RELATION OF MISSOURI RIVER FLOWS TO SANDBAR MORPHOLOGY WITH IMPLICATIONS FOR SELECTED BIOTA

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by
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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled

RELATION OF MISSOURI RIVER FLOWS TO SANDBAR
MORPHOLOGY WITH IMPLICATIONS FOR SELECTED BIOTA

Presented by Emily Tracy-Smith

A candidate for the degree of Master of Science

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TABLE OF CONTENTS

EFFECTS OF DISCHARGE ON THE AQUATIC-TERRESTRIAL TRANSITION ZONE (ATTZ) OF LOWER MISSOURI RIVER SANDBARS AND THEIR USE BY SELECTED BIOTA

LIST OF TABLES

LIST OF FIGURES

RELATION OF MISSOURI RIVER FLOWS TO SANDBAR MORPHOLOGY WITH IMPLICATIONS FOR SELECTED BIOTA

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ABSTRACT

Channel modification and flow regulation in historically braided large rivers, have reduced sandbars and associated highly productive habitats for riverine biota. Rehabilitation of sandbars and adjacent shallow water is a management priority in the Lower Missouri River. Sandbars are an important interface between aquatic and terrestrial environments, i.e. an aquatic-terrestrial zone (ATTZ), within the main channel of the Lower Missouri River. Predictive models of sandbar morphometry (area, wetted perimeter, elevation, and water-surface slope) were developed to determine how changes in discharge affect the quantity of submergent-sandbar ATTZ (depth) and emergent-sandbar ATTZ (elevation) for a representative sample of Lower Missouri River sandbars. Thirteen sandbars of two dominant classes were evaluated: point sandbars (formed on the inside of river bends) and wing-dike sandbars (formed downstream of navigation structures). Models of sandbar area as a function of discharge were applied to high- and low-flow scenarios proposed by resource agencies to explore the effect of sandbar habitat availability on foraging of migratory shorebirds and wading birds, nesting of softshell turtles, and nursery of riverine fishes. Both sandbar types provide a variety of ATTZ habitat conditions in the current channel. Point sandbars were as much as 22 times greater in mean area than wing-dike sandbars for submergent and emergent ATTZ, whereas wing-dike sandbars were more abundant, composing 85% of all sandbars in the Grand River to Osage River segment of the Lower Missouri River. Rehabilitation of sandbars should incorporate aspects of the natural hydrograph (e.g., low flows) to benefit the ATTZ. This will enhance habitat diversity and functional integrity within the main channel of the Lower Missouri River, while maintaining other beneficial uses. Contemporary flows (CWCP) and flows under selected management alternatives (GP1528 and GP2021), within the current channel configuration, created more habitat for selected biota than under modeled flows of the natural flow regime (ROR). Reduced summer flows associated with alternatives GP1528 and GP2021 increased available wetted perimeter in July and August for post breeding wading birds and during the beginning of autumn shorebird migration while also creating more emergent-sandbar habitat during softshell turtle nesting. Flows under the current water control plan (CWCP) and selected management alternatives provided greater available area of shallow-depth ATTZ during the initial months of age-0 riverine fish nursery than under the natural flow regime (ROR). Hence, the natural flow regime could limit age-0 recruitment of many riverine fishes. Results can be used to further understand the effects of river management on sandbar habitat availability and provide guidance in selecting future flow management alternatives.

CHAPTER I

OVERVIEW OF STUDY

Sandbars in rivers are dynamic habitats important to many birds, fishes and reptiles. Their morphology fluctuates with cycles of erosion and deposition as surface area alternates between aquatic and terrestrial environments, known as the "aquatic/terrestrial transition zone" (ATTZ) (Junk et al. 1989). Sandbars have only sparse plant cover and little or no woody vegetation, whereas islands have woody riparian vegetation (Ward et al. 2001). Studies reporting the function and ecological role of islands and sandbars exist on a number of rivers, including the Tagliamento in NE-Italy (Gurnell et al. 2001, van der Nat et al. 2001, Tockner et al. 2003) Danube in Austria (Ward et al. 2001), the Colorado (Rubin et al. 1990, Webb et al. 1999), Snake (Osterkamp 1998), Mississippi (Johnson and Jennings 1998), and Missouri (Gale et al. 1985) in the Untied States. Sandbars and islands within large rivers and the shallow, low-velocity flows associated with them increase habitat diversity in the main channel (Johnson and Jennings 1998).

Importance of Flow

Sandbars exist as a consequence of interactions among channel geomorphology, sediment transport, and river flow. This dynamic relationship contributes to varying rates of erosion and deposition conducive to formation and maintenance of sandbars. Rates of sandbar deposition and erosion vary with flow magnitude and duration, tributary sediment supply, amount of sand stored in river channel pools and eddies, and local channel hydraulics (U.S. Department of the Interior 1995). Timing of river flow influences plant composition and successful riparian seedling establishment on sandbars (Dixon 2003) and also availability of habitat conditions important to riverine biota. For example, populations of the federally endangered interior least tern *(Sterna antillarum)* typically nest on sandbars (Smith and Renken 1991), in particular reaches below Gavins Point Dam, the upper Missouri River Basin (Ziewitz et al. 1992), and in the Mississippi River valley (Smith and Renken 1991). Least terns forage on small fishes in shallow water on the sandbar's edge. Tibbs and Galat (1998) presented a conceptual model of temporal linkages among river stage, least tern reproduction, sand island area, and forage fish availability in the lower Mississippi River in Missouri. River stage, in their model, determines when the floodplain is available to fishes for spawning, which determines the abundance of small fishes, and stage also influences availability of sand islands for least terns to nest and when they will require forage for their young (Tibbs and Galat 1998).

