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NUTRIENT CONTRIBUTIONS FROM ALLUVIAL SOILS ASSOCIATED WITH THE RESTORATION OF SHALLOW WATER HABITAT IN THE LOWER MISSOURI RIVER

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ABSTRACT

The Missouri River has been extensively altered as the result of channelization, bank stabilization, and the construction of six main stem reservoirs. In response to the resultant habitat loss, the US Army Corps of Engineers was tasked with restoring approximately 8100 ha of shallow water habitat (SWH), in part, for the benefit of the endangered pallid sturgeon (*Scaphirhynchus albus*). Construction of off-channel habitats involves the removal and disposal of excavated alluvium either by direct discharge into the river or by secondary erosion, which raised concerns regarding the introduction of sediment and associated nutrients into the Missouri River.

Soils from nine side-channel chutes were sampled to represent nutrient concentrations from habitat restoration activities. Soils from 12 historically undisturbed sites were also sampled to represent reference conditions in the Missouri River flood plain. The results of this study indicate that nutrient characteristics of soils from selected SWH locations generally are similar to those of historically undisturbed soils. The estimated mass of total phosphorus from chutes accounted for 1.9% of Missouri River and 0.5% of Mississippi River total phosphorus loads during the 1993–2012 analysis period. The mass of nitrate, the constituent most closely related to gulf hypoxia, was 0.01% or less of the Missouri and Mississippi River nitrate loads. Sediment volumes from the chutes accounted for 3.1 and 1.5% of total suspended loads from the Missouri and Mississippi Rivers. Overall, the introduced sediment from side-channel chute construction associated with SWH restoration accounts for a small portion of total nutrient and sediment transport in the Missouri and Mississippi Rivers. Published 2014. This article is a U.S. Government work and is in the public domain in the USA. *River Research and Applications* published by John Wiley & Sons, Ltd.

KEY WORDS: shallow water habitat; side-channel chutes; Missouri River; river restoration; alluvial soils

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INTRODUCTION

The management and operation of lotic systems for societal and economic benefit have led to extensive flow and channel modifications, the creation of dams and impoundments, and subsequent changes in flood plain habitat availability, quality, and connectivity of large rivers (Gore and Petts, 1989; Gore and Shields, 1995; Ward and Stanford, 1995; Gleick, 2003). The Missouri River is an example of an extensively altered large-river system, engineered for the purposes of flood control, hydropower generation, water supply, recreation, and commercial navigation. These alterations were primarily the result of the US Army Corps of Engineers (USACE) Bank Stabilization and Navigation Project (BSNP) and the construction of six main stem reservoirs (US Army Corps of Engineers, 2006).

The Missouri River's transformation from a free-flowing, dynamic system to the regulated and channelized system it is today has resulted in large reductions in sediment transport and the loss of approximately 211 000 ha of riverine and flood plain habitat (Hesse *et al*., 1989; Hesse and Sheets, 1993; US Fish and Wildlife Service, 2000, 2003; Jacobson *et al*., 2009; National Research Council (NRC), 2011). The loss of habitat and habitat diversity has led to the decline of several native fish and wildlife species, which, in part, prompted the US Fish and Wildlife Service (USFWS) to list the pallid sturgeon (*Scaphirhynchus albus*) under the federal Endangered Species Act (US Army Corps of Engineers, 1981; National Research Council (NRC), 2011). In response to the USACE's continued operation of the Missouri River system, the USFWS issued a biological opinion in 2000 and an amendment in 2003 (collectively referred to as the BIOP) (US Fish and Wildlife Service, 2000, 2003). The BIOP requires the restoration of approximately 8093 ha, 7.5 ha km^{-1} from Sioux City, Iowa to St. Louis, Missouri, of shallow water habitat (SWH; <1.5-m water depth, <1-m s^{-1} velocity, during August). SWH is an ecological feature that was lost because of the BSNP activities, 1912–1981, and includes side channels, backwaters,

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depositional sandbars detached from the bank, and low-lying depositional areas adjacent to the shoreline.

The USACE began restoring SWH on the lower Missouri River in the mid-1990s by modifying existing river control structures and constructing off-channel habitats, such as chutes and backwaters. Chute construction requires the removal and disposal of dredged or excavated river alluvium, which can often exceed 500 000 t per project (US Army Corps of Engineers, 2012). Excavated material is usually disposed of by direct discharge into the river or side cast along the bank of the pilot channel whereby the river will eventually capture the material through bank erosion (Jacobson *et al.*, 2009). Chute construction consists of excavating a narrow pilot channel and allowing natural erosion of the bed and banks via river flows to increase chute size and develop sinuosity with a diversity of velocities and depths.

Concerns regarding the introduction of nutrients, specifically N and P, into the Missouri River and downstream receiving water bodies such as the Gulf of Mexico have become a national issue. Evidence indicates that N loading, primarily in the form of NO_3, is most directly correlated with the increase in Gulf Hypoxia (Rabalais *et al.*, 2002; Donner *et al.*, 2002), but P also may be a seasonal or regional limiting nutrient to Gulf phytoplankton productivity (Sylvan *et al.*, 2006).

