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Malia A. Volke
South Dakota State University

Michael L. Scott
South Dakota State University

W. Carter Johnson
South Dakota State University

Mark Dixon
University of South Dakota

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The Ecological Significance of Emerging Deltas in Regulated Rivers

MALIA A. VOLKE, MICHAEL L. SCOTT, W. CARTER JOHNSON, AND MARK D. DIXON

Sedimentary deltas forming in the world's regulated rivers are a glaring gap in our knowledge of dammed riverine ecosystems. Basic ecological information is needed to inform the current debate about whether deltas should be retained and managed to gain ecosystem services lost under reservoirs or whether they should be partially removed to improve flow conveyance and to resupply sediment-starved reaches below dams. An examination of nine deltas on the heavily regulated upper and middle Missouri River showed the following: The sizes, dynamics, and biotic communities vary widely across deltas; riparian forest has established on portions of most deltas; the current delta area is over 1000 square kilometers, exceeding forest area in remnant unimpounded reaches and offering considerable land area for restoration actions; and small adjustments to reservoir operations could improve the restoration potential of deltas. Ecological studies are urgently needed to determine the future role that deltas could play in river ecosystem restoration.

Keywords: restoration, riparian, ecosystem services, dams, flow regulation

Rivers naturally form sedimentary deltas where they enter lakes, seas, or oceans. They are morphologically distinctive because of their frequently deltoid shape often traversed by distributary channels (Olariu and Bhattacharya 2006). Deltas characteristically support highly productive agriculture and ecologically diverse wetland ecosystems (Stanley and Warne 1993, Glenn et al. 2001). Many of the world's large deltas (e.g., the Colorado, the Danube, the Nile) have been altered by upstream changes to hydrologic regimes and sediment supplies (Glenn et al. 2001, Dutu et al. 2014, Stanley and Clemente 2014). Deltas are now forming as novel ecosystems in regulated river systems where the mainstem river and tributary streams enter reservoirs. They are relatively permanent and expanding features that were absent or ephemeral during preregulation times, because alluvium deposited at tributary junctions would have been quickly removed by flood flows on free-flowing trunk streams. Their formation is evidence of a sediment imbalance associated with the dam and reservoir system (Graf et al. 2010). Despite their potential ecological significance as shallow water and subirrigated environments, these nascent deltas have gone largely unstudied.

Other ecological effects of river damming have been well researched. Many large dams worldwide have been in place for decades, long enough for researchers to observe and understand the main effects of river regulation on aquatic and riparian ecosystems (Johnson et al. 1976, Ward and Stanford 1979, Williams and Wolman 1984, Rood and Mahoney 1990, Stanford et al. 1996, Nilsson and Berggren 2000, Greet et al. 2013). In short, reservoirs formed by dams replace the original riparian and riverine ecosystem with a novel lacustrine ecosystem, while downstream of dams, the natural balance between water and sediment is altered (Wolman and Leopold 1957, Dynesius and Nilsson 1994, WCD 2000, Stevens et al. 2001, Johnson 2002, Hupp et al. 2015). Remnant reaches that are not permanently flooded occur downstream of reservoir complexes and in gaps between reservoirs; their natural riverine appearance belies slow but chronic long-term physical and biotic adjustments to flow regulation. System responses to damming in remnant reaches often include channel incision, the narrowing of active channels, reduced active floodplain area and geomorphic complexity, and less extensive and diverse aquatic and riparian ecosystems (Vinson 2001, Graf 2006, Dixon et al. 2012, Johnson et al. 2012, Skalak et al. 2013, Yager et al. 2013).

The downstream effects of dams have been considered reversible by prescribing flows that mimic the predevelopment hydrograph (Richter et al. 1996, Poff et al. 1997, Michener and Haeuber 1998, Richter et al. 2003). Following this approach, flow releases for a number of rivers have been prescribed and in a few cases actually implemented (Rood et al. 2003, Melis et al. 2012, Wilcox and Shafroth 2013). It is now widely recognized that flow prescriptions for ecological restoration also must include resupplying sediment along with flow to restore natural channel and floodplain processes (Kondolf 1998, Piégay et al. 2005, Florsheim et al. 2008). Moreover, a debate is growing over whether deltas

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should be retained and even managed as important ecological habitat or mined and transported to regain storage capacity and to resupply sediment-starved reaches below dams (Coker et al. 2009, USACE 2013a). The engineering options to remobilize sediment in deltas and move it past mainstem dams have been reviewed in detail by the National Research Council (2011).

Why are reservoir deltas so understudied? The most significant reason is that deltas are just now becoming large enough to emerge as recognizable landforms, especially where tributary streams enter deep reservoirs. Second, they are neither distinctly lotic nor lentic, so they may be overlooked by scientists interested either in rivers or lakes. Third, delta vegetation may be seen as too ephemeral with high turnover because of widely fluctuating reservoir levels. Finally, the public may not view reservoir deltas favorably because they may interfere with on-reservoir recreation, may contribute to reduced flow conveyance and increased backup flooding on private lands, and may produce widespread recruitment of noxious weeds during reservoir drawdowns (NRC 2011).

Nonetheless, as reservoirs age, mainstem and tributary deltas will continue to expand up and down the gradient. Because of progressive sediment accumulation, reservoir fluctuations, and the often less-regulated tributary streams, reservoir deltas represent some of the more hydrologically dynamic and geomorphically active environments remaining in regulated riverine landscapes. These highly dynamic environments may offer opportunities to replace or restore some of the geomorphic processes, shallow aquatic environments, and early successional vegetation dynamics that have been lost because of river regulation (Johnson 2002).

Key questions about reservoir deltas that need to be addressed include the following: (a) Are the vegetation communities that are currently establishing on deltas similar to those that were present on predam mainstem rivers? (b) Are deltas better choices for riparian forest restoration than flow- and sediment-impaired floodplains in mainstem remnant reaches? (c) Is there currently enough delta land that would support riparian forest to offset historic and expected future losses of forests in the remnant reaches? (d) How can reservoir management be adjusted to enhance the biodiversity and ecological dynamics of deltas?

Research conducted along the Missouri River can begin to answer these questions. The ecological effects of flow regulation on floodplain forests have been well studied on the Missouri (Dixon et al. 2012, Johnson et al. 2012, Scott et al. 2013), and an investigation of its tributary deltas is now underway. The Missouri River is the longest river in the United States, stretching 3767 kilometers (km) across an expansive drainage basin that encompasses parts of ten states and two Canadian provinces and that represents approximately one-sixth of the land area of the continental United States (NRC 2002). The six large mainstem reservoirs on the Missouri River (figure 1) have a combined storage capacity of 90.5 cubic kilometers (km^3), making it the largest water storage system in North America (USACE 2006). We estimated from geographic information system (GIS) feature classes representing the regulated Missouri River that approximately 70% of the river length in the Dakotas has been replaced by reservoirs.

The so-called cottonwood problem, now known to exist on most rivers in the drylands of central and western North America, was first introduced to the ecological science community from studies of the regulated Missouri River (Johnson et al. 1976, Johnson et al. 2012). The once-expansive plains cottonwood (*Populus deltoides* ssp. *monilifera* (Ait.) Eckenw.) forests that dominated the predam Missouri River floodplain throughout most of its length have failed to reproduce in the postdam environment. Cottonwood recruitment was dependent on frequent large floods, which eroded existing floodplain and created new, unvegetated alluvial surfaces (Johnson 1992, Scott et al. 1997, NRC 2002). These floods also created a variety of channel and floodplain features that maintained a rich diversity of riparian and aquatic plant and animal species.