Sandbar and Island Habitats

Sandbars and islands provide habitat conditions used by a number of species. Both sandbars and islands serve as temporary or permanent habitats for aquatic invertebrates, fishes, and amphibians (van der Nat et al. 2001, Tockner et al. 2003). Islands provide shallow-water habitat and access to different forms of food for macroinvertebrates (Thorp 1992). The large number of sandbars and islands on the Tagliamento River (Gurnell et al. 2001) create habitats for terrestrial invertebrates and the link between islands and large woody debris helps maintain both habitat and amphibian diversity (Tockner et al. 2003).

Surfaces of islands and sandbars facilitate deposition and storage of large woody debris (Gurnell et al. 2002) which in turn stabilizes sandbars sufficiently to initiate plant colonization. In time, plant community succession can lead to established islands (Kollmann et al. 1999). The accumulation of fine sediments is important for moisture retention that influences establishment of riparian tree species (Gurnell et al. 2001). Riparian zones of islands produce more snags and leaf litter than nearby main channel banks and these habitat conditions, when submerged, support a diversity of benthic macroinvertebrate assemblages (Thorp 1992). Coutant (2004) hypothesized that submerged riparian habitats located downstream from sturgeon spawning locations provide surfaces for fertilized egg attachment, hiding places, and invertebrate food sources for Acipenserid sturgeon larvae.

Sandbar Shoreline and Edge Habitat

Perimeters of emergent sandbars and islands are a source of edge-of-water (edge) or shoreline habitats within the main channel of rivers. Edge is an important habitat in large rivers, especially channelized rivers where little edge currently exists (Hesse 1995). Both the amount of edge and its shape (sinuosity) are important. High shoreline sinuosity increases microhabitat availability of important nursery areas and refugia for larval and juvenile fishes as well as enhances zooplankton production (Schiemer et al. 2001a). Maximum diversity in a river system should occur where there is an optimal mix of patch and edge habitat (Tockner and Ward 2001). Edge habitats are used by many riverine species including; softshell turtles (Plummer 1977a), shorebirds (Rundle and Fredrickson 1981) and riverine fishes (Scheidegger and Bain 1995, Johnson and Jennings 1998). Edge habitats include shallow, low-velocity habitats, important for providing nursery habitat to larval fishes, especially in rivers that lack connection to their floodplain (Scheidegger and Bain 1995). Edge habitat of sandbars shifts by way of the "moving littoral" (Junk et al. 1989) where fluctuations in water surface elevations change the shape and location of the sandbars edge. The perimeter of sandbars provides inshore retention areas that determine hydraulic and morphologic conditions important for productivity of riverine zooplankton and nursery areas for larval and juvenile riverine fishes (Schiemer et al. 2001a). Retention of fish larvae and their food resources will affect recruitment of species that depend on the conditions of isolated inshore areas (Schiemer et al. 2001a, Winemiller 2004).

The Flood Pulse

The annual hydrograph of large rivers, including flood pulses and low-flow periods, is believed to play a primary role in biotic productivity (Junk et al. 1989, Poff and Ward 1989, Poff et al. 1997). Flooding of floodplains and the interchange between aquatic and terrestrial ecosystems is essential to the well being of amphibious plant species (Sand-Jensen and Frost-Christensen 1999), for recruitment of fishes (Bénech and Penáz 1995, Gehrke et al. 1995), to support large populations of waterbirds (Kingsford 1995), and proper nutrient cycling and maintenance of riparian forest mosaics (Steiger et al. 1998). The flood pulse is thought to be important for the natural redistribution of sediments and linkage between the river and its floodplain, both of which are important for the productivity and interactions of the major biota in river-floodplain systems (Junk et al. 1989). Changes in the timing and duration of flooding may have long term effects on ecological processes within river-floodplain systems (Kingsford 2000).

Aquatic-Terrestrial Transition Zone (ATTZ)

According to Junk et al. (1989) a "river-floodplain system" includes permanent main-channel lotic habitats, permanent lentic habitats, and the floodplain, the latter referred to by them as the "*aquatic/terrestrial transition zone*" or *ATTZ.* Junk et al. (1989) and Junk (2005) define the ATTZ as synonymous with "floodplain" because it alternates between aquatic and terrestrial environments. Here the flood pulse creates a dynamic edge as the "*moving littoral*" traverses the ATTZ (Junk et al. 1989, Junk and Wantzen 2004, Junk 2005). Junk et al. (1989) *flood pulse concept* (FPC) explains the functions of large-river floodplain ecosystems and the dynamic relations between biota and the environment of unaltered, large-river floodplain systems. However, I argue that their definition of the ATTZ is overly restrictive, especially in its exclusion of main-channel areas that also exhibit a moving littoral, albeit with different frequency.

The main channel of altered and unaltered rivers represents more than permanent lotic habitats, they also contain marginal areas that alternate between aquatic and terrestrial environments, i.e. ATTZ. The FPC diminishes the importance of main-channel habitats, asserting that most fishes use the main channel only to gain access to the floodplain's more suitable habitats (Junk et al. 1989). Research on habitat use by fishes in eight north-temperate large rivers concluded that >25% of native fish species were capable of completing their lifecycle exclusively in the main channel (Galat and

Zweimüller 2001). The collection of large numbers of larval and juvenile fishes in main channel habitats (Holland and Sylvester 1983, Copp 1997, Gadomski and Barfoot 1998, Jurajda 1999, Dettmers et al. 2001) indicates the ability for fishes to use habitats within the main channel for spawning and nursery areas.