The Missouri River has long played an integral role in the conveyance of sediment from interior uplands to the Gulf of Mexico, and the post-impoundment river is considered as a sediment supply-limited system (Meade and Moody, 2010). The loss of Louisiana coastal wetlands has been attributed, in part, to the reduced sediment load from the Mississippi and Missouri River Basins (Kesel, 1989; Kim *et al.*, 2009). Sediment reintroduction into the Missouri River system, the primary supplier of sediment to the Mississippi River, has been suggested (Mississippi River Delta Science and Engineering Special Team, 2012) to restore the 70–90% decline in suspended-sediment loads in the Missouri River following reservoir construction (Heimann *et al.*, 2011). As river management, land use, and trends in sediment and nutrient concentrations continue to change, it is necessary to evaluate the potential water quality effects that discharging sediment to the river has at local and regional scales (National Research Council (NRC), 2011).

An evaluation by the NRC of USACE restoration and sediment management actions within the Missouri River Basin highlighted the lack of available information regarding historical concentrations of N and P in the Missouri River and alluvial sediments. The NRC suggested that ‘development of numeric criteria for sediment and nutrients be based on further understanding of the sediment and phosphorus history of the river’ (National Research Council (NRC), 2011). Therefore, a study was conducted to estimate nutrient concentrations in reference (historically undisturbed) and SWH locations to aid in evaluating potential effects of the reintroduction of alluvial sediments during habitat restoration activities. The objectives were to determine if differences in nutrient concentrations exist between reference alluvial sediments and alluvial sediments reintroduced during SWH restoration efforts and estimate potential sediment and nutrient contributions from SWH restoration activities.