Landscape-level losses of biodiversity in remnant reaches of the Missouri River are expected because of severely reduced rates of cottonwood forest establishment (Johnson 1992, Dixon et al. 2012, Scott et al. 2013) and because of the accidental introduction of pathogens (Hale et al. 2008) and pests (Herms and McCullough 2014) that kill tree species that replace cottonwood via succession. Xerification of the floodplain from reduced flooding is another reported cause of lowered biodiversity (Reily and Johnson 1982, Johnson et al. 2012). Losses of floodplain and riverine habitat contribute to a wider range of natural resource concerns, including degraded spawning, rearing, and recruitment conditions for threatened and endangered native river fish species; greatly diminished sandbar nesting habitat for endangered shorebirds; and reductions in nesting and overwintering habitat for the bald eagle (*Haliaeetus leucocephalus* L; NRC 2002).

More specifically, the US Army Corps of Engineers and the US Fish and Wildlife Service have linked the cottonwood problem to the recovery needs of the bald eagle (see the Missouri River Recovery Program, *www.moriverrecovery.org*). Cottonwood is the only native tree species on the floodplain of sufficient size and canopy structure when mature to support the roosting and nesting of the bald eagle (SDGFP 2005). In a recently released cottonwood management plan (USACE 2011), the preservation of existing stands and the reestablishment of new stands along the Missouri River on retired cropland and along created fluvial features such as side channels, oxbow lakes, and backwaters were proposed. This is a welcome and long-awaited program that could potentially help solve a problem first reported 40 years ago. Because of the scarcity of information on deltas during the time that material was gathered for the management plan, the potential of deltas as habitat for cottonwood establishment was not considered as part of the solution. However, the evidence presented below suggests that deltas may offer distinct advantages over mainstem, remnant reach

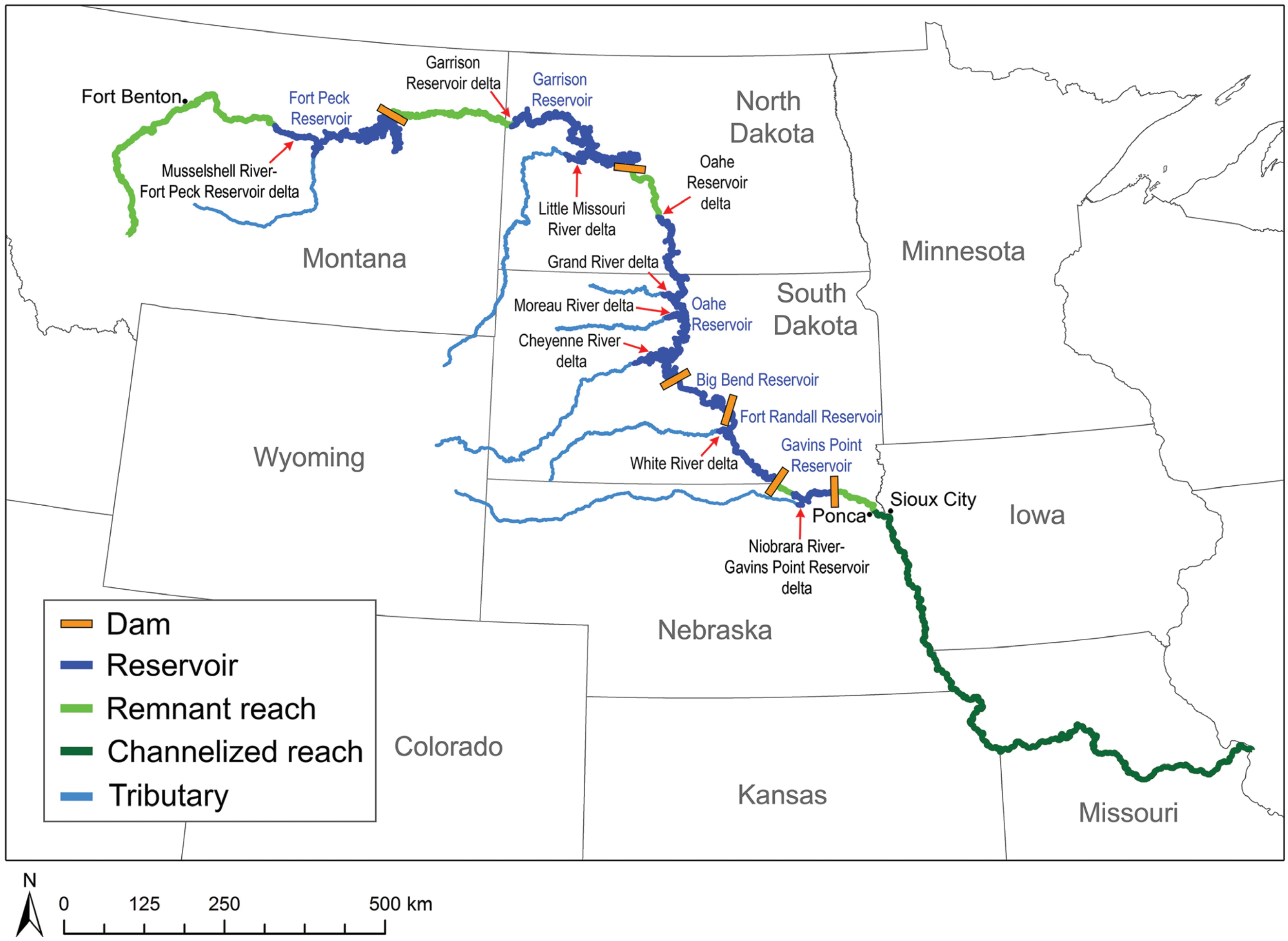

Figure 1. The location of the major dams and reservoirs on the Missouri River along with the mainstem, tributary, and tributary–mainstem combination deltas (table 1) selected for this study. The study reach extends from Fort Benton, Montana, to Ponca, Nebraska. The reservoirs are named after the associated dam; other names are in usage (see supplemental material). Abbreviation: km, kilometers.

restoration sites or, at least, should be considered within the mix of solutions.

The geomorphology of reservoir deltas

Deltas are forming in two places in the mainstem Missouri River reservoirs: at the upstream end of the reservoirs, where the mainstem river flows into the calm reservoir pool (mainstem deltas), and at the mouths of tributary streams (tributary deltas) that enter the reservoirs laterally (figure 2). Tributary–mainstem combination deltas occur where a tributary stream enters near the upstream end of a reservoir. Reservoir deltas vary considerably in size and shape, but they all share a geomorphic organization similar to the subaqueous and subaerial portions of natural deltas (Swenson et al. 2005, Olariu and Bhattacharya 2006). Four functionally and morphologically distinct zones are apparent on the basis of our observations: (1) a subaquatic reservoir zone, (2) a subaerial–subaquatic delta transition zone, (3) a subaerial delta zone, and (4) a fluvial–delta transition zone (figure 3). The boundaries between zones are fuzzy and likely to shift over time in response to water supply and reservoir management.

Missouri River deltas: Location and size

We selected the two largest mainstem deltas, the five largest tributary deltas, and two tributary–mainstem combination deltas on the Missouri River to determine the range of delta characteristics (figure 1, table 1). These deltas constitute the large majority of delta area in the river system. The Fort Peck, Garrison, and Oahe Reservoirs are primarily managed for storage and exhibit a wide vertical range of water levels as a function of wet and dry periods (a range of 11 meters [m] to 14.1 m). Fort Randall is the smallest of the storage reservoirs and exhibits a narrower vertical range of water levels (5.9 m). Gavins Point Reservoir has a largely “run of the river” release pattern, with a very narrow vertical range (1 m) (US Army Corps of Engineers).

