Sand and Gravel Dispersal Rates using Mine Tailings Tracers in Big River, Ozark Highlands

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Introduction

Bed material characteristics and transport processes exert a fundamental influence on river channel form and behavior (Leopold, 1992; Rosgen, 1996; Church, 2002; Kasprak et al. 2014). Empirical models are available to predict flow conditions and bed sediment transport rates in natural channels (Nelson et al., 2003; Lewis et al. 2016). Nevertheless, bed load estimates for natural streams can deviate by up to an order of magnitude from field measurements due to poor understanding of channel processes and sediment factors (Wilcock et al., 2009; Poorhosein et al., 2014). Indeed, channel morphology, sediment sorting, and flood characteristics can influence mobility and travel distances of bed sediments irrespective of grain size and shear stress (Powell, 1998; Wilcock et al., 2009; Vazquez-Tarrio et al., 2018; and R.J. Batella, 2019).

To reduce transport errors, pebble tracer data including bed material characteristics and transport distances are needed to calibrate and verify modeling approaches (Gomez and Church, 1989; Martin, 2003; Haschenburger, 2013; Poorhosein et al., 2014). Small scale tracer studies have been used to determine bed mobility thresholds and transport rates at timescales ranging from individual events to several years (Laronne et al., 1992; Bunte and Abt, 2001; Gob et al. 2005; Liebault and Laronne, 2008, Hassan and Roy, 2016; Hassan and Bradley, 2017). However, tracer studies on natural streams that monitor large numbers of tracers (i.e., “thousands of stones”) over relatively long periods (>10 years) are needed to account for stochastic mobility and storage effects that tend to slow bed transport velocities over time (Nicholas et al., 1995; Powell, 1998; Haschenburger, 2011; Hassan and Roy, 2016; Hassan and Bradley, 2017).

This study reports virtual velocity values for sand- and gravel-sized sediments based on dispersal of historical mine tailings discharged after 1894 to Big River in southeastern Missouri (Figure 1). Sediment dispersal describes how particles spread laterally and vertically as well as longitudinally within channel deposits (Lewis et al. 2016). Dispersal processes for sediment pulses such as tailings inputs are generally evaluated at two scales of bed material movement: particle transport and wave migration (Lisle et al., 2001). Particle transport is quantified by virtual velocity reported as the net distance traveled by a single particle per unit time since initial release including effects of armoring and selective transport, bed characteristics, burial depth, and flood regime (Nelson et al., 2003; Lewis et al. 2016). However, wave migration refers to the organization, movement, and effects of a relatively large sediment pulse composed of many particles introduced to the channel (Nicholas et al., 1995; Lisle, 1997; James, 2010).