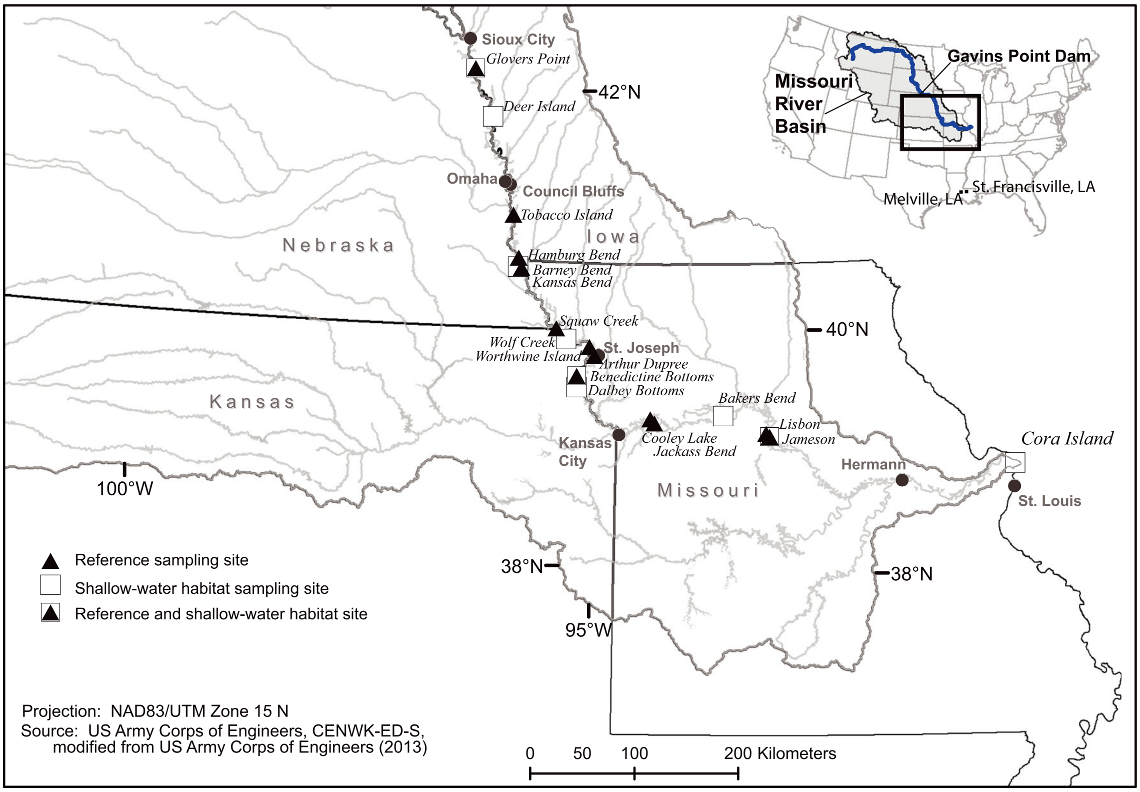
METHODS

Description of study area

The study area is the lower Missouri River from river kilometre (RKM) 1147 near Sioux City, Iowa to RKM 8 in St. Louis, Missouri (Figure 1). The lower Missouri River is defined as the free-flowing section downstream of Gavins Point Dam at RKM 1305 to the confluence with the Mississippi River. The Missouri River has a drainage area of nearly 1 371 000 km^2, of which approximately 770 000 km^2 (56%) drains the area downstream of the Gavins Point Dam. The lower Missouri River valley can generally be described as an alluvium filled trench underlain by limestone, dolomite, shale and sandstone in the upper reaches with harder, more resistant sedimentary rocks dominated by limestone and dolomite in the lower reaches (Spooner, 2001). The alluvium thickness ranges from 18 to 37 m and consists of highly permeable basal glacial outwash (sand, gravel, and boulders) overlain by post-glacial sand and gravel, which, in turn, are overlain by post-glacial interbedded sand, silt, and clay (Schmudde, 1963; Jacobson *et al.*, 1999; Spooner, 2001). A central characteristic of the pre-regulated Missouri River was the migration of its channel meanders that resulted in a continuous reworking of its flood plain deposits (Interagency Floodplain Management Review Committee, 1994). Bank stabilization has restricted further movement of the channel and minimized any chance of progressive shifts of the thalweg or avulsion of the channel, although the creation of side-channel chutes has been observed to occur in rare cases during extreme high water events (Jacobson *et al.*, 1999) if left unrepaired by the BSNP.

Site selection

Shallow water habitat site selection. Alluvial soils at SWH locations generally were accreted as a result of the BSNP with a history that may have included agricultural land use. Soil samples from these sites were compared with soils at reference sites in the flood plain that represented non-accreted (in existence prior to BSNP) and non-agricultural conditions. Of the 42 SWH projects to date (2012), including 20 side-channel chute projects, backwaters, and bank notch and revetment chutes, 9 side-channel chute sites were selected for soil sampling to represent current and future SWH creation activities (Table I, Figure 1). This study was limited in focus to side-channel chutes because the disposal of sediment during and after construction originated from the flood plain



Projection: NAD83/UTM Zone 15 N
Source: US Army Corps of Engineers, CENWK-ED-S, modified from US Army Corps of Engineers (2013)

Figure 1. Location of reference and shallow-water habitat sampling sites.

that is not currently subject to natural erosion because of existing river training structures and because side-channel chutes currently comprise the majority of sediment disposal projects on the Missouri River. Sediment from bank notches and revetment chutes will erode from the flood plain but in smaller volumes compared with side-channel chutes. Dike notches comprise the majority of constructed SWH acres accounted for in the lower Missouri River (Jalili and Pridal, 2010); however, the volume of sediment eroded from the flood plain is small compared with chutes and instead comes from a reworking of the current river channel bed through a change in hydraulic conditions near the dike structures. The type of habitat restoration chosen at each site is dependent on the habitat already present, the amount of land available, adjacent infrastructure, the local hydrology, the location along the river corridor, and the desired physical and subsequent biological response.

Reference site selection. Twelve reference sites were selected to represent historical conditions in the Missouri River flood plain (Table I, Figure 1). Reference sites were selected from the same soil series (Natural Resources Conservation Service, 2012b) identified at SWH sampling sites. Because reference sites did not have delineated alignments for sampling, the same sampling density and spacing used at SWH sites were applied to the reference sampling sites. Locating areas that represent natural, background concentrations of nutrient concentrations is difficult because most areas of the current and historical Missouri River flood plain have had anthropogenic impacts, including an engineered river channel that accreted stable river bottom land that was historically non-existent. Therefore, reference sites were located in areas that were the least impacted by human activity.

Three factors hypothesized to have the largest impact on nutrient concentrations in flood plain soils were the following: (i) alluvial sediments deposited during flooding; (ii) agricultural chemicals applied during farming; and (iii) biological activity in the topsoil. Unless large levees were present, nearly all sites in the Missouri River flood plain have been inundated by flooding, at least during the 1993 flood, making them subject to alluvial sediment deposition. Accordingly, least impacted areas would appear to be non-accreted lands (referring to accretion as a result of the USACE BSNP construction) that have never been in agricultural production.

Landforms that existed before the BSNP were identified by overlaying historic Missouri River channel maps from 1879 to 1894 and comparing those to contemporary Missouri River channel maps that were post-BSNP. Five layers of land

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Table I. Characteristics of reference and shallow-water habitat, side-channel chute sampling sites

Site name	Chute construction status	Sampling dates	Sample size
	Reference sites		
Jameson Island Unit, Big Muddy Wildlife Area	NA	15/2/2012	13
Lisbon Bottoms Unit, Big Muddy Wildlife Area	NA	21/2/2012	3
Jackass Bend Unit, Big Muddy Wildlife Area	NA	22/2/2012	3
Cooley Lake Conservation Area	NA	30/11/2011	3
Benedictine Bottoms Wildlife Area	NA	7/11/2011	9
Arthur Dupree Conservation Area	NA	12/3/2012	5
Worthwine Island Conservation Area	NA	5/3/2012	9
Squaw Creek National Wildlife Refuge	NA	16/2/2012	4
Kansas Bend Mitigation Site	NA	21/11/2011	7
Hamburg Bend Wildlife Area	NA	30/1/2012	8
Tobacco Island Mitigation Site	NA	1/2/2012	5
Glovers Point Bend Mitigation Site	NA	1/7/2009	1
			70
	SWH side-channel chute sites		
Cora Island Unit, Big Muddy Wildlife Refuge	Proposed	4/4/2012	25
Jameson Island Unit, Big Muddy Wildlife Refuge	Completed	19/11/2007, 16/4/2011	13
Baker's Bend Mitigation Site	Proposed	23/4/2012	9
Dalbey Bottoms Mitigation Site	Completed	19/4/2009	18
Benedictine Bottoms Wildlife Area	Proposed	11/11/2011	12
Wolf Creek Bend Conservation Area	Proposed	25/4/2012	13
Barney Bend Mitigation Site	Proposed	1/3/2011	7
Deer Island State Game Management Area	Under construction	14/4/2010	3
Glovers Point Bend Mitigation Site	Completed	1/7/2009	1
			101