We delineated the area of each delta using 2012 or 2013 aerial imagery from the National Agriculture Imagery Program (NAIP) in a GIS platform. We did not include the

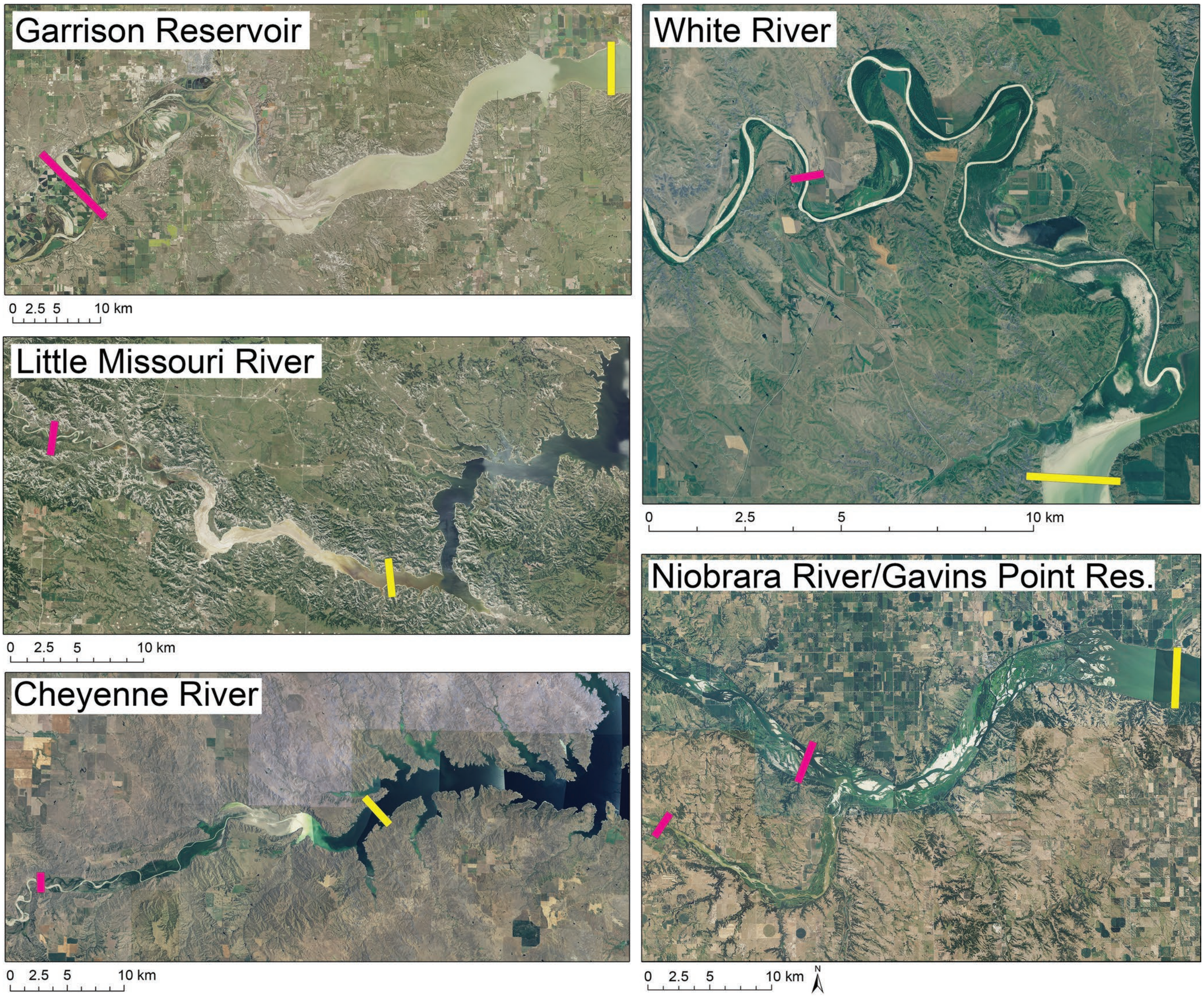

Figure 2. Aerial photographs of one mainstem delta (Garrison), three tributary deltas (Little Missouri, Cheyenne, and White), and one tributary–mainstem combination delta (Niobrara River–Gavins Point Reservoir) on the Missouri River. The magenta line marks the upstream extent of each delta, and the yellow line marks the downstream extent of each delta. Source: US Department of Agriculture, National Agriculture Imagery Program (2012 and 2013). Abbreviation: km, kilometers.

areal extent of the subaquatic reservoir zone in our measurements, because it could not be reliably identified from the available imagery and there was insufficient bathymetric data. Moreover, the subaquatic reservoir zone is permanently submerged even under the minimum operating reservoir pool and therefore does not currently support terrestrial or riparian vegetation. The downstream boundary of each delta was drawn at the approximate minimum reservoir pool (the upstream boundary of the subaquatic reservoir zone) as estimated from a combination of reservoir water level data and aerial imagery in Google Earth from 1996 to 2013. The upstream end of the fluvial–delta transition zone was drawn where there was a distinct visual change in vegetation—that is, where the vegetation pattern on the floodplain transitioned to that typical of the upstream riverine environment. On some deltas, this boundary coincided with the downstream extent of tillage agriculture. River valley walls formed the lateral boundaries of the deltas, with the exception of the distal lobe of the White River delta, which was bounded by the approximate minimum reservoir pool.

The combined area of the nine deltas was over 1000 square kilometers (km^2; table 1). The area of individual mainstem deltas far exceeded that of tributary deltas, sometimes by nearly an order of magnitude. Mainstem delta length was typically more than twice that of tributary deltas. The area and length of tributary–mainstem combination deltas fell somewhere in between. Delta size and length appeared to be influenced by many interacting factors, including the

