Significant Human Modification of the Lower Arkansas River Sediment Budget

Hehe CHEN[1], John Shaw[1], Glenn Sharman[2], and Jill A. Marshall[2]

[1]University of Arkansas at Fayetteville
[2]University of Arkansas

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Abstract

Large river systems provide many services, including water resources, barge transport, and sand and gravel (S&G) for mining. However, unlike damming, the impacts of channel dredging and S&G mining are poorly monitored. We quantify these impacts on the Lower Arkansas River, U.S.A., where anthropogenic processes are well documented. The construction of dams caused a 98% reduction in suspended sediment discharge (Q_{ss}). Since dam construction, fluvially-transported Q_{ss} and suspended sand discharge (Q_{sand}) varied on the decadal scale, but the average of Q_{ss} (4.4 ± 0.5 Mtyr^{-1}) and Q_{sand} (1.1 ± 0.1 Mtyr^{-1}) at Van Buren are of the same order as sediment removal rates by dredging (1.2 ± 0.1 Mtyr^{-1}) and S&G mining (1.7 ± 0.1 Mtyr^{-1}). During 1975-2019, the cumulative sediment deficit caused by dredging and S&G mining (1.7 Mtyr^{-1}) outpaced the cumulative post-dam fluvial sediment deficit (0.7 Mtyr^{-1}), indicating sediment extractions are now essential parts of rivers' sediment balance.

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Significant Human Modification of the Lower Arkansas River Sediment Budget

Hehe Chen[1,2], John B. Shaw[1], Glenn R. Sharman[1], and Jill A. Marshall[1]

[1]Department of Geosciences, University of Arkansas, Fayetteville, AR, 72701, USA.

[2]School of Ocean Sciences, China University of Geosciences, Beijing, 100083, China.

Corresponding author: Hehe Chen (hehechen@uark.edu), John Shaw (shaw84@uark.edu)

Key Points:

- Navigation dredging and sand and gravel mining significantly contribute to the sediment discharge decline on the lower Arkansas River.
- Influenced by flood disturbance-recovery processes, sediment discharge fluctuated significantly on a multi-year timescale.
- Magnitude of engineering extraction is the same order as the magnitude of modern fluvial sediment transport in the Lower Arkansas River.

Abstract

Large river systems provide many services, including water resources, barge transport, and sand and gravel (S&G) for mining. However, unlike damming, the impacts of channel dredging and S&G mining are poorly monitored. We quantify these impacts on the Lower Arkansas River, U.S.A., where anthropogenic processes are well documented. The construction of dams caused a 98% reduction in suspended sediment discharge (Q_{ss}). Since dam construction, fluvially-transported Q_{ss} and suspended sand discharge (Q_{sand}) varied on the decadal scale, but the average of Q_{ss} (4.4 ± 0.5 $Mtyr^{-1}$) and Q_{sand} (1.1 ± 0.1 $Mtyr^{-1}$) at Van Buren are of the same order as sediment removal rates by dredging (1.2 ± 0.1 $Mtyr^{-1}$) and S&G mining (1.7 ± 0.1 $Mtyr^{-1}$). During 1975-2019, the cumulative sediment deficit caused by dredging and S&G mining (1.7 $Mtyr^{-1}$) outpaced the cumulative post-dam fluvial sediment deficit (0.7 $Mtyr^{-1}$), indicating sediment extractions are now essential parts of rivers' sediment balance.

Plain Language Summary

Large rivers provide many services to society. We dam rivers to manage agricultural irrigation, dredge rivers for barge transportation, mine sand and gravel for construction, etc. Damming has been proven significantly reduce the sediment flux in rivers and thus resulted in the shortage of sediments (mostly sands) in coastal zones, yet we know little about how channel dredging and sand and gravel mining contribute to the sediment flux reduction in rivers. The Lower Arkansas River in the U.S.A provides a good chance to quantify these impacts. Our analysis shows that the dams on the Lower Arkansas River reduced sediment flux in the river by 98%. While the sediment flux and sand flux in the Lower Arkansas River fluctuated on a decadal scale, the period averaged sediment flux and sand flux are of the same order as the sediment extraction rates by dredging and sand and gravel mining. Between Van Buren and Little Rock in the Lower Arkansas River, the cumulative sediment extraction by dredging and sand and gravel mining is greater than the post-dam sediment mass balance in this river reach, indicating sediment extractions by humans are now significantly influencing the sediment mass balance of rivers.