classifications were identified and used in this analysis: undisturbed grasslands, undisturbed forests, 1879 channel, and 1894 channel, with the remaining area representing either the current active channel or accreted land as a result of the BSNP. Undisturbed forest locations were derived by intersecting georeferenced maps of Major Suter's chart of the Missouri River from 1879 (Wellman, 1879) and maps compiled by the Missouri River Commission in 1892–1894 (Missouri River Commission, 1895) to an existing vegetation cover derived from the Landscape Fire and Resource Management Planning Tools (LANDFIRE) data set (LANDFIRE, 2012). Forested areas were identified as cottonwood, forested, oak, and willow, or their combinations, which were then combined together into one land cover representing forested areas in 1879 and 1894. Undisturbed grassland areas were identified from the biophysical settings (BpSs) derived from the LANDFIRE data sets. The BpS data layer represents vegetation that may have been dominant on the landscape prior to Euro-American settlement and is based on both the current biophysical environment and an approximation of the historical disturbance regime.

Soil sampling

Flood plain sediment cores at SWH and reference sites were collected with a Geoprobe® Macro-Core® sampler at approximately 300-m intervals (sample size in Table I). Cores at SWH sites were oriented and collected along the proposed chute excavation alignments, whereas cores at reference sites were oriented along the primary length axis of the defined area. Borings were advanced to the depth of the saturated zone or a maximum of 6 m. Each soil boring was homogenized for nutrient analysis, and discrete samples at 1-m intervals were also collected at 10% of sites to assess the changes in nutrient concentrations with soil depth.

Field duplicates (additional sample within 1 m of original boring) or replicates (splits) were collected at 10% of sites. Nutrient concentrations in field duplicates were on average within 20%, whereas nutrient concentrations in field sample splits were within 6%.

Laboratory analyses

The soil borings from each sample location were homogenized and analysed for total phosphorus (TP) and total Kjeldahl nitrogen using US Environmental Protection Agency (USEPA) Methods 365.1 and 351.1 respectively (US Environmental Protection Agency, 2012). Total orthophosphorus (TRP) and nitrate + nitrite nitrogen (NO_3) were analysed using USEPA Methods 365.3 and 353.1 respectively following a 1-hr aqueous extraction from the soil. Ammonia (NH_3) was analysed according to USEPA

Method 350.1 following a sulphuric acid extraction from the soil. Total organic carbon was analysed using USEPA Method 9060A. Soil particle size was determined using the American Society for Testing and Materials method D422 sieve and hydrometer analysis (ASTM Standard D422, 2007). Multiple laboratories were used in the analysis of SWH site soil samples through time and included Mitkem Corporation in Warwick, Rhode Island, Katahdin Analytical Laboratory in Scarborough, Maine, Test America Laboratory in Nashville, Tennessee, and Applied Research and Development Laboratory (ARDL), Inc. in Mt Vernon, Illinois. The stated analysis methods were consistent among laboratories. All reference site samples were analysed by ARDL, Inc.

Data analyses

Differences between distributions of all soil constituents at SWH and reference sites were assessed with the Wilcoxon signed-rank test using Spotfire S+ software (TIBCO Software Inc., version 8.1). All statistical tests were assessed using a significance level (α) of 0.05.

Annual suspended-sediment loads for the Missouri River at Hermann, Missouri, Mississippi River at St Francisville, Louisiana, and Atchafalaya River at Melville, Louisiana, were obtained from the US Geological Survey (USGS) National Water Information System database (US Geological Survey, 2013a), whereas 1993–2012 NO_3, TN, TRP, and TP loads for these stations were obtained from US Geological Survey (2013b).

Potential nutrient contributions from all SWH chute restoration activities were estimated using the averaged nutrient concentrations from sampled side-channel chute projects. Volumetric estimates of reintroduced sediment from each site were based on documented constructed dimensions (Chance Bitner, USACE, written communication, 2012), design specifications, and an assumed 5-year erosion period to attain target conditions. The reintroduced volume of chute material was converted to a mass using a site-specific bulk density estimated with the Soil Water Characteristics Program (Natural Resources Conservation Service, 2012a) and measured soil texture and estimated organic matter content (Table II; Nelson and Sommers, 1996). The computed mass of chute sediment was multiplied by the average nutrient concentrations in the homogenized cores from the sampled sites to determine the mass of reintroduced nutrients. The average concentration of all sampled SWH sites was used to estimate the reintroduced nutrient mass from unsampled sites. Any in-river disposal of sediment during the construction of the side-channel chutes was accounted for in the year of construction. Side-cast material and the volume of chute material representing the difference between the constructed pilot channel and the final design channel were allocated over a period of 5 years.