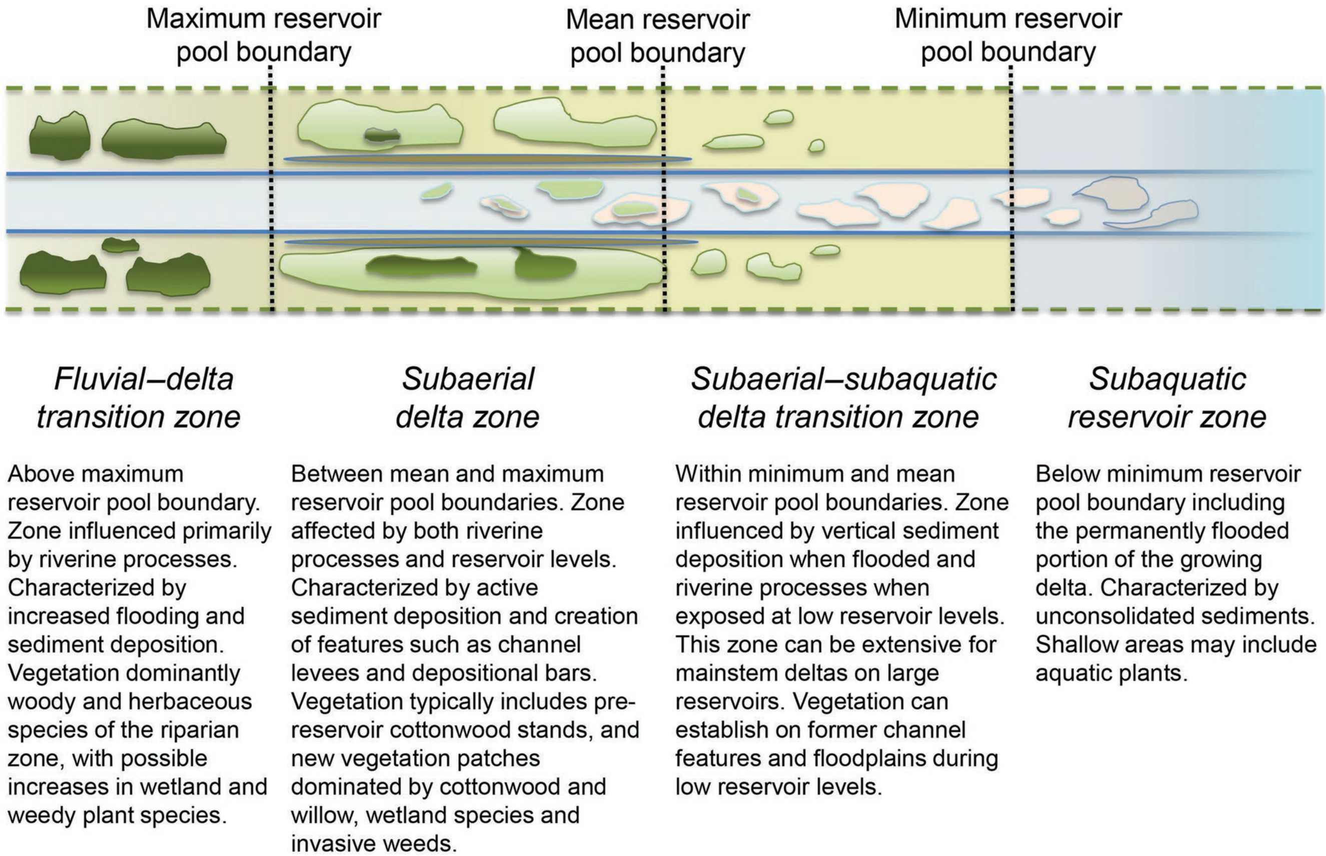

Figure 3. A generalized diagram of a reservoir delta depicting the four functional delta zones. The dark green patches are prereservoir cottonwood stands, and the light green patches represent postreservoir vegetation. The linear features in the subaerial delta zone represent channel levees and depositional bars. Source: Adapted in part from Swenson and colleagues (2005) and Olariu and Bhattacharya (2006).

vertical range of the receiving reservoir, which can fluctuate widely between low and high pool cycles, dramatically altering the area of delta that is affected.

We were curious about the relative area of delta habitat with the potential to support riparian forest compared with the remaining cottonwood-dominated forest associated with the Missouri River remnant reaches. To assess this, we estimated the current forest area of predam (1950s) and postdam origin in five remnant reaches from Fort Benton, Montana, to Ponca, Nebraska. The river is channelized from Ponca downstream to St. Louis, Missouri, with no additional reservoirs or reservoir deltas (NRC 2002).

Forest stands were mapped in GIS using 2006 NAIP imagery, digitized for each reach, and ground truthed (Dixon et al. 2012, Johnson et al. 2012, Scott et al. 2013). The GIS database was used to estimate the total area of predam forest (more than 50 years old), postdam transitional forest (25–50 years old) and postdam forest (less than 25 years old). Only the postdam forest area is likely to be sustained under current flow management because it best represents the current regime of the river. Total remnant forest area constituted 406 km^2, with over 70% of that area being predam forest (figure 4). Therefore, large areas of remnant forest throughout the Missouri River system will provide increasingly fewer ecological benefits as they deteriorate structurally and compositionally over time as predicted (Johnson et al. 2012).

The current delta area between Fort Benton, Montana, and Ponca, Nebraska, was over twice that of the area of all remnant forest (figure 4). This was an unexpected result and provides compelling evidence for the importance of deltas based on their size alone, not to mention their potential ecological importance as a novel habitat for both terrestrial and aquatic organisms. Deltas currently exhibit a mix of terrestrial cover types, including riparian forest and shrubland, herbaceous wetlands, bare sediments, and shallow water habitats. Moreover, these deltas will assuredly continue to expand.

The formation of reservoir deltas

Delta depositional landforms and dynamics are influenced by several interacting factors, including the size, valley slope, stream flow, and sediment regime of the mainstem or tributary streams, along with the age, size, and depth of the reservoir and the frequency and magnitude of water-level fluctuations. Moreover, the dynamics of a given delta

Table 1. The characteristics of deltas and reservoirs of the upper and middle Missouri River examined in this study.

Delta type and name	Delta area (in km^2)	Delta length (in rkm)	Associated reservoir	Year of dam closure[a]	Reservoir surface area[a] (in km^2)	Reservoir storage capacity[a] (in km^3)	Vertical range of reservoir[a,c] (in m; 1967–2013)	Average mean annual discharge of contributing streams[a,b] (in m^3/s)
Mainstem								
Garrison Reservoir	312.5	92.2	Garrison	1953	1,546	29.4	11.0	571.2
Oahe Reservoir	276.3	106	Oahe	1958	834	28.5	12.7	637.2
Tributary								
Little Missouri River	32.9	35.7	Garrison	1953	1,546	29.4	11.0	15.5
Grand River	41.3	40.1	Oahe	1958	834	28.5	12.7	7.5
Moreau River	50.1	54.8	Oahe	1958	834	28.5	12.7	7.7
Cheyenne River	51.9	37	Oahe	1958	834	28.5	12.7	22.6
White River	24.4	33.6	Fort Randall	1952	413	6.7	5.9	16.5
Tributary–mainstem combination								
Musselshell River–Fort Peck Reservoir	137.3	117	Fort Peck	1937	991	22.8	14.1	7.8/253.6
Niobrara River–Gavins Point Reservoir	138	59	Gavins Point	1955	125	0.6	1.0	49.7/669.9
Total	1065							

Note: The length units are in river kilometers (rkm). Additional information, including the periods of record for stream discharge data, is available in the supplemental material for this article. Abbreviations: km^2, square kilometers; km^3, cubic kilometers; m, meters; m^3/s, cubic meters per second. [a]US Army Corps of Engineers. [b]US Geological Survey. [c]Calculated as the difference between the average minima and the average maxima water levels.

can be influenced by both upstream and downstream dams. Mainstem deltas enter the shallow, upstream ends of reservoirs with low valley gradients. As a consequence, the distance between the minimum and maximum pool boundaries can be extensive. For example, this distance for the Oahe delta is approximately 90 river kilometers. The elevation of the reservoir surface ranges by as much as 12.7 m between wet and dry periods (table 1). The upstream portion of this reach (upper subaerial delta zone) includes sandbars, forest, abandoned channels, and agricultural fields (figure 5). Channel cross-section resurveys show that it has been aggrading since the completion of the dams but at a diminishing rate (Skalak et al. 2013). Accordingly, the slope of this subreach (0.09 m per km) is flatter than the slope of the remnant reach upstream of the delta (0.13 m per km) (US Army Corps of Engineers).

