study provides context for whether and how restoration designs could consider including LW in accordance with natural river processes. For example, it may not be necessary to place LW where it is already relatively abundant or where the likelihood of LW retention and storage is low (U.S. Army Corps of Engineers, 2012). Our study may not be useful for assessing LW abundance at specific potential restoration sites, however, given the coarseness of our data compared to information gained during actual site visits. Our study did not examine temporal patterns of LW occurrence which also may be useful for prioritising study reaches or aquatic areas for LW enhancements.

Our results underscore the importance of maintaining forested floodplains for sustaining LW in great rivers. Floodplain forest restoration and management has been an important priority for the UMRR Program because of the numerous threats to forest health and coverage (Guyon et al., 2012) and declines in forest coverage over time (De Jager & Rohweder, 2022; De Jager, Rohweder, & Nelson, 2013). Several current threats to the integrity and abundance of UMRS forests could affect their ability to supply wood. Increased river flow (Van Appledorn, 2022), herbaceous invasive species (Guyon & Cosgriff, 2022; Oines, 2020; Romano, 2010) and insect pests like emerald ash borer (*Agrilus planipennis*) (De Jager & Rohweder, 2022) can contribute to tree mortality and poor forest regeneration. Simulation models of floodplain forest success in the UMRS have projected that forest loss may continue throughout the ecosystem, although floodplain forests are expected to remain the dominant land-cover type in the UMRS floodplain (De Jager et al., 2019). Floodplain forest loss could have consequences for LW recruitment, with cascading effects on aquatic food webs and habitat. Restoration and management efforts to maintain forest cover as critical habitat for terrestrial species may also contribute to aquatic ecosystem health.

Long-term datasets are important to restoring and managing river ecosystems (Houser, 2022), yet there are very few documenting LW patterns and dynamics (but see Reid & Hassan, 2020; Lininger & Hilton, 2022). They also can be useful for addressing research questions that were not anticipated during sampling protocol development. We documented LW occurrence in the UMRS using a relatively coarse dataset collected for the purpose of long-term fish population monitoring, rather than for understanding LW dynamics, demonstrating the utility of datasets that comprise a range of biological and physical variables. The presence/absence data we used did not convey characteristics of wood pieces (e.g., length, diameter) that can be useful for understanding LW dynamics (Wohl et al., 2010) and are not suitable for quantifying LW abundance or loads, however. The data also likely underestimated total wood presence by not accounting for fully submerged pieces. Nevertheless, the LTRM fish monitoring data had characteristics that made them suitable for our study goals: the sampling design was developed to understand fundamental spatio-temporal patterns across major hydrogeomorphic features of the UMRS; protocols were rigorously standardised across dispersed field stations and over time; there was little staff turn-over for the duration of the study period (1993–2017); and all data were well-documented and publicly available. Other long-term monitoring programmes that maintain standardised measurements through time create detailed metadata including the archiving of protocol and field notes, and publicly archive data would also have the potential to address outstanding ecological questions (Lindenmayer et al., 2012; Reichman, Jones, & Schildhauer, 2011), including those beyond the original focus of the data collection effort. Accurately quantifying LW abundance in large, deep rivers can be challenging and time consuming. Therefore, developing and deploying more efficient methods for quantitative monitoring of wood abundance in the UMRS and other great rivers—such as sonar, drone or satellite-based methods—could have great potential to enhance our understanding of wood dynamics across the full river–floodplain ecosystem.

5 | CONCLUSIONS

In this paper, we described spatial patterns of LW occurrence in a great river system using a long-term monitoring dataset. Although developed for other purposes, the dataset was still able to be leveraged to elucidate information about spatial distribution and important drivers of LW occurrence in a great river system, for which LW data are sparse. The varied distributions of LW among river reaches and across aquatic area types reflected the physical complexity of the UMRS, which is important for maintaining the river's diverse biota. We tested hypotheses related to drivers of LW occurrence in great river systems to understand the relative importance of recruitment, storage and transport processes. Our work contributes to a broader understanding of LW dynamics, particularly in great river systems where such studies have been lacking. We also contribute novel descriptions of LW abundance across the UMRS. This information can inform the integration of LW into habitat restoration projects.