Three chutes—Worthwine Island, Jameson Island, and Overton Bottoms (42 RKM downstream from Jameson Island)—had bathymetric survey information available during some or all of the post-construction period. Sediment reintroduction at these sites was allocated based on the survey data rather than averaged over a 5-year period. Bathymetric surveys were performed by the Kansas City District USACE using an Odom© single-beam echosounder (accuracy 3 cm) from a small boat. Data were collected and processed with HYPACK© software (HYPACK, Inc, 2011). Horizontal sounding coordinates were referenced to the North American Datum of 1983 and elevations to the North American Vertical Datum of 1988. Digital elevation models (DEMs) were created from the bathymetric survey data using Environmental Systems and Research Institute (ESRI) software (ESRI, 2012). Surveys were compared using the Geomorphic Change Detection (GCD) software (Wheaton *et al*., 2010. GCD calculates volumetric change in storage from the difference in surface elevations from DEMs derived from repeat topographic surveys. The Worthwine Island chute (constructed in 2006) had three surveys completed from 2010 through 2012, Jameson Island (constructed in 2007) had six surveys between 2010 and 2012, and Overton Bottoms had six surveys beginning from construction in 2003 through 2012. National Agriculture Imagery Program aerial orthophotographs (US Department of Agriculture (USDA), Farm Service Agency, 2012) and ESRI software were used to determine the horizontal channel area and channel lengths for several different years at each of the three surveyed chutes. The average top width was estimated as the total chute surface area divided by the channel length.

RESULTS

Nutrient and physical characteristics of side-channel chute and reference soils

Nutrient concentrations ($p = 0.12–0.74$) and soil particle sizes ($p = 0.23–0.63$) were not statistically different between SWH and reference soils with the exception of TRP concentrations (Table II). The median TRP concentration was significantly ($p < 0.01$) greater in reference soils (3.1 mg kg^{-1}) compared with that of SWH soils (1.8 mg kg^{-1}; Table II). With the exception of TRP, the range in soil nutrient concentrations was greater in SWH soils compared with reference sites. Amongst soil particle size classes, sand had the greatest overall range (0.3–91.7%) and greatest variability (standard deviation, 21.5%).

A comparison of nutrients from discrete depths in soil cores from SWH and reference sites indicates that the distribution of the N and P constituents were similar with depth between site types. All nutrient constituent concentrations tended to decrease with soil depth and in a consistent manner between

Table II. Summary of selected nutrient and physicochemical characteristics in soil samples from reference and shallow water habitat sites

	NH_3 mg kg^{-1} as N	NO_3 mg kg^{-1} as N	TKN mg kg^{-1} as N	Total N mg kg^{-1} as N	TRP mg kg^{-1} as P	Total P mg kg^{-1} as P (%)	Total organic carbon mg kg^{-1} (%)	Organic matter[a] per cent	pH	Sand per cent	Silt per cent	Clay per cent
					Reference sites							
Range	1.0–49.5	0.1–23.1	85.6–1430	97.1–1442	0.74–12.4	331–500 (0.03–0.05)	—	—	—	0.3–91.7	4.3–80.1	1.6–58.4
Mean	9.22	7.88	531	539	3.62	413	—	—	—	20.1	57.0	22.5
Median	7.10	7.80	473	478	3.10	414	—	—	—	12.2	59.5	20.8
Standard deviation	8.37	5.92	287	286	2.33	42.5	—	—	—	20.7	15.7	12.0
Sample size	70	70	70	65	69	70	—	—	—	62	62	62
					Shallow-water habitat sites							
Range	1.3–110	0.55–37.7	79–1460	86.7–1465	0.29–6.51	267–642 (0.03–0.06)	910–12 400 (0.09–1.2)	0.16–2.13	7.6–8.4[b]	1.3–88.5	7.0–86.3	1.6–44.0
Mean	13.5	6.82	619	607	2.21	421	5059	0.87	—	21.5	58.4	19.2
Median	7.10	6.00	577	560	1.80	408	4650	0.81	—	11.9	61.2	18.6
Standard deviation	16.8	4.71	340	333	1.40	78.7	2517	0.43	—	21.5	15.9	9.71
Sample size	83	101	101	96	97	101	66	66	14[b]	50	50	50
Wilcoxon rank sum test *p*-value	0.43	0.26	0.12	0.22	**<0.01**	0.74	—	—	—	0.63	0.61	0.23

Values in bold indicate that there is a statistically significant difference ($p<0.05$) between the constituent in samples from reference and shallow-water habitat sites.

[a] % Organic matter = % total organic carbon * 1.724 (Nelson and Sommers, 1996).

[b] Results include five measured pH values with a range of 7.7–8.4 and supplemental data at side-channel chute locations from NRCS (2012) for a total estimated range of 7.6–8.4.

site types (Figure 2). Available particle-size data for reference sites indicated that silt and clay content decreased substantially with soil depth, and these soils were composed mostly of sand below a depth of approximately 4 m.