The rapid expansion of the Niobrara River–Gavins Point Reservoir delta has been the most visible and most publicized of the Missouri River deltas (Coker et al. 2009, NRC 2011, USACE 2013a). Cross sections remeasured by the US Army Corps of Engineers showed that the predam Missouri River channel near the maximum reservoir pool boundary had a maximum depth of 6.5 m and a width of 2.9 km. Within the 20 years following completion of the dam, the newly forming, subaerial portion of the delta at this location had nearly completely filled in the predam channel with sediment, leaving a few narrow channels separated by sandbars. The delta continued to aggrade throughout the 1990s, creating many small distributary channels separated by islands covered with herbaceous wetland vegetation. The flood of 2011 removed sediment from upstream portions of the delta and deposited it in the subaquatic portion of the developing delta. In the 60 years since the dam's completion, the subaerial delta front has prograded 8.2 km into the reservoir (USACE 2013b).

Many deltas contain thick sediments. For example, valley cross-sectional surveys for the lower Cheyenne River showed that the thalweg aggraded by as much as 15.9 m between 1958 and 2010 (US Army Corps of Engineers). These sediments occurred as a broad wedge that extended for approximately 60 km down valley (figure 6). Sedimentation occurred as far upstream as the maximum reservoir pool but was thickest at the mean reservoir pool. Similarly, the White River delta aggraded by as much as 12 m between 1954 and 2011 (US Army Corps of Engineers). The morphodynamics of these reservoir deltas created extensive exposures of freshly deposited sediment and some physical environmental conditions that have largely been eliminated in remnant reaches (Dixon et al. 2012). These geomorphic features and conditions provided the physical template upon which aquatic and riparian ecosystems have developed, as they did historically along free-flowing rivers.

The vegetation response to reservoir delta formation

As the reservoirs filled, the rising water inundated and destroyed most predam riparian forests and riverine

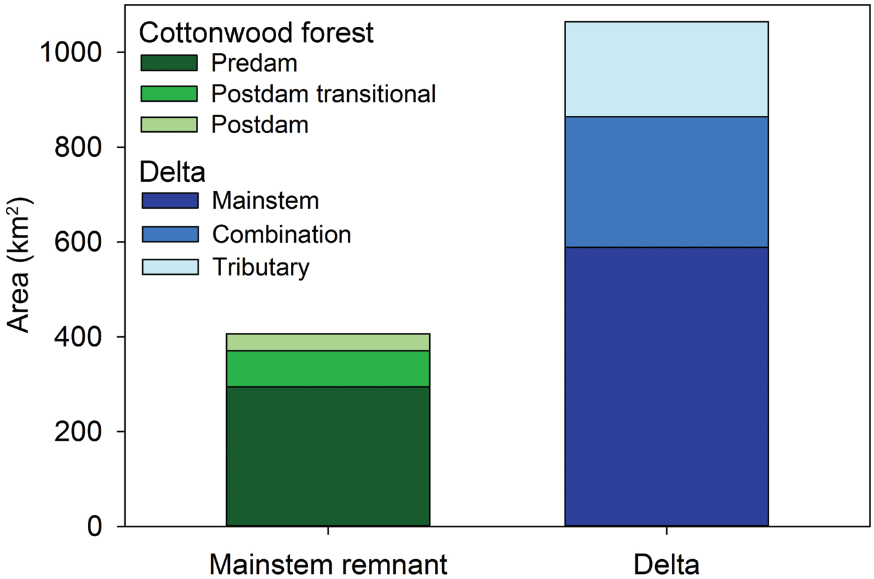

Figure 4. A comparison of delta area in 2012–2013 for mainstem, major tributary, and tributary–mainstem combination deltas in comparison with the areas of predam forest (more than 50 years old), postdam transitional forest (25–50 years old), and postdam forest (less than 25 years old) in Missouri River remnant reaches from Fort Benton, Montana, to Ponca, Nebraska. Without predam imagery for the reach below Fort Peck Dam, we included forest area from 1950s imagery in the predam category. This likely resulted in a very small increase in our estimate of the total area of predam forest in the river system.

aquatic habitat. Subaquatic portions of growing deltas filled drowned bottomlands with sediment, and expanding deltaic plains raised the riverbed considerably and flattened channel gradients. Field reconnaissance showed that these deltas exhibited relatively active geomorphic surfaces with increased overbank flooding; raised alluvial water tables during high reservoir water levels; and dry, exposed surfaces during low reservoir water levels.

This novel mix of physical processes is likely to produce a range of vegetation communities across deltas. Quantitative information collected on the White River delta provided clues into patterns of vegetation response. Forest cover on the expanding delta increased by nearly 50% from the predam period (1948) to the present (2012) (figure 7). The age structure also changed from domination by older forest in the predam period to younger forest in the postdam period. The large majority of young forest was cottonwood and willow dominated. These forests established on lower delta positions, where alluviation was most active. Smaller areas of young forest established farther upstream in the delta on abandoned agricultural land undergoing increased flooding and sedimentation. We also observed mortality of forests during the postdam period associated with the record Missouri River flood of 2011. High mortality occurred where there was prolonged flooding behind natural levees and on younger alluvial surfaces occurring closer to the reservoir.

Woody vegetation expansion similar to that found on the White River delta was observed using Google Earth on most other emerging Missouri River deltas. The Niobrara River–Gavins Point Reservoir delta, however, had very little forest; it was dominated by common reed (*Phragmites australis* (Cav.) Trin. ex Steud.) and other herbaceous wetland species. In contrast to those of the much larger storage reservoirs, the water levels of Gavins Point Reservoir fluctuated annually within a narrow range of about 1 m (figure 8).

Clearly, ecologists have just begun to focus attention on reservoir delta ecosystems, let alone to identify the complex patterns and processes of vegetation dynamics. Discussions with natural resource and land managers in the region determined that there have been no systematic surveys, studies, or reports directed at describing vegetation composition and dynamics on Missouri River reservoir deltas (Linda Vance, Montana Natural Heritage Program, personal communication, 5 March 2014; Tim Cowman, Missouri River Institute, University of South Dakota, personal communication, 30 October 2013).

Patterns of biotic diversity associated with reservoir deltas

Reservoir deltas likely provide valuable habitat for animals dependent on riverine environments; however, there are few published studies for verification. Extensive stands of cottonwood and willow have developed during long drawdown periods on the Musselshell River–Fort Peck Reservoir delta and were heavily used by white-tailed deer and elk (Randy Matchett, US Fish and Wildlife Service, personal communication, 19 February 2014). In a faunal survey of the island and bank-attached wetland marshes of the Niobrara River–Gavins Point Reservoir delta, Kerby and Swanson (2012) did not detect any bird, reptile, amphibian, or freshwater invertebrate species of regional conservation concern. They did find, however, that these delta wetlands supported large numbers of birds that were not present in comparable off-river wetlands; some of these species were uncommon in South Dakota. Likewise, two frog species were only found in delta wetlands. The midchannel sandbars and island marshes of the delta were thought to be ideal nesting habitat for marsh birds. However, in contrast to natural wetlands and the unregulated river, where water levels would typically decline following nest establishment, reservoir operations have produced rising water levels during the nesting season. This likely accounted for the low use

Figure 5. An aerial photograph depicting the heterogeneous nature of the upper portion of the subaerial zone of the Missouri River mainstem delta forming at the headwaters of Oahe Reservoir south of Bismarck, North Dakota. The direction of flow is from left to right. Source: US Department of Agriculture, National Agriculture Imagery Program (2012). Abbreviation: km, kilometers.

of these delta habitats for nesting by marsh birds (Kerby and Swanson 2012).