1 Introduction

Rivers connect zones of denudation, sediment transfer, temporary storage, and long-term deposition (e.g., Romans et al., 2016; Allen, 2017). River resources are also exploited by humans in many ways. Dams built to store and regulate water have reduced the global sediment flux to the world's coastal zone from ca. 14 $Btyr^{-1}$ to ca. 12.6 $Btyr^{-1}$ (e.g., Syvitski et al., 2005; Syvitski & Milliman, 2007), significantly affecting the sustainability of deltaic systems (e.g., Syvitski & Milliman, 2007; Tessler et al., 2015; Nienhuis et al., 2020). Barge transport on rivers is a low-cost and low-emission shipping mode used globally (Best, 2019). For example, barges accounted for the transport of ~184 Mt of raw materials on the Mississippi River in 2016 (e.g., Wetzstein et al., 2021). Dredging of navigation channels is needed on many rivers to mitigate sediment deposition to meet minimum navigation depths (e.g., USACE, 2005; Pinter & Heine, 2005; Cox et al., 2021). S&G mining is a large and growing global industry (e.g., Bendixen et al., 2019; Hackney et al., 2020), with a threefold increase in sand demand worldwide over the last two decades (UNEP 2019). Compared to studies documenting the influence of dams on sediment flux, the effects of dredging and S&G mining on sediment discharge have been less studied, resulting in poorly constrained estimates of their influences on rivers (e.g., Bendixen et al., 2019; Jordan, et al., 2019). With the demand for water, shipping, and sand likely to increase, an accurate assessment of their relative influences is vital for sustainable river management.

To improve understanding of the effects of dredging and S&G mining on sediment transport in a large, heavily modified river system, we conducted a mass balance analysis along the anthropogenically modified Lower Arkansas River (AR). In this paper, we compare the relative roles of fluvial sediment transport, damming and channel engineering, dredging, and S&G mining-altered sediment transport to document their influences on sediment mass balance in the Lower AR.

2 Background

As the second-longest tributary in the Mississippi River system, the AR has a mean annual water discharge of about 1170 m^3s^{-1} (Moody & Meade, 1992; Alexander et al., 2012; Figures 1 and S1). The McClellan-Kerr Arkansas River Navigation System (MKARNS) was constructed from 1957 to 1969 and extends from the Mississippi River upstream to Muskogee, OK, and then along the Verdigris River to the Port of Catoosa, OK (e.g., USACE, 2005; see Text S1 in the supporting information). The MKARNS consists of 18 locks and dams and hosts a barge transportation corridor that moves 8.5 Mt of goods annually, forming an essential transportation route for regional agriculture (e.g., Nachtmann and Oztanriseven, 2014; Nachtmann et al., 2015; Table S1). To ensure the efficiency of this corridor, maintenance dredging of MKARNS has been carried out by the U.S. Army Corps of Engineers (USACE) to maintain a minimum 9 feet (2.7 m) deep and 250 foot (75 m) wide navigation channel without mid-channel bars (e.g., USACE, 2005). The river also hosts a commercial S&G mining industry, supplying materials for end uses in construction, solar, hydraulic fracture, and other industries (e.g., USACE, 2005).