Estimated delivery of sediment and nutrients from SWH restoration

Recent (2003–2012) volume and width changes at three constructed side-channel chutes, Worthwine Island, Jameson Island, and Overton Bottoms, were documented during bathymetric surveys and analyses of aerial photographs (Figure 3). Temporal volume changes included some estimated periods (using an estimated 5-year erosional rate) at Worthwine Island and Jameson Island chutes, whereas the Overton Bottoms chute had a complete survey record since construction. None of the three chutes have attained the target width (width at which the installed flow control structures are fully operational) of 122 m within 5–8 years of construction, although the Jameson Island chute was approaching this width after 5 years and had the largest measured volume change during this period. Geographic information system (GIS) analyses of the chute surveys indicated that volume changes were dominated by erosional changes, but periods of aggradation were also present (Overton Bottoms chute, Figure 3). Although bathymetric surveys and available aerial photographs were not timed to fully assess the direct effects of high flows on chute geomorphology, the correlation of volume and width changes with periods that included flooding indicates that these events are a likely causative factor for change.

Adequate survey data are either not available or have not yet been processed to the necessary detail at all side-channel chutes in order to quantify cumulative volumetric changes and corresponding estimates of sediment delivery from these features. Volumetric contributions from the remaining 17 non-surveyed, side-channel chute projects were, therefore, estimated based on constructed and design specifications. The introduced volume of chute material was converted to a mass using a site-specific bulk density (range of 1.45–1.57 g cm^{-3}). The mean bulk density estimate of all sampled SWH sites (1.50 g cm^{-3}) was used if no site-specific data were available.

The estimated masses of sediment, NO$_3$, TN, TP, and TRP from side-channel chutes were determined for 1993–2012 along with the transported masses of these constituents from the Missouri and Mississippi Rivers (Table III). Utilizing these analyses and assumptions, the 35.9 million t of cumulative sediment from the side-channel chutes during 1993–2012 was estimated to account for 3.1% of the Missouri River suspended-sediment transport during this same period and 1.5% of the cumulative suspended-sediment transport from the combined Mississippi and Atchafalaya River Basins. Such comparisons are not meant to imply that all sediments and nutrients transported from the chutes will pass the outlet station in a continuous manner because in-stream processes such as species transformation and deposition can occur.

The side-channel chutes potentially contribute a greater portion of Missouri and Mississippi River TP loads during the 1993–2012 analysis period compared with other sampled nutrient species (Table III). The mass of TP from chutes (14 500 t)

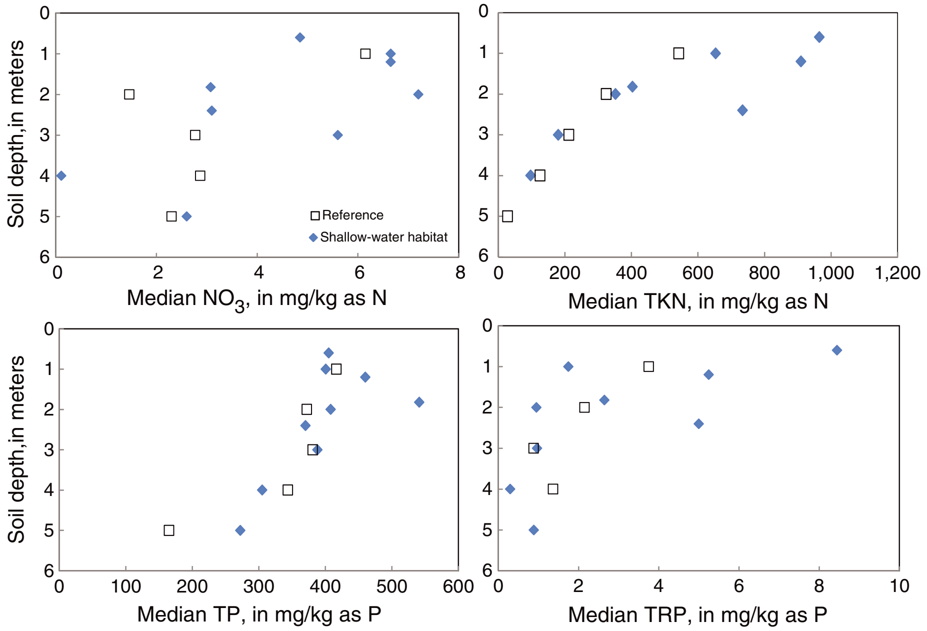

Figure 2. Nutrient concentration change with soil depth at reference and shallow-water habitat sampling sites.