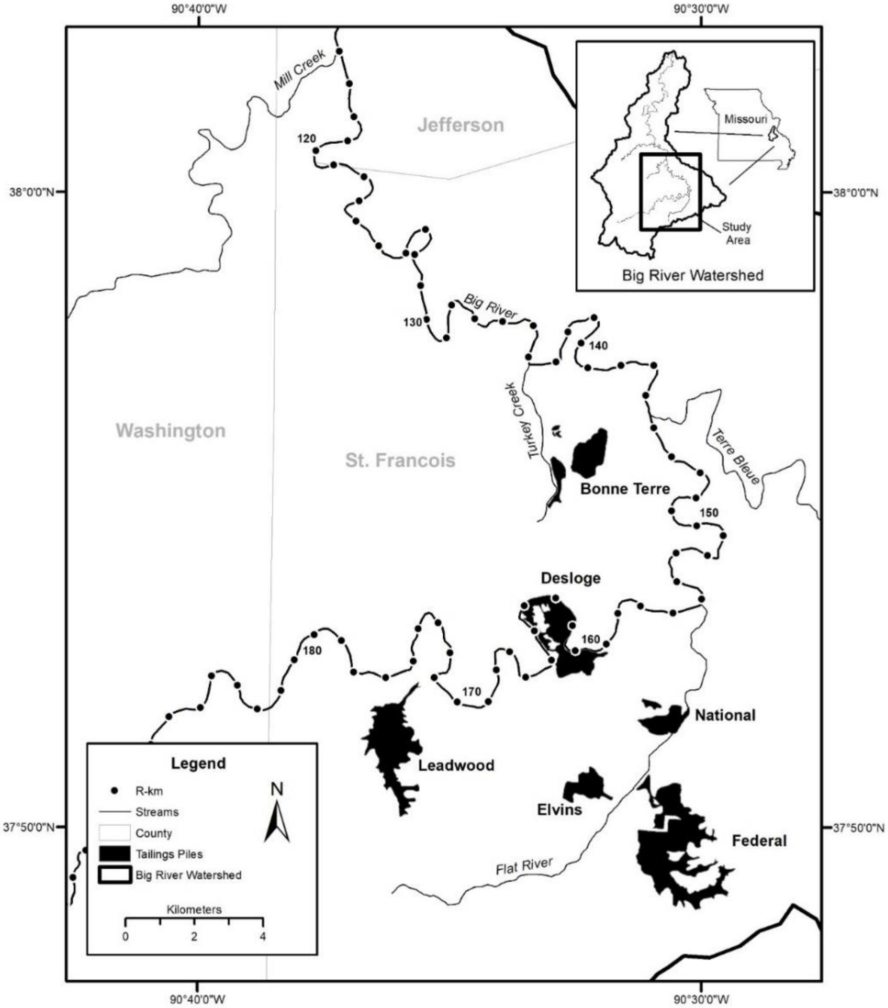

Figure 1. Big River Study Area and Mine Locations

In this study, virtual velocities are calculated for pebble tracer "waves" by dividing dispersal distances by the number of years since tailings release based on production records. While geomorphic bed waves involve a rise in bed elevation due to transport-limited conditions (Lisle et al., 1997, 2001), sediment pulses can generate wave-like transport below the source due to differences in composition between peak tracer concentrations and background sediment (Sayre et al., 1963, and Hubbell, 1965; Glover, 1964; Graf 1994, 1996). Longitudinal wave profiles are described as having a peak at the maximum tracer concentration in the channel with a wave front extending downstream to the leading edge where elevated tracer concentrations begin to increase in the channel. The base of the trailing limb of the wave indicates the upstream boundary of wave passage (Lisle et al., 1997, 2001). Dispersive waves erode in place with little net movement downstream and some deposition on the leading edge and sometimes on the trailing edge in upstream pools. Translational waves shift progressively downstream in original form, generally maintaining amplitude and length. Some sediment waves can exhibit both dispersive and translational behavior where gradual shift of the wave peak and reduction of peak height occur with travel distance downstream (Lisle et al. 2001). Wave peak migration rates in small to medium sized rivers can range from 100-1000 m/yr (Lisle, 1997).

The Big River is in the Ozark Highlands of southeast Missouri and provides a unique opportunity to assess long-term sediment dispersal of both fine and coarse bed material over a period of >100 years using mine tailings as tracers (Figure 1). The history of ore production from 1894 to 1972 by large-scale mining in the Old Lead Belt (OLB) is well documented (Table 1; Pavlowsky et al., 2017). More importantly, the discharge points, composition, and transport routes of the dolomitic mill wastes <16 mm in diameter are known (Smith and Schumacher, 1991, 1993; Mosby et al. 2009; Pavlowsky et al. 2017). Previous workers have also used mine tailings inputs to quantify fluvial sediment dispersal including long-term bed material transport rates and storages in rivers (Gilbert, 1917; Wolfenden and Lewin, 1978; Pickup et al., 1983; James, 1989; Knighton, 1989; Macklin and Lewin, 1989; Davies et al., 2018).

Widespread soil and vegetation disturbances beginning in the 1840s during Euro-American settlement and extending to the 1920s increased runoff and erosion rates in the Ozark Highlands (Jacobson and Primm, 1997; Owen et al., 2011). Historical sediment waves containing chert gravels migrated down Ozark streams due excessive sediment loads generated by gullying and channel incision in headwater valleys (Jacobson, 1995). Previous sediment wave studies in Big River and other Ozark rivers were based on geomorphic analysis using bar and bed surveys, historical aerial photographs, and historical accounts of channel deposition over time (Jacobson, 1995; Jacobson and Primm, 1997; Martin and Pavlowsky, 2011). Bed elevation changes at USGS gaging stations suggested that sediment waves migrated into tributaries by 1910 and traveled downstream to main channels by the 1940-50s (Jacobson, 1995).

This is the first tracer study to assess the time of travel for tailings and natural sediments in Big River. Information on sediment dispersal rates can help improve our understanding of historical sediment waves (Jacobson, 1995), tailings and metal contaminant transport (USFWS and MDNR, 2007; Mosby et al., 2009; Roberts et al. 2009; Pavlowsky et al., 2017), and suitability of remediation plans (Alesandrini, 2014). The three specific objectives of this study are to (1) use two types of tailings tracers to determine virtual velocities for sand and gravel sediments: calcium (Ca) concentrations in <2 mm fine sediment and grain counts of dolomite fragments in 2-16 mm coarse sediment; (2) develop sediment size-velocity relationships to predict virtual velocities; and (3) evaluate implications for sediment transport and wave theory in Ozark rivers.

Study Area

Big River (2,500 km^2) drains the Ozark Highlands of southeastern Missouri. It flows 226 km from its headwaters in the Saint Francois Mountains and through the Salem Plateau, discharging into Meramec River south of Saint Louis, Missouri (Adamski et al., 1995; Meneau, 1997). In 2018, land use in the Big River watershed was 75% forest, 16% pasture, 1% row crops, <1% water, and 7% urban. This study focuses on a 70 km segment of the main channel in Saint Francois County extending from river-kilometer (R-km) 171 at Leadwood (650 km^2) downstream to R-km 101 at Washington State Park (1,363 km^2) (Figure 1). Flat River Creek (FRC) drains three of largest mines in the OLB and flows into Big River at R-km 155. The study segment is surrounded by a rolling to rugged terrain with local relief up to 150 m and geology of horizontally bedded Cambrian and Ordovician dolomites, cherty dolomites, sandstones, and limestones, with some shale (Adamski et al., 1995; Pavlowsky et al., 2017). Upland soils are typically formed in a thin layer of silty Pleistocene loess overlying cherty or non-cherty, clayey residuum formed in dolomite, limestone, and shale (Brown, 1981). Karst features such as sinkholes and springs occur in limestone and dolomite bedrock but are not as abundant as in other areas of the Ozark Highlands (Adamski et al., 1995).

Table 1. Mining History and Tailings Production

Event	***Mines in the Old Lead Belt draining to Big River***					
	Leadwood	**Desloge**	**Elvins**	**Federal**	**National**	**Bonne Terre**
First shaft	1898	1890	1900	1891	1898	1865
First operating mill	1904	1894	1900	1894	1901	1866
Chat tailings- Start	1904	1894	1909	1907	1904	1913
End	1928	1929	1929	1931	1933	1931
Mine output (%)	9.9	11.3	19.1	30.8	17.6	11.3
"Boom" peak year	1926	1929	1926	1930	1926	1926
Period	1923-29	1924-30	1924-29	1927-31	1924-29	1923-29

Southeastern Missouri is in a moist continental climate region with an average annual temperature of 13° C, but temperatures range from an average of 0° C in January to 25° C in July. Annual rainfall averages about 102 cm with a wet spring season (Adamski et al., 1995). Since 1990, most gaging stations in the Ozarks Highlands, including two on Big River, have recorded increases in the annual peak discharge by up to 8 to 10 percent per year due to increased rainfall intensity (Heimann et al., 2018). Floodplain soils are generally composed of fine-grained overbank deposits overlying gravelly channel deposits (Brown, 1981). Historical legacy deposits indicating poor soil conservation during the post-settlement period occur on floodplains and low terraces to depths ranging from 0.5 to 3.5 m (Pavlowsky et al., 2017). Average bank-full channel characteristics in the study segment are as follows: discharge, 343 m^3/s; width, 63 m; average depth, 3.3 m; slope, 0.0007; shear stress, 2 kg/m^2; and critical sediment size, 16-32 mm.