Most delta research has focused on aquatic communities, especially fish (e.g., Kaemingk et al. 2007, Spindler et al. 2009, 2012). Greater fish diversity was found within the Niobrara River–Gavins Point Reservoir delta than in the downstream reservoir (Kaemingk et al. 2007). Because deltas include both flowing and still-water environments, they are associated with fish species from each of these habitat types. In addition, greater numbers of large river fish—such as the federally endangered pallid sturgeon (*Scaphirhynchus albus* [Forbes and Richardson]) or the paddlefish (*Polyodon*

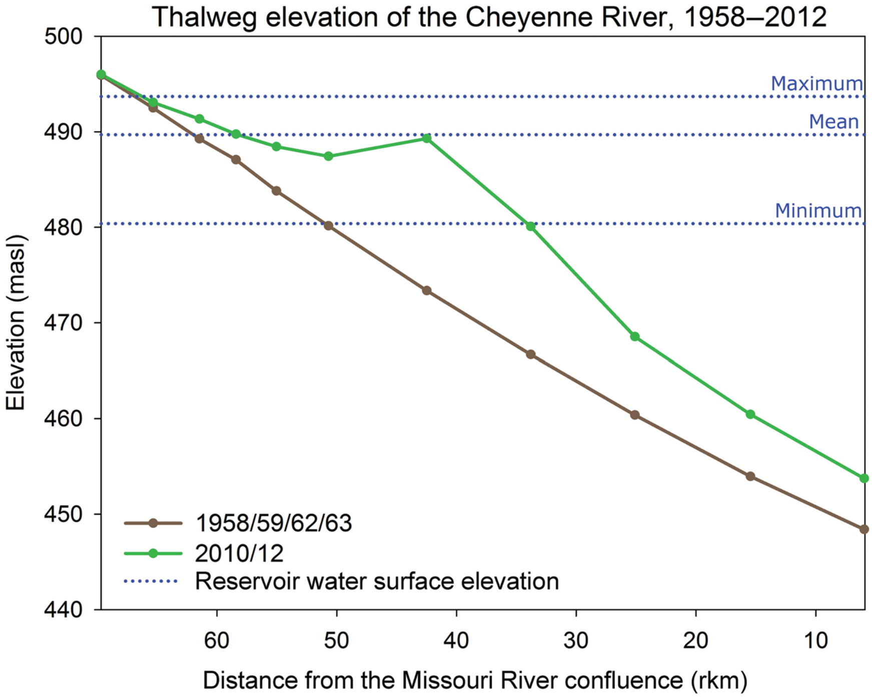

Figure 6. The stream gradient of the lowermost approximately 70 kilometers of the Cheyenne River from 1958 to 1963 and from 2010 to 2011, depicting the formation of a sediment wedge within the delta zone. The receiving Oahe Reservoir first reached its minimum operating pool in 1962 following closure of Oahe Dam in 1958. The vertical range of reservoir water surface elevations differs from that in table 1 because the lowest average and highest average elevations were used in this figure. Elevation units are in meters above sea level (masl), and distance units are in river kilometers (rkm).

spathula [Walbaum]), a species of concern—were found in delta habitats than in riverine or reservoir habitats (Spindler et al. 2009, 2012). Delta ecosystems cannot be all things to all species, but clearly, deltas provide increasing areas of once-abundant shallow water environments that are in short supply in current regulated river systems.

Restoring the riparian forest ecosystem

The expansive floodplain of the Missouri River ecosystem in the Dakotas prior to regulation was a mosaic of riparian forests with a wide range of ages, from young cottonwood and peachleaf willow (*Salix amygdaloides* Anderss.) forests a decade or two old to forests of green ash (*Fraxinus pennsylvanica* Marsh.), box elder (*Acer negundo* L.), American elm (*Ulmus americana* L.), and bur oak (*Quercus macrocarpa* Michx.) that were old enough to have lost all traces of the cottonwood pioneer element. Approximately two-thirds of the forests were early to midsuccessional (dominated by cottonwood) because of the rapidly meandering and shifting channel that eroded older forests and created sandbars and mud flats ideal for pioneer-forest establishment (NRC 2002).

The ecosystem services delivered to the public by these forests, such as biodiversity, water purification, and wild game, were considerable, and are still provided by remnant reaches today. The river's floodplain vegetation was a storehouse of biodiversity. Keammerer and colleagues (1975) found 220 species of vascular plants growing in mature forests in the remnant reach downstream of Garrison Dam in North Dakota. This inventory did not include a comparably rich flora of wetland plants found in the earliest stages of sandbar succession. The avifauna of these forests was high in species diversity, with more than 50 species of songbirds identified by Liknes and colleagues (1994); about half of these were neotropical migrants. Dean (1999) identified 39 species of neotropical migrants using Missouri River floodplain forests as stopover habitat. All in all, riparian ecosystems in the drylands of North America provide important habitat for many species and are vital to maintaining regional biodiversity (Patten 1998).

Biodiversity and the other ecosystem services historically provided by the floodplain plant community along the upper and middle Missouri River cannot be maintained without the cottonwood and willow pioneer community. Johnson and colleagues (2012) concluded that the later successional tree species (green ash, box elder, and American elm) are already in serious decline or are expected to be in the next few decades. If these later species drop out and if cottonwood declines as has been forecast (Johnson 1992, Johnson et al. 2012), primarily only shrubland and grassland would remain, and many plant and animal species dependent on forest habitat would be lost. Therefore, methods to restore an extensive, dynamic, and self-sustaining cottonwood community need to be found to maintain historical ecological services.

Restoration options

A range of options to restore pioneer forests are potentially available to the Missouri River management community.

Systemwide prescribed flood flows (including rare, unplanned floods). Ecologists have argued for the adoption of a flow regime in regulated rivers that comes as close to the historical as is possible or practical. The natural flow regime, the driver of dynamic river ecosystems (Richter et al. 1996, Poff et al. 1997, Richter et al. 2003), is recommended because it is likely the only tactic that could approach true restoration. Although this has been accomplished on several rivers in less developed landscapes (e.g., Wilcox and Shafroth 2013), prescribed floods of the magnitude needed to drive channel movement and cut and fill alluviation are problematic