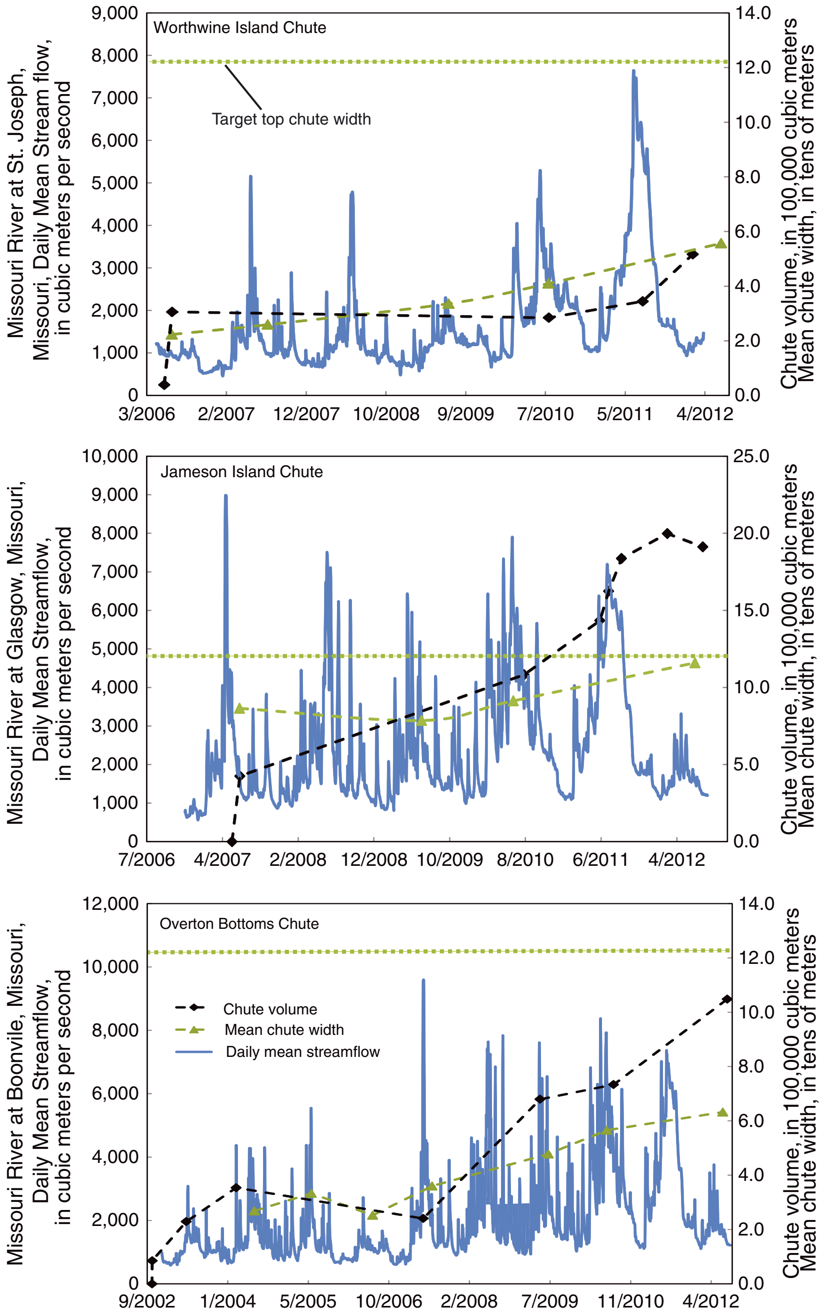

Figure 3. Temporal change in chute volume, chute width, and streamflow at Worthwine Island, Jameson Island, and Overton Bottoms side-channel chutes. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

accounted for 1.9% of cumulative Missouri River loads and 0.5% of Mississippi-Atchafalaya River loads. Chute material accounted for less than 0.5% of cumulative TN and TRP loads for the Missouri River and less than 0.08% of the cumulative loads of these constituents from the Mississippi–Atchafalaya Rivers. The mass of NO_3 in chute material (235 t) accounted for 0.01% or less of the 1993–2012 Missouri and Mississippi–Atchafalaya River loads.

DISCUSSION

Chemical and physical characteristics of side channel-chute and reference soils

Despite differences in land-use history, the SWH sites—soils accreted during the BSNP and associated with agricultural land use—and historically undisturbed reference site soils had nutrient and textural characteristics that generally

Table III. Summary of cumulative mass of selected constituents from side-channel chutes compared with observed loads of the Missouri River at Hermann, Missouri, Mississippi River at St Francisville, Louisiana, and Atchafalaya River at Melville, Louisiana

	Sediment	NO_3	Total N	TRP	Total P
Side-channel chutes					
Cumulative 1993–2012 reintroduced mass using 5-year erosion period, in metric tons	35 900 000	235	22 000	80.1	14 500
Missouri River at Hermann, Missouri					
Cumulative 1993–2012 load, in metric tons	1 160 000 000[a]	2 800 000	4 960 000	159 000	760 000
Ratio of side-channel chute load (5-year erosion rate) to Missouri River load, in %	3.1%[a]	0.01%	0.45%	0.05%	1.9%
Total Mississippi–Atchafalaya River Basin					
Cumulative 1993–2011 load, in metric tons	2 410 000 000[a]	17 900 000	26 000 000	847 000	2 820 000
Ratio of side-channel chute load (5-year erosion rate) to total Mississippi River load, in %	1.5%[a]	<0.01%	0.08%	0.01%	0.50%

[a] Sediment values for the Missouri River and Mississippi–Atchafalaya Rivers are suspended material only.

were similar. These similarities were evident in both composited cores and in discrete depth samples. The exception to this was higher TRP concentrations in reference soil composite core samples in comparison with SWH samples. The higher TRP concentrations in reference soils may be explained by possible lower pH levels (Devau *et al*., 2009) in reference soils or higher organic matter content (von Wandruszka, 2006) and associated higher levels of biological decomposition and mineralization. Both SWH and reference soils were subjected to periodic flooding, and the common flooding effects, possible minimal effects of agriculture (light grazing) at SWH sites, and the passage of time since agricultural practices, may account for the general similarities in nutrient concentrations. Soil texture was also similar between site types indicating that both site types were subjected to the same primary depositional characteristics and subsequent secondary effects of floods.