The OLB covers an area of about 100 km^2 in St. Francois County, Missouri (Figure 1). It began operations in 1864 at Bonne Terre, Missouri, reached peak production in 1910-45, and, after waning production in the 1960s, the Federal mine was the last mine to close in 1972 (Table 1). Earlier mining in the 1700s and 1800s involved the extraction of relatively large galena crystals in residual, float or placer deposits from shallow, hand-dug pits (Mugel, 2017). However, total production of these crude mines in the OLB was relatively small representing <2-3% of total Pb metal production in the OLB (Buckley, 1908; Mugel, 2017; Pavlowsky et al. 2017). Using annual records of mine production, mill capacity, and ore grade, Pavlowsky et al. (2017) estimated that about 264 million Mg of mine tailings were created by concentration mills at six mines in Big River watershed between 1894 and 1972. Only about 22% of the total is presently stored in remediated tailings piles at old mining sites. Large volumes of tailings were removed for soil amendments and construction materials. Based on metal storage estimates in alluvial deposits, possibly 35% of the tailings produced were discharged to Big River (Pavlowsky et al., 2017).

The first concentrator mills in the OLB produced coarse tailings ranging in size from 1-12.7 mm using Harz and Hancock Jigs (Taggert, 1945). After 1910, Wilfley shaking tables were added to mill circuits that also produced sand-sized (0.1-0.9 mm) tailings (Taggert, 1945). Until 1931, coarse tailings were dumped in large “chat” waste piles up to 80 m high and almost 1 km^2 in area (Table 1). Tailings piles drained into local streams including Eaton Creek, FRC, Turkey Creek, and Big River (Buckley, 1909; Rice, 1913; Coghill and O’Meara, 1932; Pavlowsky et al., 2017). Finally, after the 1929-31 period, only sand table and froth flotation circuits were used to treat ores which only produced tailings in the fine sand to silt size ranges (0.032-0.3 mm) that were discharged in piped slurries to large “slime” ponds formed by dams across small stream valleys (Coghill and O'Meara, 1932). Jig tailings produced at the Federal mill typically contained a size distribution by mass as follows: 8-16 mm, 9%; 4-8 mm, 48%; 2-4 mm, 23%; and <2 mm, 20% (Rice, 2013). Sand tailings from shaking tables were much finer at 0.25-0.9 mm, 66%; 0.1-0.25 mm, 33%; and <0.1 mm, 1% (Coghill and O’Meara, 1932).

Methods

Mine tailings released from historical mines into the main channel and FRC were used as passive exotic tracers to evaluate sediment dispersal patterns for sand and gravel bed sediments (Wilcock, 2001; Hassan and Roy, 2016). For particles <2 mm in size, Ca concentrations in the sediment were used to track the location of fine tailings pulses downstream (Adams, 1944). Twenty-nine bar and bed samples were collected from 13-18 reaches between R-km 171.7 and R-km 1.8, oven-dried, and sieved into <250 mm, 1-2 mm, and 4-8 mm fractions. Calcium concentrations were determined by X-ray fluorescence (XRF) using an Oxford Instruments Portable X-MET 3000 TXS+ (Pavlowsky et al., 2017). The 1-2 mm and 4-8 mm fractions were powdered on a ball mill prior to XRF analysis. The XRF Ca concentrations were multiplied by 0.74 to convert to equivalent aqua-regia/ICP-AES concentrations based on calibration testing at a commercial laboratory (Pavlowsky et al., 2017).

Calcium concentrations in tailings particles were usually over 25-times higher than found in natural sediments and were used to trace the location of fine tailings pulses in Big River. Pure 50:50 dolomite common to the District would be expected to contain 21.7% Ca, and ores in the OLB averaged 18.2% Ca (Dunlap, 1922). Tailings pile samples from Leadwood and National mines contained Ca concentrations as follows, respectively: <0.25 mm, 17.4 and 17.7% Ca; 1-2 mm, 16.7% and 17.9% Ca; and 4-8 mm, 16.5% and 19.6% Ca (Pavlowsky et al., 2010). Moreover, tailings grains (4-8 mm, n=11) sorted from bar sediments averaged 18.1% Ca with a coefficient of variation of 3% (1s). In contrast, background channel sediments (n=10) collected from Big River upstream of Leadwood (furthest upstream mine) yielded background threshold values (mean + 2s) of 0.7% Ca for <0.25 mm, 0.4% Ca for <2 mm, and <0.1% Ca for 2-16 mm fractions.

Visual grain counts were used to quantify the percentage of coarse tailings particles in channel deposits ranging in size from 2-16 mm (very fine-medium gravel) based on differences of lithological properties (James, 1991; Pace-Witt, 2022). Active bar samples were collected at approximately 400 m intervals in summer 2013 from Leadwood (R-km 171) to below Bonne Terre (R-km 132) (n=83) and in summer 2014 from R-km 133 to Washington State Park (R-km 101) (n=65) (Pace-Witt, 2022). Samples were collected at middle bar or tail locations from 10-20 cm depths to reach below the more variable and coarser active layer. Longitudinal and point bars were the most sampled bar types (Olson, 2017). Measurements of bar heights (n= 34, R-km 171-155 and n=47, R-km 155-132) and bed thalweg probe depths (n= 50, above R-km 155 and n=61, below R-km 155) were collected during summer 2013.