AUTHOR CONTRIBUTIONS

Molly Van Appledorn: conceptualisation, methodology, investigation, supervision, writing initial draft, reviewing and editing; **KathiJo Jankowski**: conceptualisation, methodology, investigation, supervision, reviewing and editing; **Kaija Gahm**: methodology, investigation, reviewing and editing; **Serenity Budd**: methodology, investigation, reviewing and editing; **Douglas Baumann**: funding acquisition, methodology, supervision, reviewing and editing; **Barbara Bennie**, funding acquisition, methodology, supervision, reviewing and editing; **Richard Erickson**: methodology, supervision, reviewing and editing; **Roger Haro:** Methodology, supervision, reviewing and editing; **Jason Rohweder**: investigation, reviewing and editing.

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DATA AVAILABILITY STATEMENT

All data used in this study are publicly available. Long Term Resource Monitoring (LTRM) fish data may be found at https://umesc.usgs.gov/

data_library/fisheries/fish1_query.shtml. LTRM Level 3 Aquatic Areas dataset may be found at https://doi.org/10.5066/F7VD6WH8. The 2010 LTRM Land Cover dataset may be found at https://doi.org/10.5066/F7BK1BKQ. Upper Mississippi River System Floodplain Inundation Attribute Rasters may be found at https://doi.org/10.5066/F7VD6XRT. Discharge data were accessed from the U.S. Geological Survey National Water Information System at https://nwis.waterdata.usgs.gov/.

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REFERENCES

Amoros, C. & Bornette, G. (2002) Connectivity and biocomplexity in waterbodies of riverine floodplains. *Freshwater Biology*, 47(4), 761–776. Available from: https://doi.org/10.1046/j.1365-2427.2002.00905.x

Angradi, T.R., Schweiger, E.W., Bolgrien, D.W., Ismert, P. & Selle, T. (2004) Bank stabilization, riparian land use and the distribution of large woody debris in a regulated reach of the upper Missouri River, North Dakota, USA. *River Research and Applications*, 20(7), 829–846. Available from: https://doi.org/10.1002/rra.797

Angradi, T.R., Taylor, D.L., Jicha, T.M., Bolgrien, D.W., Pearson, M.S. & Hill, B.H. (2010) Littoral and shoreline wood in mid-continent great rivers (USA). *River Research and Applications*, 26(3), 261–278. Available from: https://doi.org/10.1002/rra.1257

Barton, K. (2022) MuMIn: Multi-Model Inference. R package [online]. Available from: https://CRAN.R-project.org/package=MuMIn

Bates, D., Mächler, M., Bolker, B. & Walker, S. (2015) Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, 67(1), 1–48. Available from: https://doi.org/10.18637/jss.v067.i01

Benda, L.E. & Sias, J.C. (2003) A quantitative framework for evaluating the mass balance of in-stream organic debris. *Forest Ecology and Management*, 172(1), 1–16. Available from: https://doi.org/10.1016/S0378-1127(01)00576-X

Best, J. (2019) Anthropogenic stresses on the world's big rivers. *Nature Geoscience*, 12(1), 7–21. Available from: https://doi.org/10.1038/s41561-018-0262-x

Bilby, R.E. & Ward, J.W. (1989) Changes in characteristics and function of woody debris with increasing size of streams in western Washington. *Transactions of the American Fisheries Society*, 118(4), 368–378. Available from: https://doi.org/10.1577/1548-8659(1989)118<0368:CICAFO>2.3.CO;2

Bouska, K.L., Houser, J.N., De Jager, N.R. & Hendrickson, J. (2018) Developing a shared understanding of the upper Mississippi River: the foundation of an ecological resilience assessment. *Ecology and Society*, 23(2), 6. Available from: https://doi.org/10.5751/ES-10014-230206