Estimated delivery of sediment and nutrients from SWH restoration

The reintroduction of flood plain sediment and associated nutrients from SWH construction accounts for a small portion of total sediment and nutrient transport from the Missouri and Mississippi Rivers during 1993–2012, assuming that all reintroduced SWH materials are transported during this period, and speciation is maintained. The cumulative masses of sediment and nutrients from the side-channel chutes accounted for less than 3.1% of sediment and 1.9% of the nutrient loads from the Missouri and Mississippi Rivers. Phosphorus loadings from SWH chutes account for a greater portion of 1993–2012 Missouri (1.9%) and Mississippi River (0.5%) loads than N constituents (<0.01–0.5%). This finding is in agreement with the National Research Council (NRC) (2011), which estimated that P loadings to the river from SWH projects are likely to constitute a greater portion of the nutrient load than N loadings. The TP value of 0.5–1.9% is substantially less than the National Research Council (NRC) (2011) upper bound estimate of 6–12% of Mississippi Basin loads from all SWH construction activities. The nutrient mass estimates from the chutes represent a maximum contribution from these SWH features as sediment and associated nutrients entering the river are likely to be transported episodically to the outlet stations over a period that may exceed the 1993–2012 analysis period.

The chute target width is used as an assumed point in the natural channel development where control structures would begin to more actively limit flows in the side channel, and long-term net rates of volume change would be expected to approach a dynamic equilibrium. Of the three chutes with available bathymetric surveys and chute width analyses, none had attained width or volume equilibrium over the 5–8 years of monitoring nor had any of the three attained

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the target width (Figure 3). The results indicate that chute development following construction may take a decade or longer to attain a dynamic equilibrium, depending on flows, site characteristics, and design features.

In 2010, side-channel and revetment chute projects accounted for about 26% of the total created SWH surface area (Jalili and Pridal, 2010) and about 70% of the SWH displaced design volumes of sediment from the flood plain (Chance Bitner, USACE, written communication, 2012). Approximately 6700 additional hectares of SWH are planned to be created through 2024 with additional potential for reintroduced sediment and nutrients. However, main-channel modifications, which constituted approximately 62% of the total constructed SWH area in 2010 (Jalili and Pridal, 2010), likely will provide a substantial portion of the future area but not provide a substantial source of reintroduced flood plain sediment. Direct reintroduction of sediment into the river during chute construction has not been practiced in Missouri since 2008 but has continued to be a component of upstream projects. The reintroduction of side-cast material and the channel widening by which the majority of soil is reintroduced are accomplished by natural erosional processes. The reintroduction and transport of sediment and nutrients associated with constructed, side-channel chutes and other SWH features is, therefore, primarily a flow dependent process. A comparison of the minor chute development at Worthwine Island and the substantial changes at the Jameson Island chute following flooding in 2011 (Figure 3) indicates that other factors also are involved. Continued monitoring of side-channel chute dynamics as well as other SWH features will allow for more accurate estimates of the equilibrium geomorphology, rate of change, and relation of SWH feature dynamics with river hydrology and other physical factors.

The scale and nature of SWH restoration activities are unique in the Missouri River system making comparisons of results to similar studies difficult, but the transport of sediment and associated materials is an ecological consequence of other restoration activities, particularly small-scale dam removal (Hart *et al*., 2002; Stanley and Doyle, 2002). A similarity of this effort with other such restoration activities is the need to quantify potential detrimental effects along with the derived benefits.

CONCLUSIONS

There is a difficult balance in the management of large complex systems, including the Missouri River. With competing interests, trade-offs are necessary, and the development of selected habitat for one ecological benefit can have adverse effects on another. SWH features along the lower Missouri River are created to compensate for habitat losses but often involve the reintroduction of sediment and associated nutrients into the river. The results of this study indicate that concentrations of nutrients from selected SWH locations are similar to those of historically undisturbed flood plain soils. Sediment from the chutes accounted for 3.1–1.5% of total suspended loads from the Missouri and Mississippi Rivers during the 1993–2012 analysis period. The studied side-channel chutes potentially contribute a greater portion of Missouri (1.9%) or Mississippi River (0.5%) TP loads compared with other nutrient species. Chute contributions of nitrate, the constituent most closely related to gulf hypoxia, were 0.01% or less of the Missouri and Mississippi River loads. The quantification of secondary effects of habitat restoration is necessary to evaluate the potential water quality effects that discharging sediment to the river has at local and regional scales.

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