Samples were dried and sieved into 2-4 mm, 4-8 mm, and 8-16 mm fractions for grain counting. Tailings grains were easily distinguishable from the natural sediment (see photographs in Pace-Witt, 2022). Coarse tailings were composed of angular, blue-gray dolomite from the mineralized Bonne Terre formation, while natural sediments were composed largely of sub-angular to sub-rounded lighter colored chert with some quartz and feldspar grains (Smith and Schumacher, 1991, 1993; Pace-Witt, 2022). Sub-samples of 100-150 grains from each size fraction were visually sorted into tailings and non-tailings particles. The percent tailings content for each sample was calculated as: 100 x (number of tailing grains / total number of all grains counted). Locally abundant (<10%) grains of coal, slag, or shale were not included in the total grain count.

The tailings release point was assumed to be R-km 161 km which represents source points at both the Federal mine on FRC and Desloge mine on Big River. The Shaw Branch confluence on FRC was selected as one release point. It is located about 6 km above R-km 155 on Big River (Figure 1). Shaw Branch drained the Federal mine which was the most productive and longest running mine in the OLB and its valley was filled with aggraded tailings until remediation beginning about 10 years ago. More than two-thirds of the chat tailings until 1931 were produced on FRC at the Elvins-Rivermines (19% of total chat tailings), Federal (31%), and National (18%) mines (Table 1). Further, Shaw Branch is centrally located in relation to mine sources on FRC, since the Elvins-Rivermines mine was located two km upstream and National mine two km downstream. The second source point was the Desloge tailings pile (11% of chat production) which drained into Big River along a channel segment flowing from 10 to 4 km above the FRC confluence. Therefore, the Desloge mine provides a similar source point-distance as the Federal Mine at about R-km 161.

Leadwood (R-km 171) (10% of total chat tailings) and Bonne Terre (11%) mines were assumed to have little influence on the tailings transport trends of interest to this study. The Leadwood mine was located about 5 km upstream of the Desloge mine on Big River, so its contributions to sediment loads would travel behind the primary wave front and be overwhelmed by ongoing inputs from the downstream mines. The Bonne Terre mine was located in the headwaters of Turkey Creek about 4 km above R-km 132 on Big River. While sediment contamination has occurred in Turkey Creek, the influence of mine wastes on Big River appears to have been negligible compared to other upstream mine sources (Pavlowsky et al., 2017) (Figure 1).

Two tailings release dates were used in this study to evaluate transport distances for both the leading edge (1904) and rising peak of the sediment pulse (1924). The date of 1904 was used as the initial tailings release date for significant inputs of coarse tailings available for downstream transport in FRC or Big River at Desloge. This date is applied to the time of travel for the leading edge and maximum extent of the tailings pulse. The first working mills began in 1894 at the Desloge mine and 1894-1901 on FRC. However, while coarse tailings dumps were being produced at Desloge in 1894, significant dump accumulations occurred later along Flat River Creek from 1904-09 (Table 1). It is assumed that there was a time lag between the opening of a mine and the time when tailings storage areas expanded in size to enter local drainageways and be transported into Big River. Further, an eye-witness account in 1906 indicated that gray tailings clouded Big River and its tributaries, and a photograph showed tailings accumulations along the valley floor of FRC below Shaw Branch (Buckley, 1909). The year 1924 marked the period prior to the peak years of production. This date is associated with the time of travel of the top of the advancing pulse front just ahead of the peak. The upper limb of rising ore production was 1924 for Desloge, Elvins, and National mines and 1927 for the Federal mine. The peak in coarse tailings production occurred during 1926-30 (Table 1).

Results

During sampling, gray tailings-rich sediments were visible in pools and bars along many reaches of Big River from Desloge (R-km 160) to below Bonne Terre (R-km 132). Channel morphology and bed pebble counts were completed in 2009-10 (Pavlowsky et al., 2010). Channel width and bar areas were measured using 2013 aerial photography every 500 m along the channel (Pavlowsky et al., 2017). The mean and quartile range of channel bed and bar characteristics from FRC (R-km 155) to about the leading edge of the tailings front (R-km 130) are as follows: active width, 38 m (34-43 m); bar area of total bed, 24 % (14-34%); bar height above thalweg, 1.00 m (0.60-1.56 m); and thalweg probe depth to refusal, 0.54 m (0.32-0.84 m). Generally, bed and bar sediment depths in the mining area were similar to those found in downstream segments, generally varying according to riffle-pool locations and not by tailings discharge points (Pavlowsky et al., 2017). Further, the ratios of the sum of peak bed and bar sediment depths (1.5-3.2 m) to a wave base length of 20 km in Big River mostly fall below the lower limit for geomorphic wave forms of $H/L = 0.0001$ reported by Lisle et al. (2001). Therefore, the wave-like distribution of tailings concentrations in bar sediments was described as a sediment pulse in this study in contrast to a geomorphic bed wave (Lisle, 1997; James, 2010). Note that previous auger tests and freeze core sampling indicated that tailings sediments were well mixed into bed and bar deposits to depths of 2-3 m (Pavlowsky et al., 2010; Smith, 2013).

Big River bar sediment is typically composed of medium-very coarse sand and very fine to medium gravel (Table 2). Average bar sediment size distributions in Big River ranged among segments as follows: 2-16 mm, 30-54%; 0.25-2 mm, 42-64%; and <0.025 mm, 3-6% (Table 2). While not evaluated here, the >18 mm fraction comprises <15% of the bulk bed sediment below the active pavement layer. Coarser bar sediments occur upstream of FRC in segments 1 and 2. Percentages of medium-very coarse sand (0.025-2 mm) become greater than the percent gravel fraction below Terre Bleue Creek due to higher fine tailings loads and natural inputs from friable sandstone outcrops (Pavlowsky et al., 2017). Surface pebble counts from channel glides above riffle crests between FRC and R-km 133 are generally composed of fine to coarse gravel with an average distribution as follows: D16, 6 mm; D50, 15 mm; and D84, 28 mm.