Whereas Junk et al. (1989) defined the ATTZ to encompass only the inundated zone within the floodplain, I extend the ATTZ herein to also include the moving littoral along the border of the primary channel and the moving littoral associated with islands and sandbars, referring to it hereafter as the *channel-margin ATTZ* (Reeves 2006). The channel-margin ATTZ is an integral part of the total river-floodplain ATTZ. In large rivers with intact floodplains, the channel-margin ATTZ area might be small relative to the floodplain ATTZ. For example, the Tagliamento River in NE Italy is a pristine river floodplain system that has retained a dynamic, intact river corridor along almost its entire length, lateral floodplain connectivity, and high habitat heterogeneity, including a large number of vegetated islands (Tockner et al. 2003). Islands in the Tagliamento River are areas of channel-margin ATTZ that enhance biodiversity as their shorelines create a mosaic of habitat patches (Gurnell et al. 2001). The Tagliamento River represents a natural river with areas of both channel-margin ATTZ and floodplain ATTZ that maintain habitat heterogeneity throughout the entire river corridor.

However, for many large rivers throughout the world, including the Missouri River, a disconnected floodplain is common. Flow regulation, one consequence of damming, disrupts the structure and function of river-floodplain systems by altering the frequency, magnitude, timing, and duration of flooding of the floodplain (Ward and Stanford 1995, Richter et al. 1996, Poff and Hart 2002). Levees further disconnect floodplains from rivers by preventing lateral migration of the flood pulse and increasing flood stages for overbank discharges (Bayley 1995, Sparks 1995, Schiemer et al. 1999). Together, flow regulation and levees decrease effectiveness of the floodplain ATTZ. Channelization (straightening, narrowing, and deepening the channel for purposes of navigation and channel stability) affects the river-floodplain system by reducing geomorphic complexity within the banks. The cumulative effect of levees and channelization reduces hydrologic connectivity to the floodplain (Sparks 1995) and reduces the amount of channel-margin ATTZ (Schiemer et al. 1999).

I have expanded the Junk et al. (1989) principle of ATTZ by incorporating both the channel-margin ATTZ and floodplain ATTZs as separate but complementary components of a comprehensive river-floodplain ATTZ. Applying the ATTZ and moving littoral principles (Junk et al. 1989, Junk 2005) to the entire cross section of a river-floodplain system facilitates consideration of the ecological importance of a much broader range of flows than the floodplain ATTZ alone. Whereas the importance of channel and floodplain connectivity and the effects of flow regulation on the ecological integrity of river-floodplain systems has been recognized (Ward and Stanford 1995, Steiger et al. 1998, Stanford and Ward 2001), fewer studies have focused on the significance of in-channel habitats (Humphries et al. 1999, Dettmers et al. 2001, Galat and Zweimüller 2001, Humphries et al. 2002) or the ATTZ (Schiemer et al. 1991, Humphries et al. 1999, Schiemer et al. 2001a, Humphries et al. 2002).

Within the main channel of the flow-regulated and channelized Missouri River, many areas have a moving littoral. The moving littoral occurs at the margins of sandbars (hereafter *sandbar ATTZ*) and islands, at the river’s natural landward bank, and along the edges of engineered structures (e.g. rock dikes or groynes, shoreline revetment). I focus on and define the sandbar ATTZ as the sandbar margins (moving littoral) that are alternately above and under water within the annual hydroperiod (Fig. 1.1).

The moving littoral is dynamic in that its location is constantly changing with the stage of the river. Although the flood pulse is subdued in many regulated rivers, they still experience frequent, albeit smaller, water level fluctuations or "flow pulses" (Tockner et al. 2000). These flow pulses are particularly important in maintaining habitat heterogeneity within the channel-margin ATTZ.

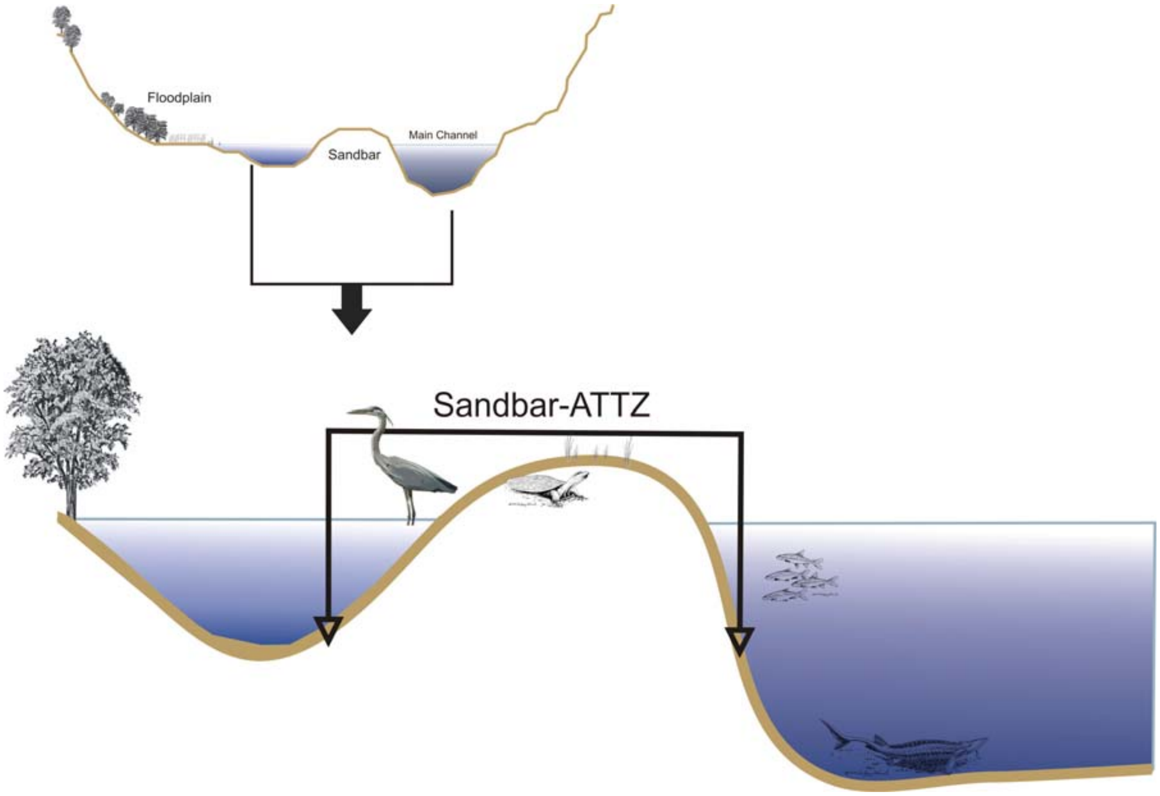


Figure 1.1. Diagram of the aquatic-terrestrial transition zone associated with sandbars and the habitat available to riverine biota. Clip art images of softshell turtle, sturgeon, and plains minnow were provided by ©2002 Zachery Zdinak.