Bouska, K.L., Houser, J.N., De Jager, N.R., Van Appledorn, M. & Rogala, J.T. (2019) Applying concepts of general resilience to large river ecosystems: a case study from the Upper Mississippi and Illinois rivers. *Ecological Indicators*, 101, 1094–1110. Available from: https://doi.org/10.1016/j.ecolind.2019.02.002

Bull, W.B. (1977) The alluvial-fan environment. *Progress in Physical Geography*, 1(2), 222–270. Available from: https://doi.org/10.1177/030913337700100202

Burdis, R.M., DeLain, S.A., Lund, E.M., Moore, M.J.C. & Popp, W.A. (2020) Decadal trends and ecological shifts in backwater lakes of a large floodplain river: Upper Mississippi River. *Aquatic Sciences*, 82(2), 27. Available from: https://doi.org/10.1007/s00027-020-0703-7

Comiti, F., Lucía, A. & Rickenmann, D. (2016) Large wood recruitment and transport during large floods: a review. *Geomorphology*, 269, 23–39. Available from: https://doi.org/10.1016/j.geomorph.2016.06.016

De Jager, N.R., Rogala, J.T., Rohweder, J.J., Van Appledorn, M., Bouska, K.L., Houser, J.N. & Jankowski, K. (2018) *Indicators of ecosystem structure and function for the Upper Mississippi River system*. U.S. Geological Survey Open-File Report 2018-1143. Reston, VA: U.S. Department of the Interior, U.S. Geological Survey. Available from: https://doi.org/10.3133/ofr20181143

De Jager, N.R. & Rohweder, J.J. (2012) Spatial patterns of aquatic habitat richness in the Upper Mississippi River floodplain, USA. *Ecological Indicators*, 13(1), 275–283. Available from: https://doi.org/10.1016/j.ecolind.2011.06.013

De Jager, N.R. & Rohweder, J.J. (2022) Land Cover. In, *Ecological status and trends of the Upper Mississippi and Illinois Rivers*. U.S. Geological Survey; 72–81. U.S. Geological Survey Open-File Report 2022–1039. Reston, VA: U.S. Department of the Interior, U.S. Geological Survey. Available from: https://doi.org/10.3133/ofr20221039

De Jager, N.R., Rohweder, J.J. & Nelson, J.C. (2013) Past and predicted future changes in the land cover of the Upper Mississippi River floodplain, USA. *River Research and Applications*, 29(5), 608–618. Available from: https://doi.org/10.1002/rra.1615

De Jager, N.R., Van Appledorn, M., Fox, T.J., Rohweder, J.J., Guyon, L.J., Meier, A.R., et al. (2019) Spatially explicit modelling of floodplain forest succession: interactions among flood inundation, forest successional processes, and other disturbances in the Upper Mississippi River floodplain, USA. *Ecological Modelling*, 405, 15–32. Available from: https://doi.org/10.1016/j.ecolmodel.2019.05.002

Dobney, F.J. (1978) *River engineers on the Middle Mississippi: a history of the St. Louis district*. Washington, D.C.: U.S. Army Corps of Engineers. U.S. Government Printing Office.

Elliot, C.M. & Jacobson, R.B. (2006) *Geomorphic classification and assessment of channel dynamics in the Missouri National Recreational River, South Dakota and Nebraska*. U.S. Geological Survey Scientific Investigations Report 2006-5313. Reston, VA: U.S. Department of the Interior, U.S. Geological Survey. Available from: https://doi.org/10.3133/sir20065313

Fremling, C.R. (2004) *Immortal river: the Upper Mississippi in ancient and modern times*. Madison, WI: University of Wisconsin Press.