Calcium concentrations in the 4-8 mm, 1-2 mm, and <0.25 mm fractions showed peaks between R-km 160 and R-km 140 and decreasing trends downstream of the mining district partially due to dilution and burial/storage (Figure 2). However, selective transport and longer transport distances are also evident since the fronts of tailings pulses shift downstream for finer sediment sizes. Compared to the 4-8 mm fraction, the 1-2 mm fraction has been transported 7.4 km (36%) farther downstream at the "top" of the tailings front near the peak and 17.2 km farther (62%) at the "bottom" of the pulse front at the leading edge (Table 3). Anomalous dispersion occurs in Big River as shown by the extreme downstream extension of tracer tails indicating faster virtual velocities for some particles or more burial/resting for others (Hassan and Bradley, 2017). The maximum distance of tracer transport ("max") before reaching background (i.e., zero tailings for 1 km) extended 13.9 km (31%) for 1-2 mm and 11.8 km (42%) for the 4-8 mm fractions farther downstream than the pulse front (Table 3). Elevated Ca concentrations in <0.25 mm fraction occur >30 km further downstream than the 1-2 mm fraction with the maximum distance of anomalous dispersion 52 km further downstream (Table 3). This finer fraction may contain silt and clay particles that can be dispersed rapidly by suspension during floods and preferentially deposited further downstream on wider floodplains along Big River (Pavlowsky et al., 2017).

Tailings materials often account for more than 50% of the channel bed and bar sediment deposits in Big River between R-km 170 and R-km 130 (Pavlowsky et al., 2010, 2017). In this study, coarse tailings tracers were found at relatively high percentages in bar sediments near the mines (Table 4). Median percentages >40% occur over 25 km below source to R-km 132 for the 2-4 mm and R-km 136 for the 4-8 mm fractions. The highest median percentages of 6% in the 8-16 mm fraction occurs in the channel segment ending at R-km 136. Maximum concentrations of the 2-4 mm fraction at >60% exceed its relative concentration in jig tailings (20-30%) suggesting that finer tailings materials were transported at higher rates to Big River compared to coarser tailings. The relatively low abundance of the 8-16 mm tailings fraction in bar sediment also underscores the selective transport of finer materials from the tailings dumps to Big River. For the most part, tailings grain percentages decrease to near zero below Mill Creek at R-km 115 for fine gravel and below Turkey Creek at R-km 136 for medium gravel (Table 4).

Downstream dispersal trends for dolomite tracers again show selective transport for the finer sizes which traveled farther downstream and anomalous dispersion with tails extending farther downstream beyond the pulse front (Figure 3). Compared to the coarsest 8-16 mm fraction, travel distances increased for the 2-4 mm fraction as follows: Top of pulse, 17.3 km (210%); Bottom of pulse, 14.6 km (63%); and Maximum distance, 22.5 km (83%) (Table 3). The relative travel distance of anomalous transport beyond the wave front distance varied as follows: 2-4 mm, 32%; 4-8 mm, 32%; and 8-16 mm, 17% (Table 3). While the locations of sediment pulse fronts and leading edges are relatively easy to identify given concentration trends, tailings peaks

Table 2. Bar sediment size distribution by downstream segment (<16 mm)

Segment		Segment (R-km)		n	<16 mm Fraction (% size distribution)		
		Upper	Lower		2-16 mm	0.25-2 mm	<0.25 mm
1	Leadwood	171	165	18	52	45	3
2	Desloge	165	155	20	54	42	4
3	Flat River	155	144.4	20	49	49	3
4	Terre Bleau Creek	144.4	136	17	47	50	3
5	Turkey Creek/Bonne Terre	136	132.2	9	30	64	6
6	Cabanne Course Creek/Hwy E	132.2	115	37	40	56	4
7	Mill Creek to Washington SP	115	101.7	27	44	53	3