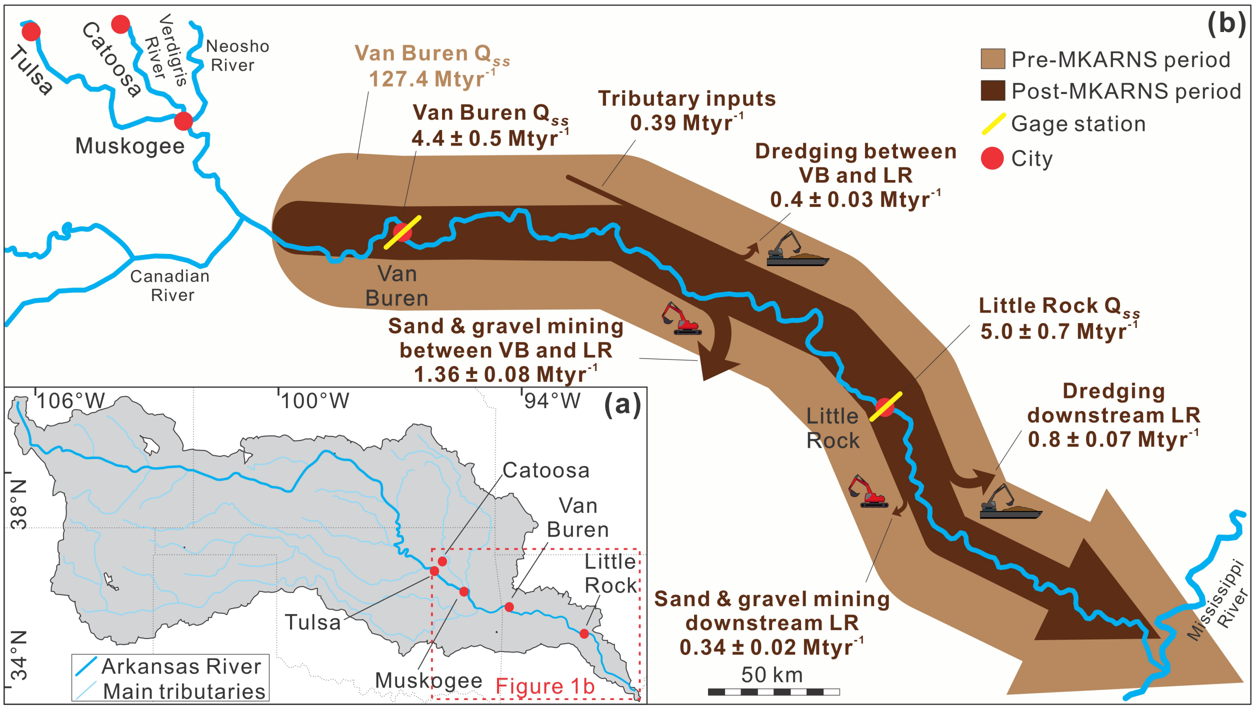

Figure 1. Location of the Arkansas River basin (a) and a sediment budget diagram in the pre- and post-MKARNS periods of the Lower Arkansas River (b) along with the location of streamflow gaging stations and cities. Note the pre-MKARNS sediment budget is not shown to scale.

3 Dataset and methods

We compiled suspended sediment concentration (1941 samples) and suspended sand concentration (913 samples) measurements, spanning 1945 to 2019, from eight U.S. Geological Survey (USGS) streamflow gaging stations on the AR (Figure 1; Data Set S1). We calculated sediment rating curves based on the available sediment concentration measurements in each gaging station and used water discharge measurements from the USACE to estimate sediment discharge due to data gaps in 1993, 1994, and 2013 (Figure S2; see Text S2 in the supporting information). The sediment data at Van Buren and Little Rock gages were used to estimate the sediment mass balance influenced by damming, dredging, and S&G mining in MKARNS reaches. The sediment data from Lee Creek, a tributary of the Lower AR, was used to estimate the sediment contribution from other tributaries in Ozark and Ouachita Mountains with the BQART method (Data Set S1). Although measurements on bedload transport are lacking, bedload flux is estimated to be small relative to suspended sand flux over long timescales (i.e., about 5% of the cumulative suspended sand load, Ashley et al., 2020), so is neglected here.

Volumes of dredged sediment (1007 records) were compiled from USACE records within the MKARNS downstream of Van Buren, AR between 1969 and 2019 (Figure 1; see Text S4 in the supporting information). We assumed a bulk density of 1.3 Mgm^{-3} for dredge spoils (e.g., Pinter et al., 2004). Dredge spoils are usually disposed behind wing-dikes and these spoils can potentially be eroded and re-enter the river channel. To quantify this transfer, we measured the areas of 117 wing-dike fields and the bars between Van Buren and the confluence of the Mississippi River in 1961, 1994, and 2017, to calculate the volume capacity and filling ratio of wing-dike fields (see Text S5 in the supporting information). The minimum dredging depth of MKARNS by the USACE is 9 feet (2.7 m) and wing-dike fields extend from the bank into the river, thus we assume an average thickness of bars of about 5 feet (1.5 m). USGS grab samples (303 samples) of the AR bed show mud fractions that are generally 0% and ranges up to 36%, with an average of about 1% (USACE, 2005). Hence, we estimate the mud fraction of dredge spoils as 1%, with the remainder being sand and gravel.