Frick, H., Chow, F., Kuhn, M., Mahoney, M., Silge, J., Wickham, H. & Posit Software, P.B.C. (2022) rsample: general resampling infrastructure [online] Available from: https://rsample.tidymodels.org (Accessed 15 August 2023)

Guiney, M.R. & Lininger, K.B. (2022) Disturbance and valley confinement: controls on floodplain large wood and organic matter jam deposition in the Colorado Front Range, USA. *Earth Surface Processes and Landforms*, 47(6), 1371–1389. Available from: https://doi.org/10.1002/esp.5321

Gurnell, A.M., Piégay, H., Swanson, F.J. & Gregory, S.V. (2002) Large wood and fluvial processes. *Freshwater Biology*, 47(4), 601–619. Available from: https://doi.org/10.1046/j.1365-2427.2002.00916.x/full

Gutreuter, S., Vallazza, J.M. & Knights, B.C. (2006) Persistent disturbance by commercial navigation alters the relative abundance of channel-dwelling fishes in a large river. *Canadian Journal of Fisheries and Aquatic Sciences*, 63(11), 2418–2433. Available from: https://doi.org/10.1139/f06-129

Guyon, L., Deutsch, C., Lundh, J. & Urich, R. (2012) *UMR systemic forest stewardship plan*. Rock Island, Illinois: U.S. Army Corps of Engineers.

Guyon, L.J. & Cosgriff, R.J. (2022) Japanese hops (*Humulus japonicus*) control and management strategies in large river floodplains. *Journal of Forestry*, 120(2), 156–169. Available from: https://doi.org/10.1093/jofore/fvab055

Houser, J.N., ed. (2022) Ecological status and trends of the Upper Mississippi and Illinois Rivers. U.S. Geological Survey Open-File Report 2022-1039. Reston, VA: U.S. Department of the Interior, U.S. Geological Survey. Available from: https://doi.org/10.3133/ofr20221039

Ickes, B.S., Sauer, J.S., Richards, N., Bowler, M. & Schlifer, B. (2014) Spatially explicit habitat models for 28 fishes from the Upper Mississippi River System (AHAG 2.0) (ver. 1.1, July 2014): A technical report submitted to the U.S. Army Corps of Engineers' Upper Mississippi River Restoration-Environmental Management Program, Technical Report 2014–T002, 89 p. https://pubs.usgs.gov/mis/ltrmp2014-t002/

Jankowski, K.-J. (2022) Water Quality Indicators, chap. E. In: Houser, J.N. (Ed.) *Ecological status and trends of the Upper Mississippi and Illinois Rivers*. U.S. Geological Survey Open-File Report 2022-1039. Reston, VA: U.S. Department of the Interior, U.S. Geological Survey. 28 p. Available from: https://doi.org/10.3133/ofr20221039

Jochner, M., Turowski, J.M., Badoux, A., Stoffel, M. & Rickli, C. (2015) The role of log jams and exceptional flood events in mobilizing coarse particulate organic matter in a steep headwater stream. *Earth Surface Dynamics*, 3(3), 311–320. Available from: https://doi.org/10.5194/esurf-3-311-2015

Keller, E.A. & Swanson, F.J. (1979) Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes*, 4(4), 361–380. Available from: https://doi.org/10.1002/esp.3290040406

Knighton, D. (1998) *Fluvial forms and processes: a new perspective*. Hodder Education: London, UK.

Kramer, N. & Wohl, E. (2017) Rules of the road: a qualitative and quantitative synthesis of large wood transport through drainage networks. *Geomorphology*, 279, 74–97. Available from: https://doi.org/10.1016/j.geomorph.2016.08.026

Kramer, N., Wohl, E., Hess-Homeier, B. & Leisz, S. (2017) The pulse of driftwood export from a very large forested river basin over multiple time scales, Slave River, Canada. *Water Resources Research*, 53(3), 1928–1947. Available from: https://doi.org/10.1002/2016WR019260

Krause, S., Klaar, M.J., Hannah, D.M., Mant, J., Bridgeman, J., Trimmer, M., et al. (2014) The potential of large woody debris to alter biogeochemical processes and ecosystem services in lowland rivers: potential of large woody debris to alter biogeochemical processes. *Wiley Interdisciplinary Reviews: Water*, 1(3), 263–275. Available from: https://doi.org/10.1002/wat2.1019

Kuhn, M., Wing, J. & Weston, S. (2023) caret: classification and regression training [online]. Available from: https://github.com/topepo/caret (Accessed 15 August 2023).