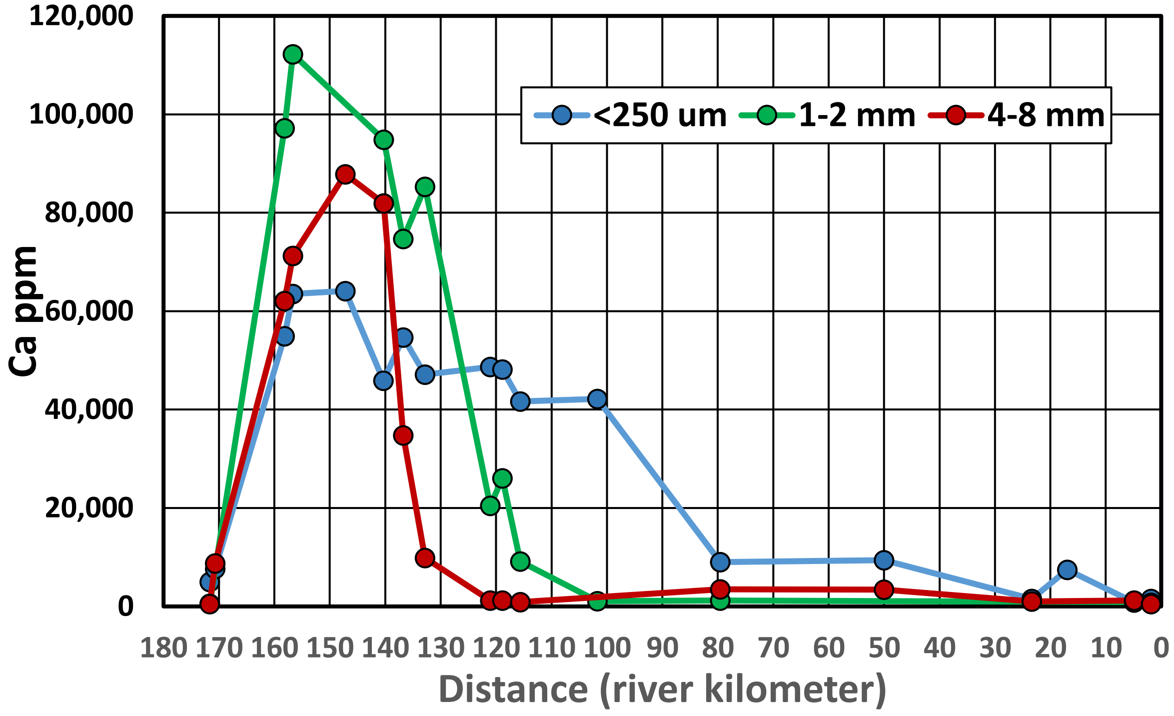

Figure 2. Calcium concentrations in bed and bar sediment in Big River (2009-10)

Table 3. Tracer pulse location, release date, and virtual velocity

Tracer	Size (mm)	Pulse location (R-km)			Virtual Velocity (m/yr)		
		Top	Bottom	Max	Top-1924	Bot-1904	Max-1904
Ca	<0.25	101.7	79.5	50.0	689	768	1047
Ca	1-2	132.9	115.6	101.7	327	428	559
Ca	4-8	140.3	132.9	121.1	241	266	377
Dolo	2-4	135.5	123.4	111.5	283	342	450
Dolo	4-8	139.0	128.8	118.6	244	293	385
Dolo	8-16	152.8	138.0	134.0	91	209	245
Ca & Dolo	Average				243	279	381
4-8 mm	RPD%				1.4	9.7	2.3

Table 4. Distribution of coarse tailings in bar sediments by size fraction

Segment	Segment (R-km)		n	2-4 mm			4-8 mm			8-16 mm		
	Upper	Lower		25%	50%	75%	25%	50%	75%	25%	50%	75%
1 Leadwood	171	165	18	12.3	15.4	37.1	10.0	17.1	23.9	1.4	2.6	4.1
2 Desloge	165	155	20	42.5	51.4	58.5	30.0	36.0	42.3	2.1	3.6	6.1
3 Flat River	155	144.4	20	42.6	48.9	63.6	24.2	40.6	50.3	3.6	5.8	10.8
4 Terre Bleau Creek	144.4	136	17	51.1	56.2	59.6	37.7	40.8	45.9	5.2	5.9	8.8
5 Turkey Creek/Bonne Terre	136	132.2	8	34.6	42.6	53.5	8.6	21.3	25.4	0	0	6.8
6 Cabanne Course Creek/Hwy E	132.2	115	38	4.7	7.8	14.3	1.1	2.4	6.3	0	0	0
7 Mill Creek to Washington SP	115	101.7	27	0	0	0.9	0	0	0	0	0	0

are variable with mixed low and high grain percentages extending upstream from the pulse front for 25 km for fine gravel fractions and 15 km for the medium gravel fraction (Figure 3). Peak lengthening may be due to reduced transport rates and deposition upstream due to pooling of flows by aggrading beds above FRC and Desloge (Lisle et al., 2001). Alternatively, peak lengthening may be the result of tailings inputs lasting almost 100 years from the start of mining to long after closure in 1972, as unstable tailings piles continued to erode by gullying and slope failure prior to remediation in the 1990s (Pavlowsky et al., 2010).

Virtual velocities were calculated by dividing the maximum distance traveled after the year of initial release (1904) or rising pre-peak production (1924) (Hassan and Bradley, 2017). Three scenarios were evaluated: (i) top of the pulse front since 1924; (ii) bottom or leading edge of the pulse front since 1904; and (iii) maximum extent of anomalous dispersion since 1904 (Table 3). The time periods allowed for tracer dispersal were 86-106 years for Ca concentrations and 90-110 years for dolomite grains. Virtual velocity values ranged from 327-559 m/yr for the 1-2 mm fraction to 91-245 m/yr for the 8-16 mm fraction. It is important to note that virtual velocity measurements developed independently using two different methods (i.e., Ca concentration and grain counts) to assess the 4-8 mm fraction produced similar results with relative percent difference values ranging from 1-10% (Table 3). Logarithmic regression equations were developed to describe the relationships between particle diameter and virtual velocity for Big River tailings tracers with R^2 values of 0.97-0.98 (Figure 4).

Discussion

Given the field methods and analytical framework used here, calculated virtual velocity values are relatively robust, since the times and distances for transport are long. Three transport scenarios were evaluated to account for variations in results due to different interpretations of how to define pulse transport time and distance (Table 3, Figure 4). These results may tend to yield faster velocities than occurred, since the Desloge and Federal mills began to discharge coarse tailings in 1894. This release time would be 10 years before the assumed initial release date of 1904 used for this study, suggesting a possible high bias by approximately 10%. Further, the maximum value of the grain size class was used as the independent variable in the virtual velocity equations (Figure 4) thus possibly shifting predictions to slightly higher velocities compared to using the minimum or middle value of the size class. The results of this study compare relatively well with painted tracer results for South Creek in Springfield, Missouri (Table 5C). For example, this study reported virtual velocities of 84-197 m/yr for coarse gravel (22.6-32 mm) with South Creek values falling in the same range from 152-170 m/yr (Breckenridge, 2020). Compared to Big River, higher transport rates would be expected for South Creek, since it is a much smaller stream (27 km^2) with higher slope (0.0032) and urban hydrology. Further, the monitoring period for South Creek was relatively short (<1 yr) thus