Flow Regulation and Engineering Modifications

Regulation of flow is a widespread occurrence for many managed rivers throughout the world (Dynesius and Nilsson 1994, Poff et al. 1997, Bunn and Arthington 2002). For example, the natural flow regime of the Murray-Darling has been altered with a considerable decrease in average monthly and annual flows and as regulation has increased there has been a decrease in the range and abundance of many native species (Maheshwari et al. 1995, Sheldon and Walker 1997, Humphries et al. 1999, Kingsford 2000). It has been estimated that European riverine floodplains have lost up to 95 % of their historical wetlands and it has been predicted that floodplains across Asia, Africa, and South America will also increasingly disappear (Tockner and Stanford 2002).

Engineering structures and regulation activities altered many historically island-dominated floodplain rivers to rivers being nearly devoid of islands (Gurnell and Petts 2002). European rivers were characterized as having multiple channels separated by vegetated islands prior to centuries of extensive river management (Petts et al. 1989, Gurnell et al. 2001). Currently, only 1% of braided and meandering sections of Austrian rivers remain intact (Tockner et al. 2003). The floodplain system along the Danube River was once active with branched channels, many gravel bars, and vegetated islands. Islands and bars on the Danube have decreased by 94% and floodplain area by 88% due to channelization and hydropower production (Jungwirth et al. 2002). Unvegetated sandbars were a common feature on the Colorado River in Grand Canyon National Park, Arizona (Schmidt et al. 1998). Since the 1966 construction of Glen Canyon Dam on the Colorado River, sandbars downstream of the dam have decreased in size and number (Kearsley et al. 1994, Hoeting 1998). Channelization of the lower Missouri River has eliminated about 40, 500 ha of aquatic habitat, 151, 500 ha of wetland and terrestrial habitat (Hesse et al. 1989), and reduced the number of sand islands and their total area by 97% (Funk and Robinson 1974).

Missouri River

The predevelopment Missouri River was characterized by braided shifting channels and numerous sandbars and islands (Galat et al. 1998, Galat et al. 2005). Since the 1920s, the U.S. Army Corps of Engineers (COE the federal agency responsible for operational management of the Missouri River) has constructed six large multi-purpose dams along the Missouri River for flood control, power production, irrigation, water supply, navigation, recreation, and fish and wildlife benefits. This six-dam river-reservoir system, extending from Fort Peck Lake (Fort Peck Dam), Montana, to Lewis and Clark Lake (Gavins Point Dam), South Dakota, impounds 1,233 km of the river (Patrick 1998). The Missouri River is confined by revetment and dike structures beginning approximately 97 km downstream from Gavins Point Dam (km 1,305). This has converted the former braided channel into largely a single channel with stabilized riverbanks that enable commercial barge navigation (Ferrell 1996). This channelized section extends 1,178 km downstream from Sioux City, Iowa, to the confluence with the Mississippi River near St. Louis, Missouri (Galat et al. 2005), and hereafter is referred to as the *Lower Missouri River* (Fig. 1.2). Releases from Gavins Point Dam supplement downstream tributary flows to maintain downstream navigation flow targets.

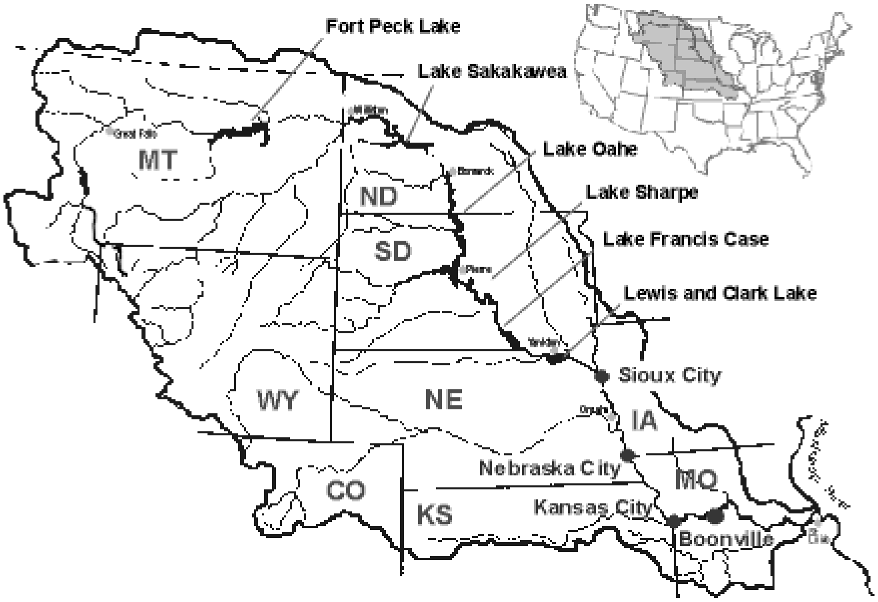


Figure 1.2. Missouri River basin and the main stem reservoir system. The Lower Missouri River extends 1,178 km from Sioux City, Iowa to St. Louis, Missouri.