S&G mining data were compiled from mining companies along the Lower AR between 2011 and 2019, archived by the Arkansas Commissioner for State Lands (records before 2011 are no longer archived). Additionally, a longer record (1971 to 2018) of Arkansas statewide S&G mining data was compiled from the USGS National Minerals Information Center (Data Set S3). Between 2012 and 2018, the S&G mining contribution ratio from the Lower AR relative to statewide is averaged at 0.176 ± 0.019. To estimate the S&G mining rate from the Lower AR between 1971 and 2011, we assume this ratio remained constant (see Text S6 in the supporting information). S&G mining consisted mostly of sand and gravel and very little mud, and we assumed the mined sediments to be 100% sand and gravel.

The infrequent measure of sediment concentration each year hindered a yearly variation analysis of sediment discharge. We divided the sediment concentration, dredging, and S&G mining data into six intervals of roughly seven years each, based on a balance between period data density and the occurrence of big floods (e.g., Jacobson et al., 2009; Gibson and Shelley, 2020; Figure 2 and DR3). To calculate period-averaged Q_{ss} and Q_{sand}, sediment concentration measurements were binned and averaged by month, and then integrated over a year (see Text S3 in the supporting information). We defined fluvial sediment deficit as the sediment discharge at Little Rock and tributary inputs minus that at Van Buren, and the total sediment deficit includes fluvial and engineering sediment deficit (see Text S7 in the supporting information).

4 Results

In the MKARNS reach, the construction of dams and maintenance of navigation channels (1957-1969) reduced Q_{ss} at Van Buren substantially (Figure 2a). Compared to the Q_{ss}=127.4 Mtyr^{-1} at Van Buren in the pre-MKARNS period (1945-1951), the post-MKARNS period (1975-2019) was Q_{ss}= 4.4 ± 0.5 Mtyr^{-1}, a 97% decrease (Figure 1b and Table S2).