Lehtinen, R.M., Mundahl, N.D. & Madejczyk, J.C. (1997) Autumn use of woody snags by fishes in backwater and channel border habitats of a large river. *Environmental Biology of Fishes*, 49(1), 07–19. Available from: https://doi.org/10.1023/A:1007346430221

Lewin, J. & Ashworth, P.J. (2014a) Defining large river channel patterns: alluvial exchange and plurality. *Geomorphology*, 215, 83–98. Available from: https://doi.org/10.1016/j.geomorph.2013.02.024

Lewin, J. & Ashworth, P.J. (2014b) The negative relief of large river floodplains. *Earth-Science Reviews*, 129, 1–23. Available from: https://doi.org/10.1016/j.earscirev.2013.10.014

Lindenmayer, D.B., et al. (2012) Value of long-term ecological studies. *Austral Ecology*, 37(7), 745–757. Available from: https://doi.org/10.1111/j.1442-9993.2011.02351.x

Lininger, K.B. & Hilton, S. (2022) Large wood in small channels: a 20-year study of budgets and piece mobility in two redwood streams. *Water Resources Research*, 58(11), e2022WR033047. Available from: https://doi.org/10.1029/2022WR033047

Lininger, K.B., Scamardo, J.E. & Guiney, M.R. (2021) Floodplain large wood and organic matter jam formation after a large flood: investigating the influence of floodplain forest stand characteristics and river corridor morphology. *Journal of Geophysical Research: Earth Surface*, 126(6), e2020JF006011. Available from: https://doi.org/10.1029/2020JF006011

MacVicar, B. & Piégay, H. (2012) Implementation and validation of video monitoring for wood budgeting in a wandering piedmont river, the Ain River (France). *Earth Surface Processes and Landforms*, 37(12), 1272–1289. Available from: https://doi.org/10.1002/esp.3240

Maurer, W.R., Claflin, T.O., Rada, R.G. & Rogala, J.T. (1995) Volume loss and mass balance for selected physicochemical constituents in Lake Pepin, upper Mississippi River, USA. *Regulated Rivers: Research & Management*, 11(2), 175–184. Available from: https://doi.org/10.1002/rrr.3450110207

Mertes, L.A.K., Daniel, D.L., Melack, J.M., Nelson, B., Martinelli, L.A. & Forsberg, B.R. (1995) Spatial patterns of hydrology, geomorphology and vegetation on the floodplain of the Amazon River in Brazil from a remote sensing perspective. *Geomorphology*, 13(1-4), 215–232. Available from: https://doi.org/10.1016/0169-555X(95)00038-7

Montgomery D.R., Collins B.D., Buffington J.M. & Abbe T.B. (2003) Geomorphic effects of wood in rivers. In: Gregory, S.V., Boyer, K.L., & Gurnell, A.M. (Eds.) *Ecology and management of wood in world riveres*. American Fisheries Society, Symposium 37. Bethesda, MD, pp. 21–47.

National Research Council. (2002) *The Missouri River ecosystem: exploring the prospects for recovery*. Washington, D.C: National Academies Press. Available from: https://doi.org/10.17226/10277

Oines, A. (2020) *Influence of flooding, gap size, and surrounding forest characteristics on the fate of UMRS floodplain forest canopy gaps*, M.S. Thesis. La Crosse, WI: University of Wisconsin - La Crosse.