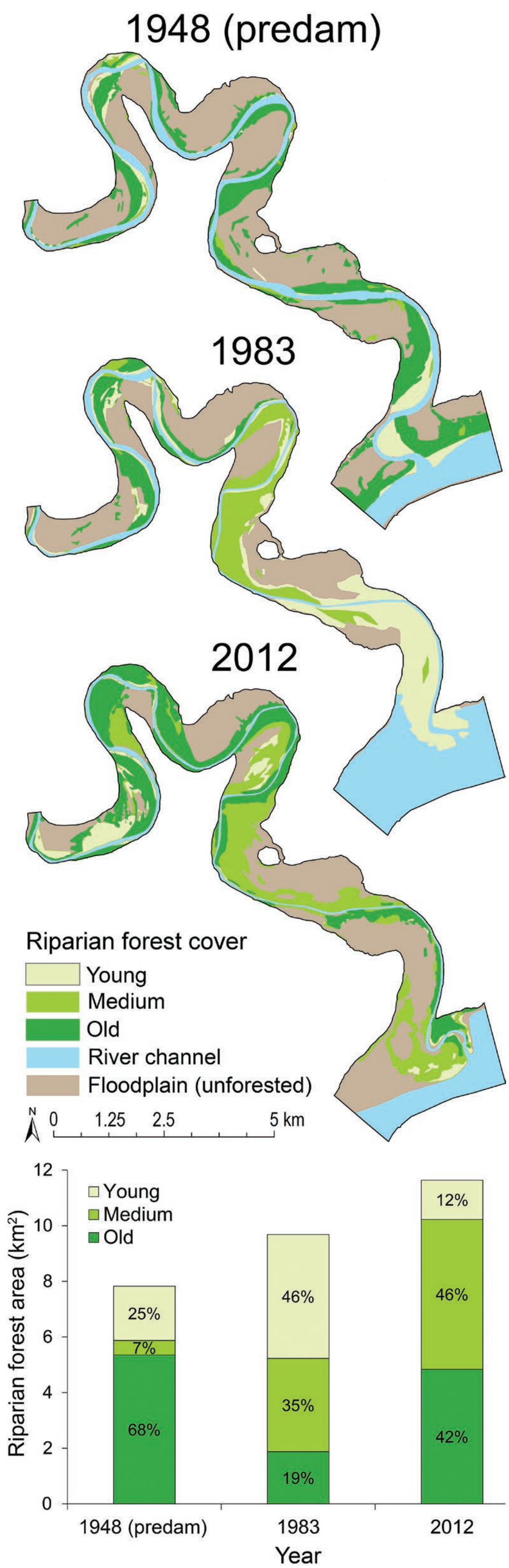

Figure 7. Changes in riparian forest age structure on the White River delta from the predam through the postdam period, showing the location of forest age classes in 1948 (4 years predam), 1983, and 2012. The graph shows the total area of forest in each age class for each measurement period. Abbreviation: km, kilometers; km^2, square kilometers.

on rivers where human infrastructure is located in flood prone areas, which is the case for most of our larger rivers. Unplanned floods may occur despite heavy regulation; however, these are generally rare events on rivers like the upper and middle Missouri (only one major flood in 60 years). When flood events do occur, flood-control policies limit maximum releases from the dams during high water, leading to unnaturally prolonged flood duration. Moreover, the postdam flow regime has changed channel structure, making restoration more challenging. Because of more than a half century of delays in restoring flood flows, process-based restoration on the Missouri may now require two phases: First, raise the incised river channel to predam elevations by oversupplying sediment, and second, provide flood-pulse flows to activate channel movement and allow bank erosion to occur (Johnson et al. 2014). The US Army Corps of Engineers strongly favors recovery projects at the site or reach scale to re-create shallow water habitat and emergent sandbar habitat for nesting shorebirds; no plans have been formulated to use systemic planned floods to restore historical riverine and floodplain ecosystem processes (NRC 2011, USACE 2011).

The protection, preservation, or conservation of existing forests. Protection of remaining cottonwood stands from clearing can slow the overall decline of pioneer forest area on the floodplain. It also can extend the value of this biodiversity storehouse as a source of native species for restoration projects for a few more decades. A key component of the US Army Corps of Engineers *Cottonwood Management Plan* (USACE 2011) is to preserve existing cottonwood stands on the Missouri River for the above purpose by discouraging land clearing and purchasing conservation lands or easements. Although this is a commendable short-term (less than 100 years), stopgap measure, we know that cottonwood cannot be "preserved" in existing stands; it will die out eventually (figure 4). True preservation of the cottonwood forest ecosystem requires preserving the processes that lead to abundant reproduction on active channel bars to replace older forests removed by erosion or those that have lost their cottonwood component because of succession.

Local creation of shallow water habitat features. The disappearance of expansive sandbars in the regulated river is the cause of widespread reproductive failure of cottonwood and willow. Associated shallow water habitat used by native, warm-water fish is likewise in short supply in the modern river. The Shallow Water Habitat Program, a division of the Missouri River Recovery Program, was developed to create long-term, beneficial impacts on the Missouri River by developing fluvial features, such as side channels, oxbow lakes, and backwaters that may inadvertently create suitable areas for cottonwood establishment. Construction of these fluvial features is largely restricted to the channelized portion of the river (in the states of Iowa, Nebraska, Kansas, and Missouri), not the reservoir portion upstream. These

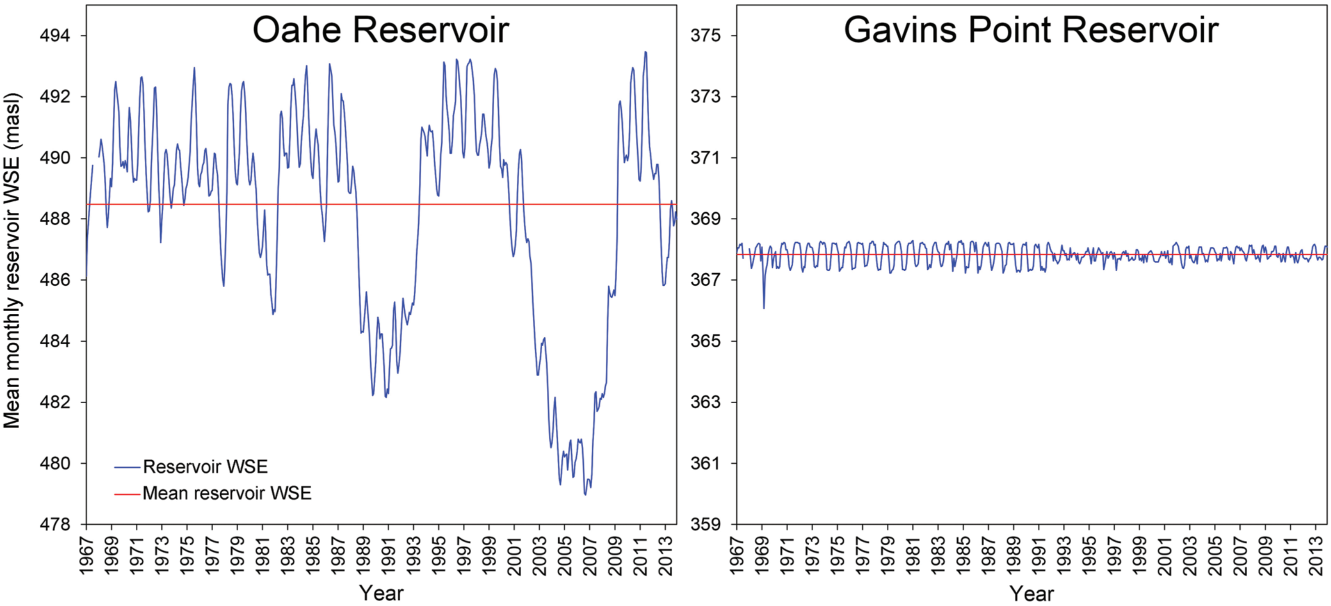

Figure 8. The mean monthly water surface elevations (WSE) in meters above sea level (masl) for the Oahe Reservoir (left) and the Gavins Point Reservoir (right), 1967–2013. The ordinate is scaled in equal units for each graph. Source: US Army Corps of Engineers.

site or reach-scale rehabilitations as currently designated will potentially benefit an extremely small proportion of the floodplain and therefore will only locally produce cottonwood patches, not the landscape scale bottomland stands of the historical Missouri.

Planting cottonwood and willow trees. One solution to the cottonwood problem proposed decades ago was that of planting early successional trees on retired agricultural land (Johnson 1992, NRC 2002). Although this approach would help to maintain cottonwood and willow trees on the floodplain, it probably would not restore the cottonwood forest ecosystem, particularly the high species diversity known to exist in preregulation stands. Preregulation forests were established on relatively low floodplain surfaces and were repeatedly aggraded by alluviation from floods. As a result, these communities supported a significant proportion of wetland-affiliated species. This species diversity cannot be restored by tree planting on relatively high, former floodplain surfaces where most farming is practiced. Moreover, it would be a daunting and expensive task for generations of managers to secure the land, plant several hundred hectares each year within remnant reaches (Dixon et al. 2012), and manage weeds and animal depredation on an increasingly larger area (Novotny and Johnson 2007).