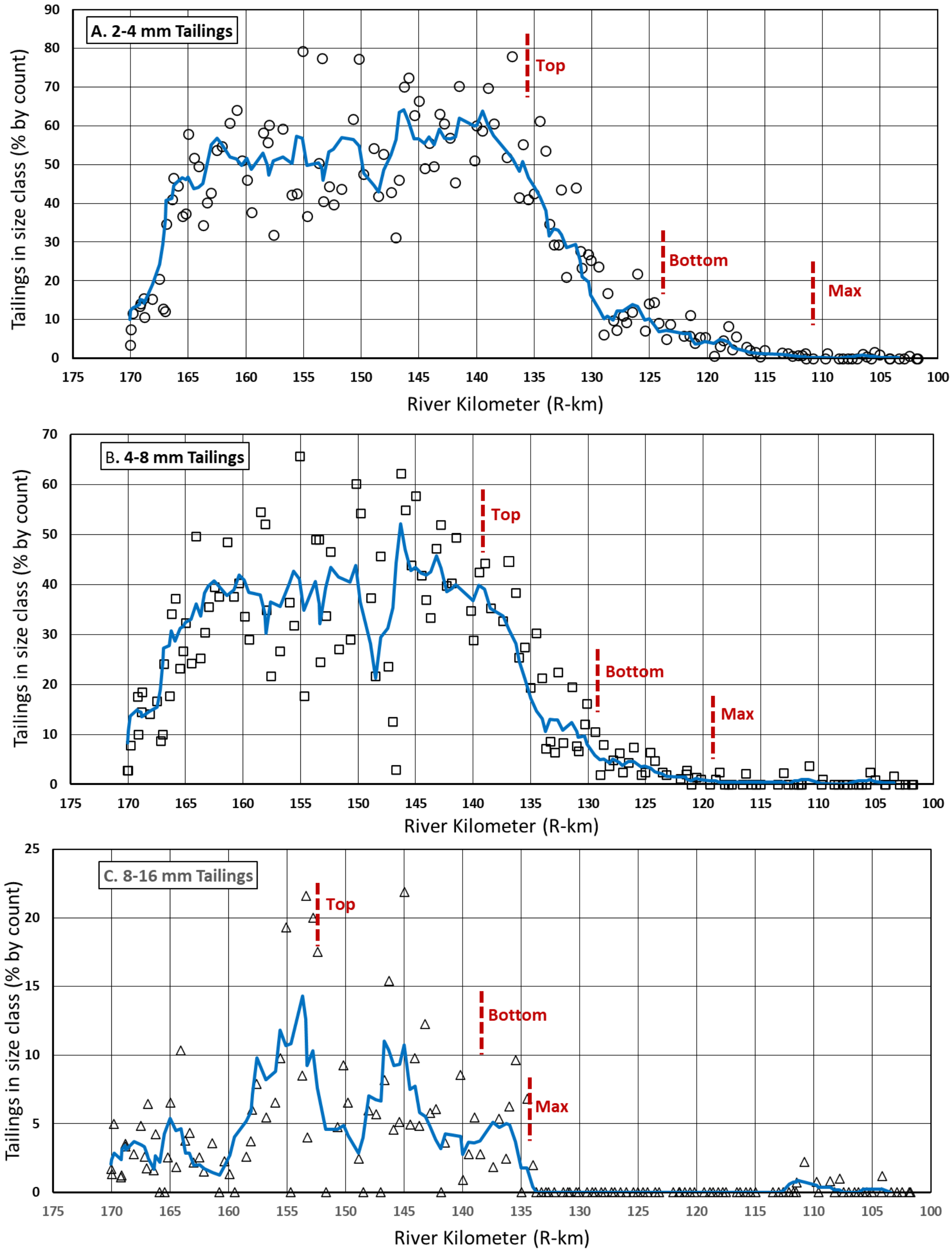

Figure 3. Coarse tailings distributi9n in bar sediments in Big River. Different sediment sizes are described in: (A) 2-4 mm fraction; (B) 4-8 mm fraction; and (C) 8-16 mm fraction. Note: A five-point moving average was used to plot the blue trend-line. Tailing pulse locations labeled in red are described in the text and Table 3.