Parsons, M. & Thoms, M.C. (2007) Hierarchical patterns of physical–biological associations in river ecosystems. *Geomorphology*, 89(1-2), 127–146. Available from: https://doi.org/10.1016/j.geomorph.2006.07.016

Pettit, N.E., Naiman, R.J., Rogers, K.H. & Little, J.E. (2005) Post-flooding distribution and characteristics of large woody debris piles along the semi-arid Sabie River, South Africa. *River Research and Applications*, 21(1), 27–38. Available from: https://doi.org/10.1002/rra.812

Petts, G.E. & Amoros, C. (1996) The fluvial hydrosystem. In: Petts, G.E. & Amoros, C. (Eds.) *Fluvial hydrosystems*. London, UK: Chapman and Hall, pp. 1–12.

Piégay, H. (2003) Dynamics of wood in large rivers. In: Gregory, S.V., Boyer, K.L. & Gurnell, A.M. (Eds.) *Ecology and management of wood in world rivers*. Bethesda, MD: American Fisheries Society, Symposium 37, pp. 109–133.

Piégay, H. & Gurnell, A. (1997) Large woody debris and river geomorphological pattern: examples from SE France and S. England. *Geomorphology*, 19(1-2), 99–116. Available from: https://doi.org/10.1016/S0169-555X(96)00045-1

R Core Team. (2023) *R: a language and environment for statistical computing. Version 4.3.1*. R Foundation for Statistical Computing: Vienna, Austria [online] Available from: https://www.R-project.org/

Ratcliff, E.N., Gittinger, E.J., O'Hara, T.M., & Ickes, B.S. (2014) Long Term Resource Monitoring Program procedures: Fish monitoring, 2nd edition. A program report submitted to the U.S. Army Corps of Engineers' Upper Mississippi River Restoration-Environmental Management Program, June 2014. Program Report LTRMP 2014-P001, 88 pp. including Appendixes A–G, https://pubs.usgs.gov/mis/ltrmp2014-p001/

Reichman, O.J., Jones, M.B. & Schildhauer, M.P. (2011) Challenges and opportunities of open data in ecology. *Science*, 331(6018), 703–705. Available from: https://doi.org/10.1126/science.1197962

Reid, D.A. & Hassan, M.A. (2020) Response of in-stream wood to riparian timber harvesting: field observations and long-term projections. *Water Resources Research*, 56(8), e2020WR027077. Available from: https://doi.org/10.1029/2020WR027077

Rogala J. (2019a) *Water depth at the 75% exceeded discharge condition for the Upper Mississippi River System (Mississippi River)*. Reston, VA: U.S. Geological Survey data release. Available from: https://doi.org/10.5066/P92PSPHG

Rogala J. (2019b) *Water depth at the 75% exceeded discharge condition for the Upper Mississippi River System (Illinois River)*. Reston, VA: U.S. Geological Survey data release. Available from: https://doi.org/10.5066/P92PSPHG

Romano, S.P. (2010) Our current understanding of the Upper Mississippi River System floodplain forest. *Hydrobiologia*, 640(1), 115–124. Available from: https://doi.org/10.1007/s10750-009-0063-8

Roni, P., Beechie, T., Pess, G. & Hanson, K. (2015) Wood placement in river restoration: fact, fiction, and future direction. Jonsson B (ed). *Canadian Journal of Fisheries and Aquatic Sciences*, 72(3), 466–478. Available from: https://doi.org/10.1139/cjfas-2014-0344

Ruiz-Villanueva, V., Piégay, H., Gurnell, A.M., Marston, R.A. & Stoffel, M. (2016) Recent advances quantifying the large wood dynamics in river basins: new methods and remaining challenges: large wood dynamics. *Reviews of Geophysics*, 54(3), 611–652. Available from: https://doi.org/10.1002/2015RG000514

Schenk, E.R., Benthem, A.J., Dixon, M.D., Mittelman, M., Skalak, K.J., Hupp, C.R., et al. (2018) Large wood distribution, mobility, and recruitment in an inter-dam river reach: a comparison with geomorphic process on the Garrison Reach of the Missouri River pre and post the historical 2011 flood. *Earth Surface Processes and Landforms*, 43(8), 1677–1688. Available from: https://doi.org/10.1002/esp.4346