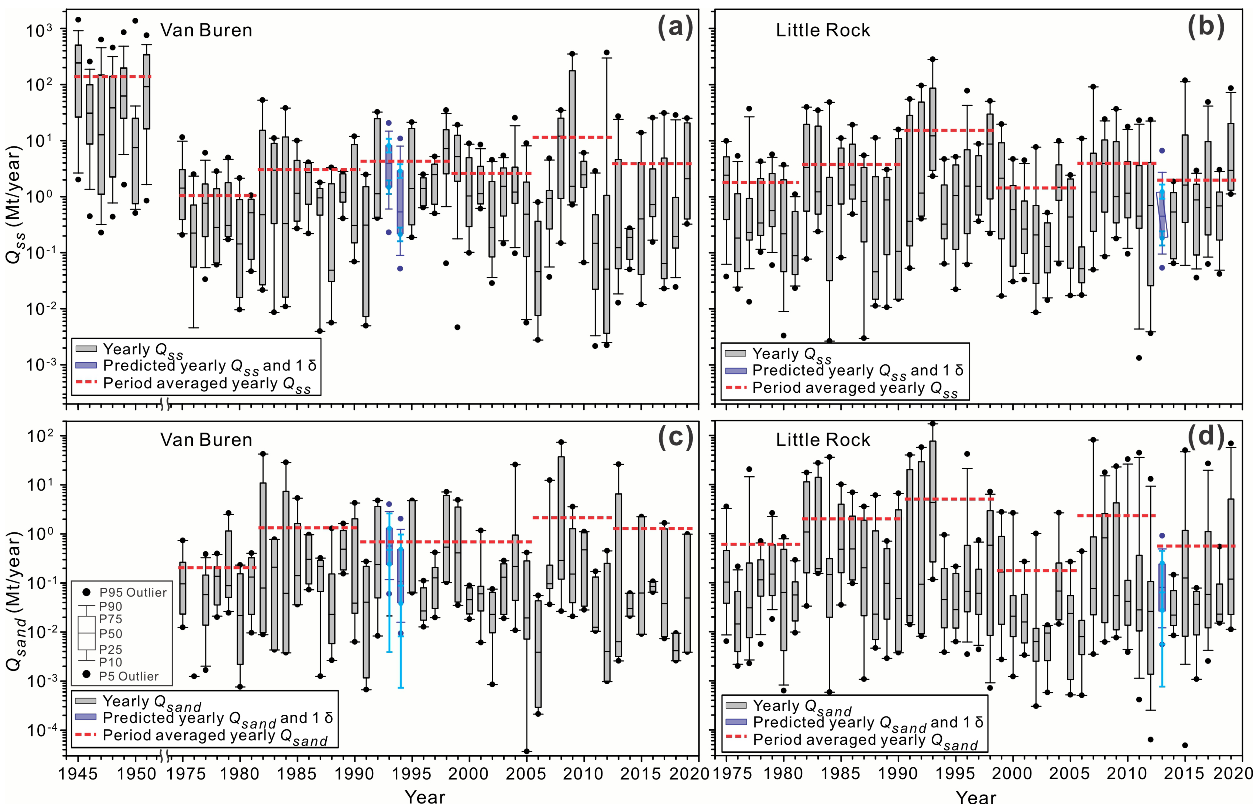

Figure 2. Annual distribution of yearly Q_{ss} (first row) and Q_{sand} (second row) at Van Buren and Little Rock in the Lower AR. Data gaps in 1993 and 1994 at Van Buren and in 2013 at Little Rock were estimated by sediment rating curves with 1 δ variation at P75 and P25 (blue lines). Red dashed lines showing period-averaged Q_{ss} and Q_{sand} values. The outliers points mark the first point outside the 5th/95th percentile. Note X-axis of Van Buren and Little Rock is different and there is a X-axis break in (a) and (c). See Text S2 in the supporting information for methods and data sources.

Post-MKARNS time series of Q_{ss} at Van Buren and Little Rock between 1975-2019 are similar: the former ranges from 1.0 to 11.4 Mtyr^{-1} with an average of 4.4 ± 0.5 Mtyr^{-1} and the latter ranges from 1.4 to 15.3 Mtyr^{-1} with an average of 5.0 ± 0.7 Mtyr^{-1} (Figure 2 and Table S2). Relatively higher and lower period-averaged Q_{ss} at both sites correlate well with flooding and post-flooding periods, respectively (Figure S3). The Q_{sand} variation is similar to the corresponding Q_{ss}, with Van Buren ranging from 0.2 to 2.1 Mtyr^{-1} with an average of 1.1 ± 0.1 Mtyr^{-1} and Little Rock ranging from 0.2 to 5.1 Mtyr^{-1} with an average of 2.0 ± 0.2 Mtyr^{-1} (Figure 2 and Table S2).

Period-averaged dredging rates between Van Buren and the Mississippi confluence varied from 0.3 Mtyr^{-1} to 2.5 Mtyr^{-1} (average of 1.2 ± 0.1 Mtyr^{-1}) and generally decreased through time (Figure 3a). Dredging between Van Buren and Little Rock accounts for about one-third of the total dredging rate (0.1 Mtyr^{-1} to 1.4 Mtyr^{-1}, an average of 0.4 ± 0.03 Mtyr^{-1}; Figure 3a), with the remainder between Little Rock and the Mississippi River (Figure 1b). Dredging quantity has no relationship with water discharge and sediment discharge in the Lower AR (Figure S4; see Text S4 in the supporting information). The accommodation of wing-dike fields is calculated at about 167 Mm^3 and the annual average wing-dike field filling ratio is about 0.63%, or 1.05 Mm^{3}yr^{-1} (Figure 3b). This scale of sediment accumulation behind wing dikes is slightly larger than the annual average dredging rate at 0.97 Mm^{3}yr^{-1} (Figure 3b). Thus wing-dikes can accommodate all dredging spoils (see Text S5 in the supporting information).