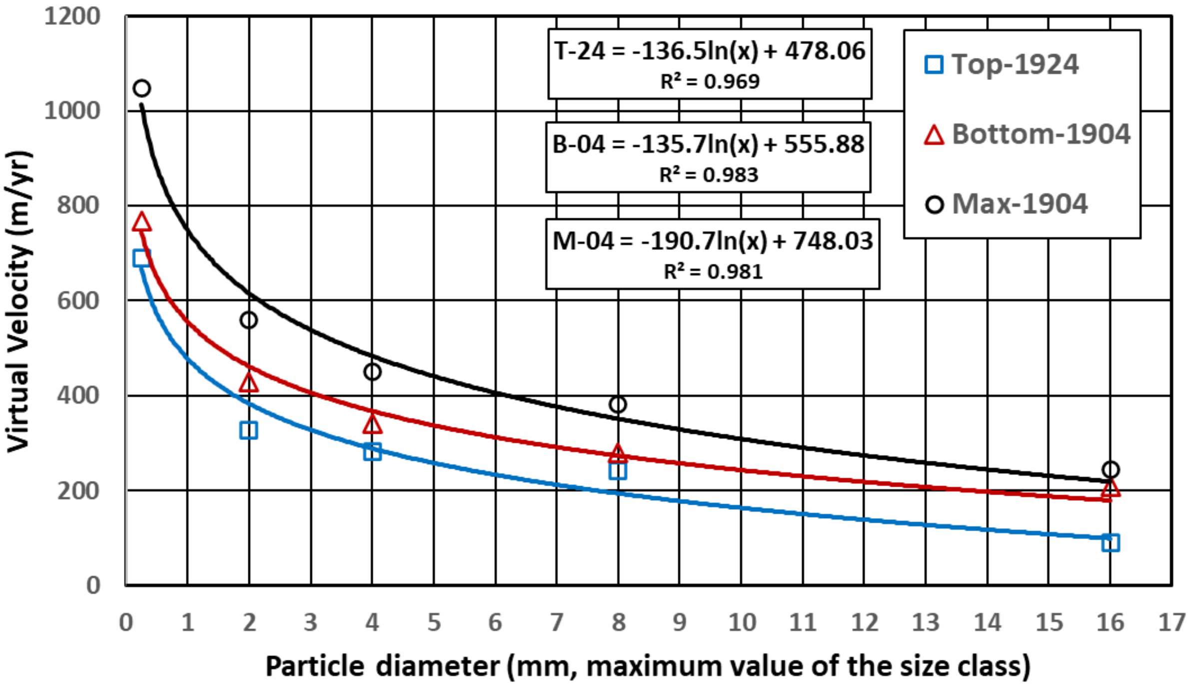

Figure 4. Virtual velocity-particle diameter relationships

Table 5. Comparison of virtual velocities for Ozarks streams

Gravel Size Class	Dia. mm	Pebble Count	Virtual Velocity (m/yr)	
			min	max
Predicted velocity using equations in Figure 5				
A) Big River, R-km 155-133 (n= 42 pebble counts)				
Fine	5.7-8	D16	233	406
Medium	11.3-16	D50	108	232
Coarse	22.6-32	D84	84	197
B) Ozark Rivers (n= 93 pebble counts)*				
Medium	11.3	D16	147	286
Coarse	22.6-32	D50	5	153
Very Coarse	45-64	D84	<1	22
Event-wieghted velocity from field measurements				
C) South Creek, Springfield Missouri (Tracer results)#				
Coarse	16-22.6	D50	202	306
Coarse	22.6-32	D75	152	170
Very Coarse	32-45	D84	87	108
Very Coarse	45-64	D90	39	45

* Panfil and Jacobson (2001) & Pavlowsky and Martin (2007)

\# Breckenridge (2020)

allowing less time for vertical mixing with bed material. Virtual velocity decreases with time after tracer release due to increased storage in channel deposits (Hassan and Bradley, 2017).

The results of this study may shed some light on the dynamics of bed waves and sediment pulses in Ozark rivers (Jacobson, 1995; Jacobson and Primm, 1997). Relationships developed by this study predict relatively low virtual velocities for the bed sediment sizes typically found in rivers draining the Ozark Highlands (Table 5B; Figure 4). For example, the velocities for the D50 (coarse gravel) range from 5-153 m/yr, while D16 velocities range up to a maximum of 286 m/yr, and D84 velocities are very low at <22 m/yr. A sediment wave model created for the Current River located about 50 km southwest of Big River yielded historical bed wave migration rates from 190 to 1,125 m/yr (Jacobson and Gran, 1999). If sediment waves migrate faster than sediment particle transport, then wave forms and their apparent migration rates may not be entirely linked to longitudinal sediment routing or virtual velocity. Indeed, lateral adjustments of channel erosion and deposition patterns due to local fluctuations in stream power and hydraulic turbulence may mimic or appear like longitudinally connected sediment pulses.

These findings further suggest that sediment transfer in Ozark streams may depend more on lateral and vertical storage interactions in regulating sediment fluxes rather than downstream dispersal rates. Indeed, gravel bar accumulations in Ozark streams have been linked to local factors such as bank supply of gravel (Panfil and Jacobson, 2001; Juracek and Perry, 2005), upstream tributary inputs (Panfil and Jacobson, 2001), and channel reach behavior (Martin and Pavlowsky, 2011). Gravel waves in the Ozarks may be discontinuous in longitudinal expression but may appear to be linked. Finally, tracking gravel bar migration at finer scales may better link virtual velocity rates to wave migration rates. For example, closer examination of gravel migration on Jacks Fork, a large tributary to the Current River, showed that bar centroids migrated downstream at 3-35 m/yr and sediment transfer between two riffles occurred at 16 m/yr (Martin, 2005). These bar migration rates closely coincide with the virtual velocity measurements produced by this study.

Conclusions

Virtual velocities were calculated from sediment samples using both a geochemical tracer (Ca) for finer bed sediments and grain counts for coarse tailings. Results are summarized as follows: 1-2 mm, 327-559 m/yr; 2-4 mm, 283-450 m/yr; 4-8 mm, 243-381 m/yr; and 8-16 mm, 91-245 m/yr (Table 3). The results of this study clearly indicate that selective transport by sediment size occurs in active bar sediments in Big River. Compared to medium gravel (8-16 mm), virtual velocities for very coarse sand (1-2 mm) are two-times greater for pulse front transport and three-times greater for the maximum transport distance by anomalous dispersion. Recall that average velocities for this study were calculated over an interval of about 100 years, so it is not known if transport rates have been uniform over time. It is possible that sediment velocities were higher early in the period of highest supply (Wilcock et al., 2009), have been gradually decreasing due to storage effects (Hassan and Bradley, 2017), or have been increasing recently due to climate change-related flooding (Heimann et al., 2018). Nevertheless, concerns about a geomorphic tailings wave migrating downstream and causing channel erosion and physical degradation of aquatic habitats are unsupported, since it will take 30-50 more years for the tailings pulse front to reach Mill Creek (R-km 115) assuming no additional storage effects that would further slow sediment velocities and reduce wave volume. However, coarse tailings may pose a long-term environmental risk to aquatic life in Big River, since they typically contain 3,000-5,000 ppm Pb mostly in association with finely disseminated galena grains (Jackson et al., 1935; Pavlowsky et al., 2017; Pace-Witt, 2022). Moreover, more research is needed to better understand how sediment particles, bar formation, and bed waves interact in an Ozark river.

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