Scown, M.W., Thoms, M.C. & De Jager, N.R. (2015) Floodplain complexity and surface metrics: influences of scale and geomorphology. *Geomorphology*, 245, 102–116. Available from: https://doi.org/10.1016/j.geomorph.2015.05.024

Sing T., Sander O., Beerenwinkel N., Lengauer T., Unterthiner T., Ernst F.G.M. (2020) ROCR: visualizing the performance of scoring classifiers [online] Available from: https://ipa-tys.github.io/ROCR (Accessed 15 August 2023)

Skalak, K.J., Benthem, A.J., Schenk, E.R., Hupp, C.R., Galloway, J.M., Nustad, R.A., et al. (2013) Large dams and alluvial rivers in the Anthropocene: the impacts of the Garrison and Oahe dams on the upper Missouri River. *Anthropocene*, 2, 51–64. Available from: https://doi.org/10.1016/j.ancene.2013.10.002

Swanson, F.J., Gregory, S.V., Iroumé, A., Ruiz-Villanueva, V. & Wohl, E. (2021) Reflections on the history of research on large wood in rivers. *Earth Surface Processes and Landforms*, 46(1), 55–66. Available from: https://doi.org/10.1002/esp.4814

Theiling, C.H., Janvrin, J.A. & Hendrickson, J. (2015) Upper Mississippi River restoration: implementation, monitoring, and learning since 1986: Upper Mississippi River restoration. *Restoration Ecology*, 23(2), 157–166. Available from: https://doi.org/10.1111/rec.12170

Theiling, C.H., Korschgen, C., De Haan, H., Fox, T., Rohweder, J.J., Robinson L. (2000) Habitat Needs Assessment for the Upper Mississippi River System: Technical Report. Contract report prepared for U.S. Army Corps of Engineers, St. Louis District, St. Louis, Missouri.

Thoms, M.C. (2003) Floodplain-river ecosystems: lateral connections and the implications of human interference. *Geomorphology*, 56(3-4), 335–349. Available from: https://doi.org/10.1016/S0169-555X(03)00160-0

Triska, F.J. (1984) Role of wood debris in modifying channel geomorphology and riparian areas of a large lowland river under pristine conditions: a historical case study. *Verhandlung Internationale Vereinigung Limnologie*, 22(3), 1876–1892. Available from: https://doi.org/10.1080/03680770.1983.11897589

Tweet, R. (1975) *A history of the Rock Island District corps of engineers*. Rock Island, IL: U.S. Army Corps of Engineers.

U.S. Army Corps of Engineers. 2012. *UMRR EMP environmental design handbook*. U.S. Army Corps of Engineers: Rock Island, IL [online] Available from: https://www.mvr.usace.army.mil/Portals/48/docs/Environmental/UMRR/HREP/EMP_Documents/2012%20UMRR%20EMP%20Environmental%20Design%20Handbook%20-%20FINAL.pdf

U.S. Army Corps of Engineers' Upper Mississippi River Restoration (UMRR) Porgram Long Term Resource Monitoring (LTRM) element (2017) UMRR 2010 Land Cover Land Use. U.S. Geological Survey data reelease, Reston, VA. Available from: https://doi.org/10.5066/F77942QN

U.S. Army Corps of Engineers' Upper Mississippi River Restoration (UMRR) Program Long Term Resource Monitoring (LTRM) element. (2018) *2010/11 level 3 aquatic areas - Upper Mississippi River System*. Reston, VA: U.S. Geological Survey data release. Available from: https://doi.org/10.5066/F7Z89BMP

U.S. Geological Survey. (2019) National Hydrography Dataset Plus High Resolution [online] Available from: https://www.usgs.gov/national-hydrography/access-national-hydrography-products (Accessed 15 August 2023)