The COE is responsible for maintaining a 2.7 m (9 ft) deep, 91.4 m (300 ft) wide channel for commercial navigation. The navigation season is usually 8 months long, beginning April 1 and ending December 1 at the mouth of the river. Materials transported include; petroleum, coal, chemicals, wheat, corn, soybeans, sand, gravel, stone, metal, and forest products. Management of the Lower Missouri River for multiple uses has engendered many conflicts (National Research Council 2002).

Dam operations have nearly eliminated natural high spring flows and low summer flows along portions of the Lower Missouri River. Dam operations affect sandbar creation by reducing sediment input and reducing high spring flows that both deposit new sandbars and scour vegetation off existing sandbars. Maintaining high summer flows for barge traffic reduces availability of shallow water adjacent to sandbars; these shallow-water areas are thought to be important to newly spawned fishes (U.S. Fish and Wildlife

Service 2000). Navigation flows in the summer also may eliminate emergent sandbar habitat for nesting softshell turtles and foraging habitat along the edge of sandbars for resident and migrating waterbirds. A comparison of the historical or predevelopment hydrograph (1925-1952) with the modern/post-development hydrograph (1967-1999) for Boonville, Missouri [River Kilometer (km) 317] illustrates the changes in timing and magnitude of peak flows, and the volume of low flows (Fig. 1.3) (Jacobson et al. 2001).

Missouri River Sandbars

The Lower Missouri River has many types of sandbars; some form off navigation structures while others form where point sandbars naturally occurred. Unlike unchannelized rivers, many sandbars are formed by flow separation downstream of navigation structures (i.e., rock wing dikes). These structures were constructed to direct river current toward the center of the channel to maintain a self-scouring channel for navigation. Point-bar sandbars form adjacent to the convex (inner) bank of meander bends as erosion occurs on the opposite concave (outside) bank (Sundborg 1956, Allen 1966, Hooke 1974, Smith 1974, Noble 1979, Nanson 1980, Dykaar and Wigington Jr 2000). Spur-dike sandbars form downstream of navigation structures that are perpendicular to the flow of the river and L-dike sandbars form downstream of navigation structures that begin perpendicular to river flow and end parallel to the flow in the shape of an L. Trailing-dike sandbars form downstream of revetment that extends from the bank parallel to the flow. Details on the design and function of river control structures are given by Lindner (1969). Tributary sandbars form directly downstream of a tributary confluence. Approximately 87% of all identified sandbars and islands and

90% of all emergent sand area present on the Lower Missouri River (km 1,178 to 0) are composed of channel islands, point, spur, and L-dike sandbars (Fig. 1.4, Table 1.1). My research focused on point sandbars because they compose the greatest total area within the selected study reach (km 402 to 209, Table 1.2) and on sandbars associated with navigation structures (i.e., spur, L-dike), hereafter wing-dike sandbars, because of their dominance in terms of frequency.

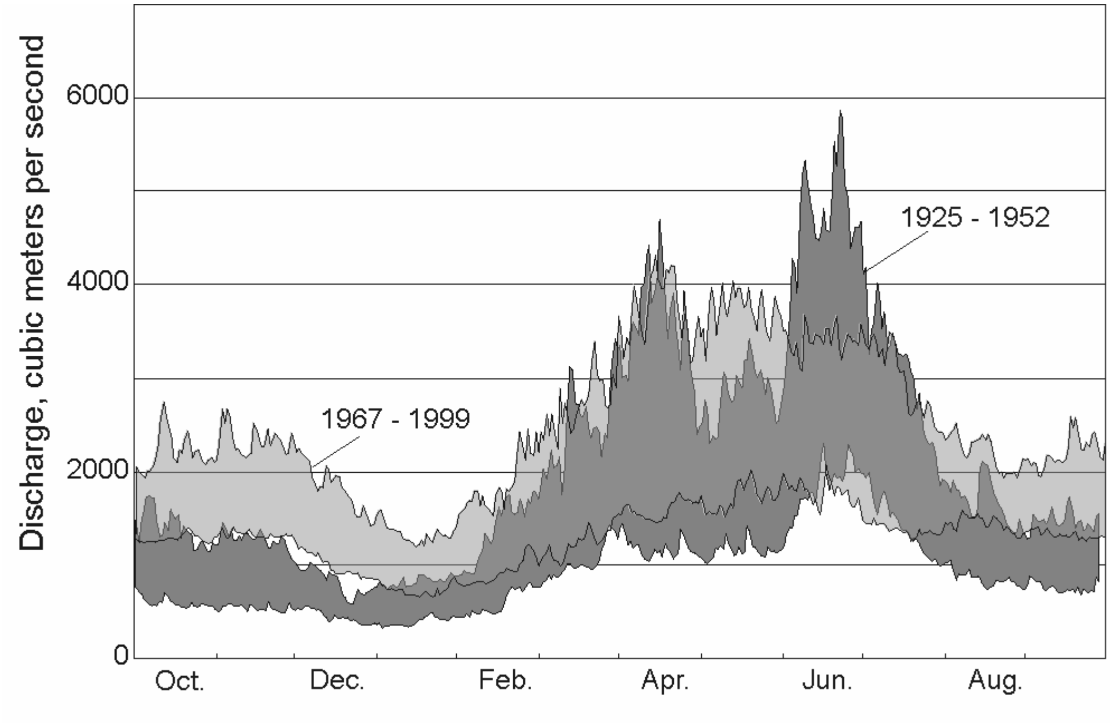


Figure 1.3. Duration hydrographs for the Missouri River at Boonville, Missouri (km 317). The shaded band of discharge for pre-regulation (1925-1952) and post-regulation (1967 – 1999) periods is the range of values between the 25th and 75th percentile of flows each day of the year. Reservoir regulation has decreased variability of flows and shifted seasonality to maintain navigation in the lower river between April and November (source: Jacobson et al. 2001).