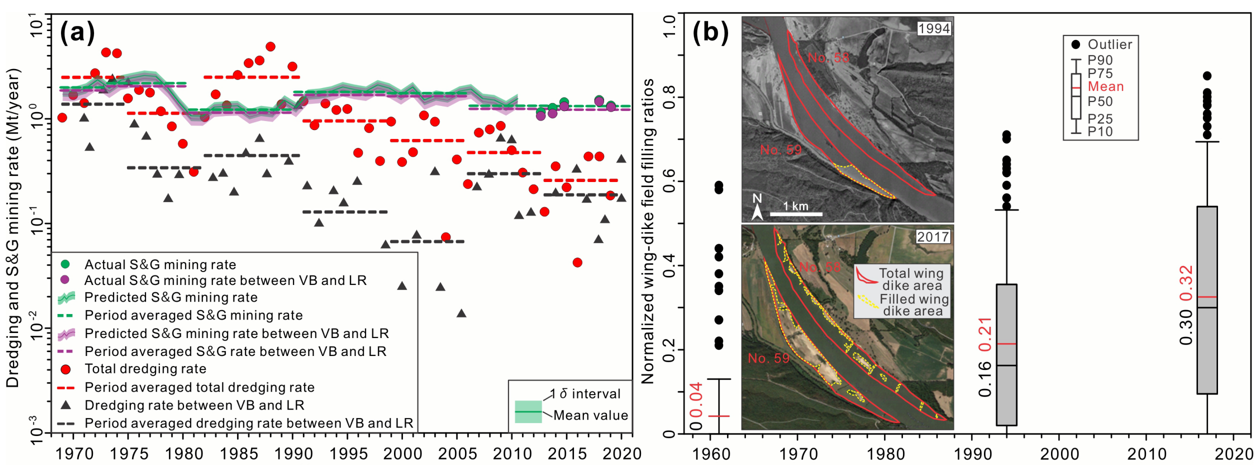

Figure 3. Rates of sediment removal in the Lower AR via dredging and S&G mining (a) and normalized wing-dike fields filling ratios in different years during the pre-MKARNS and Post-MKARNS periods and the sediment filling of No. 58 and No. 59 wing-dikes in 1994 and 2017 in the Lower AR (b). Volumes of

dredged sediment were compiled from USACE records. S&G mining data were compiled from mining companies along the Lower AR and the USGS National Minerals Information Center. The S&G mining predictions between Van Buren and Little Rock are just 80% of the predicted S&G mining rate along the Lower AR. Abbreviation: VB, Van Buren; LR, Little Rock. See Text S5 in the supporting information for methods and data sources.

Records of S&G mining show an increasing trend from 2011 to 2019, ranging from 1.2 $Mtyr^{-1}$ to 1.6 $Mtyr^{-1}$ with an average of 1.4 ± 0.1 $Mtyr^{-1}$ (Figure 3a). Estimates from 1971 to 2010 show a low period in the 1980s probably due to low demand, but a slightly decreasing trend overall, ranging from 1.1 ± 0.1 $Mtyr^{-1}$ to 2.6 ± 0.3 $Mtyr^{-1}$ with an average of 1.7 ± 0.1 $Mtyr^{-1}$ (Figure 3a). The Van Buren to Little Rock reaches account for about 80% of the sand and gravel mined along the Lower AR (Figure 3a).

The drainage basin area of Lee Creek is about 1200 km^2 and the total drainage basin area of the Ozark and Ouachita Mountains is about 20300 km^2 (see Lee Creek table in Data Set S1). Based on the BQART model (Syvitski & Milliman, 2007), we assumed the Q_{ss} is simply positive to the square root of the drainage basin area. Thus, sediment data from Lee Creek enables a first-order Q_{ss} estimation for all tributaries in Ozark and Ouachita Mountains at 0.39 $Mtyr^{-1}$ (Data Set S1). Reservoirs were built on these tributaries and we assume the Lower AR received negligible Q_{sand} from these tributaries.