Cottonwood restoration on delta surfaces. There are several reasons for which deltas—and certain deltas in particular—are promising locations for riparian forest establishment. First, field observations confirm that the early successional plant community, including cottonwood and willow, has been establishing under current reservoir operations on most deltas. This is hard evidence that deltas have generally become favorable for natural recruitment and beneficial for desired biodiversity, even if recruitment in subaerial portions of reservoir deltas during prolonged drawdowns may be short lived because of eventual reflooding. Second, some deltas may be more successful sites for active restoration than would be parcels of the Missouri River floodplain in remnant reaches. The deltas associated with unregulated or lightly regulated contributing rivers, such as the White River or the Missouri River mainstem upstream of Fort Peck Reservoir, retain many natural riverine processes such as overbank flooding, sedimentation, and spring flood pulses and summer drawdown. These processes, known to maintain healthy riparian ecosystems, would be a missing ingredient for success in restoring riparian forests on remnant floodplains. Third, much of the delta land is under public (state or federal) ownership; therefore, large-scale restorations can be conducted more easily and effectively than on the patchwork of lands comprising the Missouri River floodplain. For example, as the deltas were forming on the White, Cheyenne, and Moreau rivers, backup flooding and sedimentation were occurring that led to federal lawsuits initiated by private landowners and tribes (e.g., USCFC 1997). As a result, much of the land that became too wet to farm was procured and is now overseen by various state government entities.

However, reservoir deltas may be imperfect places to invest restoration dollars, especially under current reservoir operating conditions. Although some new forests persist on these deltas, others that are flooded for extended periods during high reservoir water levels are killed. Young forest turnover can be relatively high, with only a small proportion reaching advanced ages in stands that are the highest in biodiversity. Nonetheless, these young, transitory forests may provide short-term benefits to wildlife, as observed on the Musselshell River–Fort Peck Reservoir delta. The age structure of forests on emerging deltas is determined by the age of the delta surfaces and the amount of vegetation turnover due to long-term flooding from the reservoir. The proportional effect of these two factors is likely to vary widely across the range of deltas.

Both natural forest establishment and stand survival could be improved by the slight modification of reservoir storage rules to better mimic the natural flow regime: higher water in spring and lower water in summer and fall. Declining water levels during the seed dispersal period (June–July) would increase recruitment of cottonwood and willow on exposed sand and mudflats (Mahoney and Rood 1998). A second modification of current reservoir operation rules would be to avoid the occasional prolonged high water levels that exceed the flood tolerance of cottonwood (2–3 growing-season months; Amlin and Rood 2001). Mortality of some young cottonwood forests on the White River delta occurred because of the Missouri River flood in 2011 when the level of Fort Randall Reservoir was raised above flood stage for 2.5 months (US Geological Survey, US Army Corps of Engineers). Adjusting storage reservoir water level regimes, however, may have consequences for operational objectives, such as hydropower production. Therefore, any ecological benefits would have to be weighed against operational costs.

Many of the deltas in the Missouri River system are massive in area and in complexity. Pioneer forests have established in places, but their areal extent and vegetation composition have not been quantified. The extensive areas flooded under normal high reservoir levels but exposed during drought cycles makes for complicated vegetation patterns in space and in time. Before restoration recommendations can be formulated, study of postdam forest recruitment patterns on reservoir deltas needs to be completed using remote sensing and field investigations. As was described above, reservoir storage patterns could be modified to favor both recruitment and survival of young forests on deltas, but recommendations should await the results from research. This paper is a call for ecological research directed at reservoir deltas.

Conclusions

Our initial findings from the numerous deltas forming in the Missouri River reservoirs should apply to the many sediment-rich, regulated rivers in the drylands of the American West historically dominated by *Populus* and *Salix* forests and woodlands. In our study, we have determined that reservoir deltas on the upper and middle Missouri River represent more than twice the current area of riparian forest in remnant reaches. These deltas, which constitute four distinct physical environmental zones, continue to enlarge.

Preliminary examination suggests that reservoir deltas may offer distinct advantages over mainstem, remnant reach restoration sites or at least should be considered within the mix of ecological restoration solutions. The potential for deltas to contribute to riverine and riparian ecological restoration is high because riparian vegetation similar to predam types has already established on some deltas and the large and growing area of deltas offers land mostly in public ownership for restoration in the future. Small changes in reservoir operations could improve recovery, either by increasing unassisted establishment and survival of pioneer forest vegetation (largely passive restoration) or by survival of planted stands (active restoration).

Deltas offer new opportunities to counterbalance losses of high biodiversity riparian ecosystems along the Missouri and other regulated rivers. Riparian ecosystems in western North America occupy only a small percentage of the total land area but are vital to maintaining regional biodiversity and ecological services (Patten 1998). The majority of the upper and middle Missouri River floodplain forest ecosystem was destroyed by reservoirs during the twentieth century. What remains is aging and losing biodiversity in the absence of the natural flow and sediment regimes, especially flooding. Deltas offer promise as recruitment sites for the pioneer cottonwood community; therefore, deltas are one bright spot in a rather dark future for biodiversity along the Missouri River and probably other regulated river systems.

The ecological literature is clear that the best approach to restoring regulated riverine and riparian ecosystems to predevelopment norms is to restore the natural flood and sediment regimes. The track record of this idealistic approach is spotty and limited. For numerous reasons, a piecemeal rather than a systemic approach has been adopted, often designed to recover listed riverine species rather than entire aquatic and terrestrial ecosystems, including the floodplain. We point out that deltas may offer a new opportunity for river recovery, in light of the low probability that systemic solutions will be adopted. Our recent research on the Missouri River suggests that recovery of the mainstem remnant reaches is becoming more complicated the longer we delay reach-scale restoration because of channel incision, sediment trapping in reservoirs, and the proliferation of human infrastructure associated with the channel and floodplain.

Dufour and Piégay (2009) stated that restoration should emphasize human benefits, not simply be targeted to natural, preregulation conditions: “We argue that the reference-based strategy should be progressively replaced by an objective-based strategy that reflects the practical limitations of developing sustainable landscapes and the emerging importance of accounting for human services of the target ecosystem” (p. 568). Incorporating deltas into river restoration programs aligns with Dufour and Piégay’s (2009) approach. We may have to accept delta plant communities that are less than perfect replicas of those of the past.

There is surprisingly little information regarding the physical and ecological processes that shape these emerging deltas. Further study of the potential of deltas to assist in the recovery of riverine and riparian ecosystems and to raise the level of ecosystem services provided to the public on regulated rivers is urgently needed.

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Supplemental material

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Malia A. Volke (malia.volke@gmail.com) is a PhD candidate in the Department of Natural Resource Management at South Dakota State University, in Brookings. Michael L. Scott (scottmikeski@gmail.com) is an adjunct assistant professor in the Department of Watershed Sciences at Utah State University, in Logan. W. Carter Johnson (carter.johnson@sdstate.edu) is a distinguished professor in the Department of Natural Resource Management at South Dakota State University, in Brookings. Mark D. Dixon (mark.dixon@usd.edu) is an associate professor in the Department of Biology at the University of South Dakota, in Vermillion.