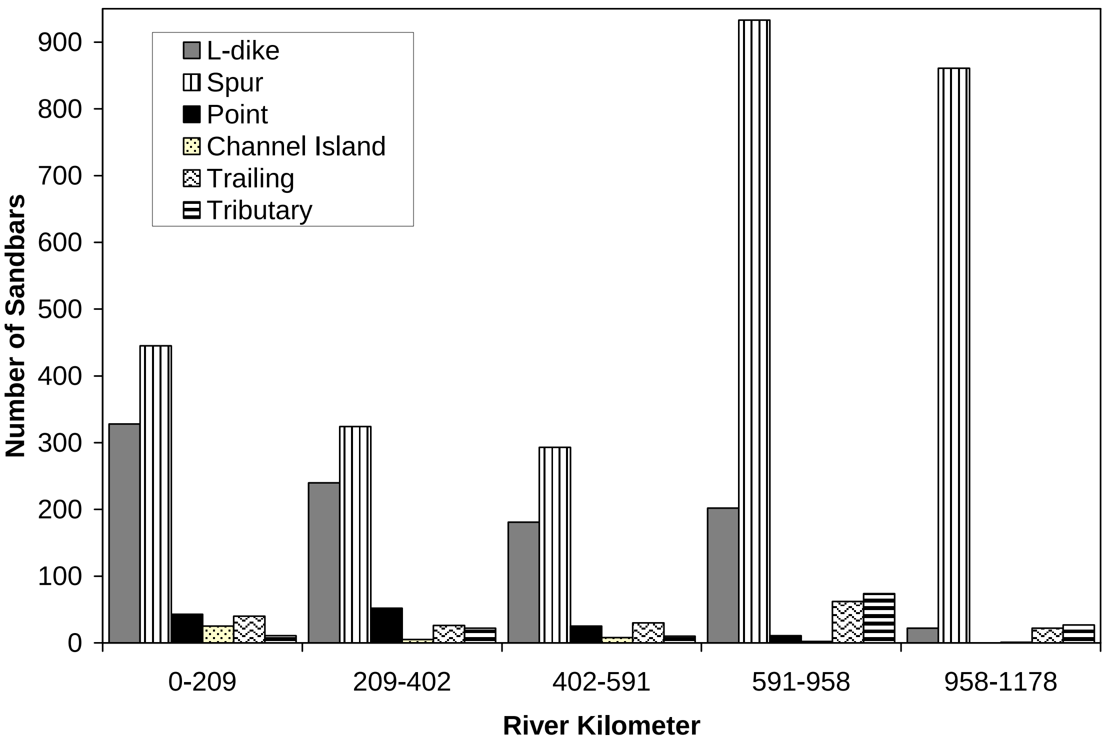


Figure 1.4. Plot of all emergent sandbars, classified by sandbar type, from digital orthophotographs of the Lower Missouri River between river kilometer 1178, near Sioux City, Iowa, and the confluence of the Missouri and Mississippi Rivers, at river kilometer 0.0 at St. Louis, Missouri. River kilometer divisions represent segments of the Lower Missouri River based on hydrologic (tributaries) and anthropogenic (impoundment, channelization) features. Photos were collected by the US Army Corps of Engineers between February and March 2000. See text for definitions of sandbar types.

Defining shallow-water habitat within the ATTZ

The COE was requested by the U.S. Fish and Wildlife Service (USFWS) to formally consult on their operations of the Missouri River main-stem system and operation and maintenance of the Missouri River Bank Stabilization and Navigation Project (U.S. Fish and Wildlife Service 2000). The USFWS was specifically interested in how COE operations related to the federally listed endangered pallid sturgeon and least tern, and the threatened piping plover and bald eagle. The USFWS concluded in their

“Biological Opinion” (BiOp) on the operation of these projects that the COE had severely altered natural hydrology, and degraded and reduced riverine aquatic habitat, sandbar habitat, and terrestrial floodplain habitat important to listed and non-listed species in the Missouri River System (U.S. Fish and Wildlife Service 2000). The USFWS determined that a portion of the historical shallow-water, low-velocity habitat defined by them as ranging from 0-5 ft (0-1.5 m) deep and from 0-2 ft/s (0-0.6 m/s) water velocity must be restored and set a restoration goal of 7,924 ha for the lower Missouri River (U.S. Fish and Wildlife Service 2003). I integrated definitions of shallow-water habitat (SWH) into my concept of ATTZ. I view SWH as a component of channel-margin ATTZ and specifically sandbar ATTZ. Shallow-water habitat represents a fixed measurement of habitat, when habitat intrinsically is not static because it is constantly changing via physical and biological factors (Stanford et al. 2005). The ATTZ emphasizes the dynamic nature of the moving littoral and thus is a more realistic depiction of the diversity and dynamic nature of habitats associated with sandbars.

Numerous habitat mitigation projects have since been initiated by the COE to create or enhance sandbars along the lower Missouri River (U.S. Army Corps of Engineers 2004b). The COE is responsible for protection and maintenance of existing sandbar habitat and the restoration of a diversity of shallow/slow-water sandbar/island habitats through flow management, restoring chutes and side channels, manipulating summer flows, and mechanically creating SWH habitat, or combination thereof, to implement alternatives defined by the USFWS (U.S. Fish and Wildlife Service 2003).

Table 1.1. Frequency, total area, and percentages of each, classified by sandbar type for all sandbars identified on the Lower Missouri River, MO (1,178 km to 0) from US Army Corps of Engineers orthophotographs (extensive dataset) between February and March 2000. See text for description of sandbar types.