5 Discussion and conclusions

5.1 Sediment supply vs. anthropogenic sediment extraction

While engineering projects clearly reduce downstream sediment supply, it is unclear to what extent dredging and S&G mining influence sediment transport in river systems. Dredging and S&G mining activity has only been well documented in a few places (i.e., the Mekong River) and estimated globally (e.g., UNEP 2019; Peduzzi, 2014; Hackney et al., 2020; Syvitski et al., 2022). Compared to the post-MKARNS average Q_{ss} of 4.4 ± 0.5 $Mtyr^{-1}$ at Van Buren, dredging and S&G mining rates accounted for 23%-31% and 34%-44% of this Q_{ss}, respectively (Figure 4a and Table S2). Compared to the post-MKARNS average Q_{sand} at Van Buren of 1.1 ± 0.1 $Mtyr^{-1}$, the dredging rate is 95%-121% and the S&G mining rate is 138%-172% of this Q_{sand}, respectively (Figure 4b and Table S2). These findings are consistent with an estimate of global Anthropocene sediment loads in 2010 that suggested S&G mining from river beds and coastlines

(2 Gt) and dredging (9.8 Gt) together were ~157% of fluvially transported sediments (7.5 Gt) (Syvitski et al., 2022). While sediment discharge to coastlines from rivers is decreasing due to dams (Syvistki et al., 2005; Dunn et al., 2019), results of this study suggest that navigation dredging and S&G mining may be significantly contributing to this decline.