Van Appledorn, M. (2022) Hydrologic Indicators, chap. B. In: Houser, J.N. (Ed.) *Ecological status and trends of the Upper Mississippi and Illinois Rivers*. Reston, VA: U.S. Geological Survey Open-File Report 2022-1039; 18 p. Available from: https://doi.org/10.3133/ofr20221039

Van Appledorn, M., De Jager, N.R. & Rohweder, J.J. (2018) UMRS Floodplain Inundation Attribute Rasters. Reston, VA: U.S. Geological Survey data release. Available from: https://doi.org/10.5066/F7VD6XRT

Van Appledorn, M., De Jager, N.R. & Rohweder, J.J. (2021) Quantifying and mapping inundation regimes within a large river-floodplain ecosystem for ecological and management applications. *River Research and Applications*, 37(2), 241–255. Available from: https://doi.org/10.1002/rra.3628

Van Appledorn, M. & Rogala, J.T. (2022) Geomorphic indicators, chap. C. In: Houser, J.N. (Ed.) *Ecological status and trends of the Upper Mississippi and Illinois Rivers*. Reston, VA: U.S. Geological Survey Open-File Report 2022-1039; 14 p. Available from: https://doi.org/10.3133/ofr20221039

Wasley, D. (2010) Concentration and movement of nitrogen and other materials in selected reaches and tributaries of the Upper Mississippi River System., M.S. Thesis, University of Wisconsin - La Crosse: La Crosse, WI. Available from: https://search.library.wisc.edu/catalog/9910436839002121

WEST Consultants, Inc. (2000) *Upper Mississippi River and Illinois waterway cumulative effects study - volume 1: geomorphic assessment*. ENV Report. Rock Island, IL. Available from: http://www.mvs.usace.army.mil/Portals/54/docs/navigation/SEIS/Library/Other_Documents/Nav_Study_Cumulative_Effects_Vol_1_Geomorphic_Assessment.pdf (Accessed 17 September 2017)

Wiens, J.A. (2002) Riverine landscapes: taking landscape ecology into the water. *Freshwater Biology*, 47, 501–515. Available from: https://doi.org/10.1046/j.1365-2427.2002.00887.x

Wilcox, D.B. (1993) An aquatic habitat classification system for the Upper Mississippi River System. In: *Long term resource monitoring program technical report*. Onalaska, WI: Environmental Management Technical Center.

Wohl, E. (2013) Floodplains and wood. *Earth-Science Reviews*, 123, 194–212. Available from: https://doi.org/10.1016/j.earscirev.2013.04.009

Wohl, E. (2014) A legacy of absence: wood removal in US rivers. *Progress in Physical Geography*, 38(5), 637–663. Available from: https://doi.org/10.1177/0309133314548091

Wohl, E. (2017) Bridging the gaps: an overview of wood across time and space in diverse rivers. *Geomorphology*, 279, 3–26. Available from: https://doi.org/10.1016/j.geomorph.2016.04.014

Wohl, E. (2020) Wood process domains and wood loads on floodplains. *Earth Surface Processes and Landforms*, 45(1), 144–156. Available from: https://doi.org/10.1002/esp.4771

Wohl, E., Cenderelli, D.A., Dwire, K.A., Ryan-Burkett, S.E., Young, M.K. & Fausch, K.D. (2010) Large in-stream wood studies: a call for common metrics. *Earth Surface Processes and Landforms*, 35(5), 618–625. Available from: https://doi.org/10.1002/esp.1966

Wohl, E., Kramer, N., Ruiz-Villanueva, V., Scott, D.N., Comiti, F., Gurnell, A.M., et al. (2019) The natural wood regime in rivers. *Bioscience*, 69(4), 259–273. Available from: https://doi.org/10.1093/biosci/biz013

Wohl, E., Uno, H., Dunn, S.B., Kemper, J.T., Marshall, A., Means-Brous, M., et al. (2023) Why wood should move in rivers. *River Research and Applications*, 1–12. Available from: https://doi.org/10.1002/rra.4114

SUPPORTING INFORMATION

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