Sandbar Type	Number of Sandbars	Percent	Total Area (ha)	Percent Area	Perimeter (m)
Island	41	1	1,005	34	85,415
L-dike	973	21	298	10	301,746
Spur-dike	2,856	62	655	22	856,356
Point	131	3	709	24	154,969
Trailing-dike	180	4	44	1	51,306
Tributary	144	3	26	1	29,099
Other	256	6	230	8	126,984
Total	4,581	100	2,967	100	1,605,875

Research Goals

My research project was initiated to provide objective information to the COE and other management agencies to aid in their evaluating potential biological outcomes of management activities. Existing sandbars on the Lower Missouri River were used to quantify river discharge sandbar area relations and develop predictive models of this relation. Life-history information on select biota was applied to river discharge sandbar area models to evaluate habitat availability in relation to its use by biota for reproduction and foraging. Furthermore, I contributed to the definition of ATTZ by looking at the moving littoral associated with sandbars and evaluating its potential influence on biota.

Table 1.2. Frequency and total area (ha) of all emergent sandbars, classified by sandbar type, from orthophotographs of the Lower Missouri River (extensive dataset) between river kilometer 1,178 (mile 732), near Sioux City, Iowa and the confluence of the Missouri and Mississippi Rivers, at river kilometer 0 (mile 0). River kilometer divisions represent segments of the Lower Missouri River based on hydrologic (tributaries) and anthropogenic (impoundment, channelization) features. See text for description of sandbar types.

	Segment designation by river kilometer				
Sandbar Type	0 – 209	209 – 402	402 – 591	591 – 958	958 –1178
Island	25 (903)	5 (29)	8 (56)	2 (5)	1 (12)
L-dike	328 (136)	240 (83)	181 (50)	202 (27)	22 (2)
Spur-dike	71 (128)	50 (66)	21 (9)	57 (10)	57 (17)
Pointbar	43 (395)	52 (256)	25 (53)	11 (5)	0
Trailing-dike	445 (199)	324 (111)	293 (82)	933 (168)	861 (95)
Tributary	40 (16)	26 (9)	30 (7)	62 (11)	22 (3)
Other	11 (5)	22 (11)	10 (1)	74 (8)	27 (1)

CHAPTER II

EFFECTS OF DISCHARGE ON MORPHOMETRY OF LOWER MISSOURI RIVER SANDBARS

Research Objective

My objective was to develop predictive models of sandbar morphometry (area, wetted perimeter, elevation, and water-surface slope) for selected point and wing-dike sandbars from river discharge (hereafter discharge-area models). Specifically, I determined how changes in discharge affect the quantity of sandbar ATTZ for point and wing-dike sandbars within a segment of the Lower Missouri River.

METHODS

River Discharge

Discharge (Q), is the volume of water that passes through a cross-section per unit of time (Gordon et al. 1992). River stage refers to the height of the water surface above an arbitrary or absolute elevation reference point (Gordon et al. 2004). Exposure or the inundation of sandbars is a function of local river stage. Local stage is determined by river discharge distributed according to channel geometry. Local morphology will dictate the location and degree in which stage changes with discharge (Fig. 2.1).

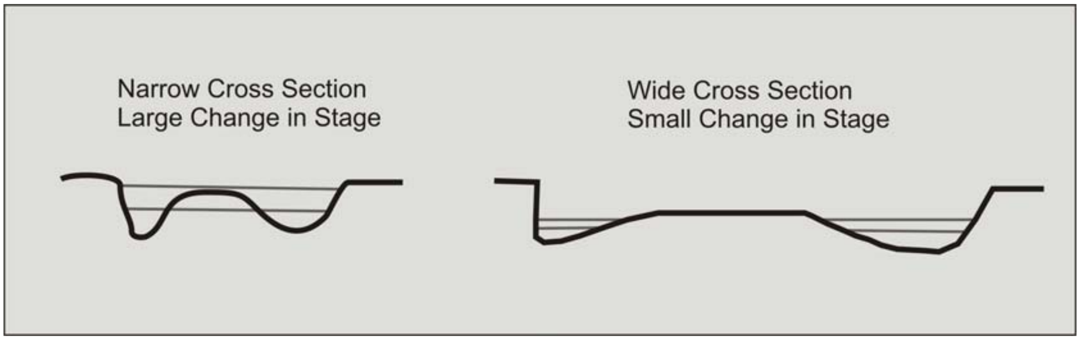


Figure 2.1. Sketch depicting stage changes between a narrow channel and wide channel at the same change in discharge. This illustrates the dependence on local morphology to determine the location and changes in stage.

Discharge is typically measured with a stream gage that records continuous water-surface height, supplemented with periodic discharge measurements that are used to create a stage-discharge relation (rating curve or table). A well-developed rating curve allows for estimation of discharge at virtually any stream stage. Over time, the relation between gage height and discharge can change, requiring periodic discharge measurements to redefine that relation.

Discharge is the variable used in my research because discharge measurements can transfer meaning between gages and locations on the river, whereas stage is specific to location. Discharge is also used to determine long-term flow frequency, and was used to evaluate the frequency, and duration of the existence of particular sandbar conditions. Missouri River discharge is presented primarily in units of thousands of cubic feet per second (kcfs) because it is the common unit used by researchers and agencies on the Lower Missouri River. I have converted these measurements to thousands of cubic meter per second (kcms) (multiplier 0.02832) to conform to international standards of scientific writing.

Study Area

The Lower Missouri River was first divided into segments based on hydrologic (tributaries) and anthropogenic (e.g., impoundments, channelization) features. Tributaries whose mean annual discharge contributed ≥ 5% to the main channel mean annual discharge were the hydrologic feature used to separate segments. This produced four channelized segments: Sioux City to Platte River, Nebraska; Platte River to Kansas River, Kansas; Kansas River to Grand River, Missouri; Grand River to Osage River, Missouri; and Osage River to Mississippi River confluence. A fifth segment was defined in the unchannelized zone between Gavins Point Dam and Sioux City. Sampling sites were selected from the channelized segment between the Grand River (km 402) and the Osage River (km 209, Fig. 2.2). The Grand River to Osage River segment of the Lower Missouri River lies within the Missouri River Alluvial Plain subsection of the Ozark Highlands Ecoregion (Nigh and Schroeder 2002).