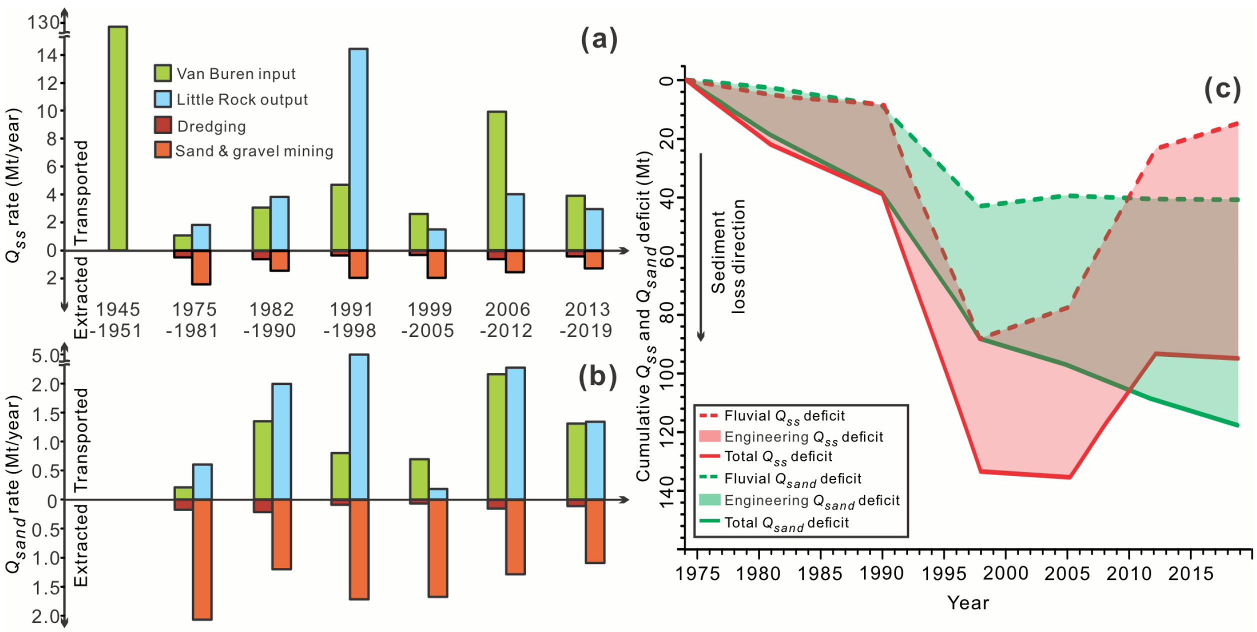

Figure 4. Comparison of fluvial transport and extraction rates for Q_{ss} (a), Q_{sand} (b), and cumulative Q_{ss} and Q_{sand} deficit (c) between Van Buren and Little Rock in the Lower AR. The positive numbers of cumulative Q_{ss} and Q_{sand} deficit in (c) indicate active sediment loss between Van Buren and Little Rock. Fluvial Q_{ss} and Q_{sand} deficits include the Lower AR input at Van Buren, tributary inputs, and AR output at Little Rock. Engineering Q_{ss} and Q_{sand} deficits include dredging and S&G mining extraction. Note the vertical distance between the fluvial Q_{ss} (Q_{sand}) deficit and total Q_{ss} (Q_{sand}) deficit in (c) represents the engineering Q_{ss} (Q_{sand}) deficit. Note the Q_{ss} rate of S&G mining in (a) equals its Q_{sand} in (b) and there is a Y-axis break in (a) and (b).

While the construction and maintenance of MKARNS and S&G mining significantly reduced sediment discharge in the Lower AR, we show that post-MKARNS sediment discharge fluctuated significantly on a multi-year timescale (Figure 2). In contrast, the USACE interpreted 1974-2004 Q_{ss} data as a sustained decreasing trend (Schmidgall, 1995; USACE, 2005). We suggest the fluctuating Q_{ss} corresponds well with flooding and post-flooding periods both at Van Buren and Little Rock (Figure 2 and DR3), indicating the fluctuation of Q_{ss} is mainly determined by flood disturbance-recovery processes (Gibson & Shelley, 2020).

5.2 Sediment mass balance within the Lower Arkansas River

Estimated rates of dredging and S&G mining extraction by humans were relatively consistent compared to the fluvial mass balance between Van Buren and Little Rock. The Lower AR exhibits significant mass fluctuations, even in its engineered state, with a 10.2 Mtyr^{-1} Q_{ss} loss between 1991-1998 and 7.8 Mtyr^{-1} gain between 2006-2012 (Figure 4a and Data Set S5), consistent with the stochastic nature of mass balances seen on other rivers (Pinter & Heine, 2005; Phillips & Van Dyke, 2016; Gibson & Shelley, 2020). By comparison, the human-induced sediment extraction rate is far more consistent and only varied between 1.3 Mtyr^{-1} to 2.4 Mtyr^{-1} (Figure 4a and Data Set S5). Over the past 45 years, this consistent sediment extraction rate has resulted in a comparable magnitude of engineering-related sediment deficit relative to fluvial sediment deficit, both for total suspended sediment (81.3 ± 0.5 Mt vs 11.7 ± 0.8 Mt) and sand (78.3 ± 0.5 Mt vs 40.9 ± 0.6 Mt) (Figure 4c and Data Set S5).

We conclude that humans have significantly altered the sediment budget of the Lower AR. While the significant reduction of Q_{ss} caused by damming was expected, we stress the importance of engineered navigation channels (both construction and maintenance) and S&G mining as the magnitude of dredging and S&G mining is of the same order of magnitude as the modern fluvial sediment transport in the Lower AR (Figure 4c). The need for increased barge transportation capacity has spurred proposals to deepen the MKARNS navigation channel from 2.7 to 3.7 m (9 to 12 feet), which would surely increase the amount of dredged sediments (USACE, 2005). Similarly, the rapidly growing demand for sand may further stress this system (e.g., Bendixen et al., 2019). These processes, deficits, and tradeoffs remain largely unquantified for the world's large rivers but maybe influence them at similar scales and magnitudes. Our work contributes to a growing body of literature suggesting that a multitude of human activities beyond damming are influencing large modern rivers.

Acknowledgments

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Data Availability Statement

Sediment data were compiled from the U.S. Geological Survey (USGS) National Water Information System (NWIS) which is accessible at https://maps.waterdata.usgs.gov. Navigation channel dredging data were compiled from the U.S. Army Corps of Engineers (USACE). Sand and gravel mining data were compiled from mining industries along the Lower Arkansas River and the USGS National Minerals Information Center (NMIC) which is accessible at https://www.usgs.gov/centers/nmic/state-minerals-statistics-and-information. Wing-dike fields and bar areas data are measured based on the historical aerial imagery compiled from the U.S. Department of Agriculture, Salt Lake City.

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