A representative sample of sandbars (nine point and ten wing-dike sandbars) was selected within the Grand River (km 402) to Osage River (km 209) segment to include the range of morphometric conditions present within this segment for each sandbar type. These sandbars are hereafter designated as the *intensive* dataset.

Data Collection

Imagery (extensive dataset)

The *extensive* dataset includes digital orthophotographs used to provide an overview of the number of sandbars and area of emergent sandbar habitat for the entire Lower Missouri River. ArcGIS was used to quantify area and perimeter of all

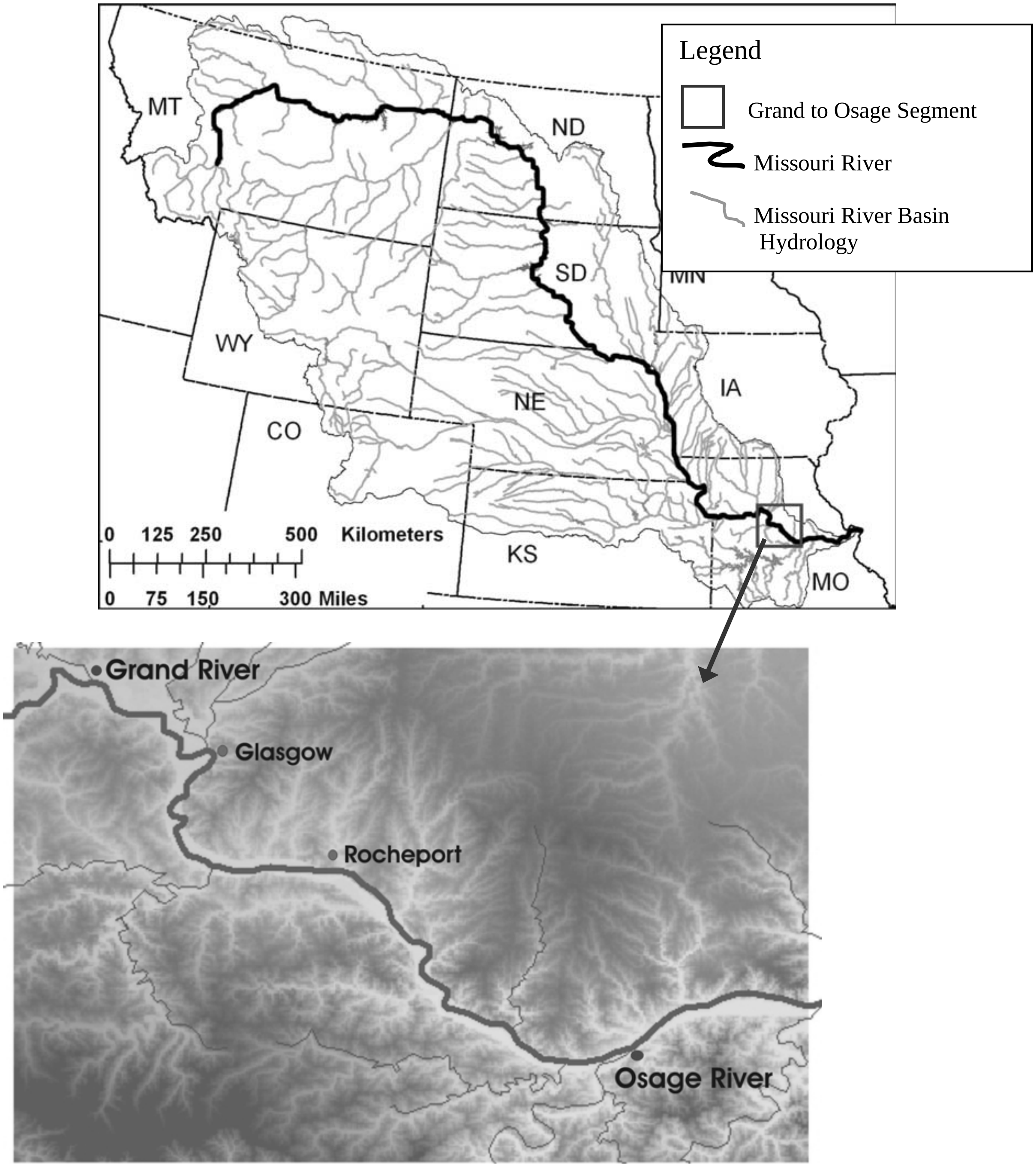


Figure 2.2 Missouri River Basin (top) and the Grand River (km 402) to Osage River (km 209) segment where study sites were located.

identified exposed sand from orthophotographs collected by the US Army Corps of Engineers (km 1,186 to 0) during 2000. The photographs were taken on various dates along different reaches of the Lower Missouri River and discharges varied among photos, ranging from 90% flow exceedance discharges near km 898 to 50% flow exceedance discharges at km 0 calculated from historical flow data, 1968 – 2003. Sandbars were classified by association with expected formation features: point sandbars are formed on the inside of bends; tributary sandbars are formed downstream of a tributary influence; channel islands are vegetated; spur-dike, L-dike, and trailing sandbars were formed in association with these distinctive channel training and revetment structures; and indistinguishable sandbar formations were classified as "other".

Ground Surveys (intensive dataset)

Morphometric variables (total area, elevation, wetted perimeter, and water-surface slope) were measured on each sandbar. Exposed sandbars were mapped using both an electronic Total Station (SOKKIA-SET5W) and Real Time Kinematic system (Trimble Unit 5700/5800) to produce detailed topographic maps. To maintain consistent elevations, permanent benchmarks were set at each sandbar; at least one on the sandbar and one on the adjacent shoreline (Fig. 2.3). Elevation was determined for each benchmark by referencing with an established benchmark using the Real Time Kinematic (RTK) system. Benchmarks were set at the highest elevation point on each sandbar for the longest potential retention time. Multiple benchmarks were set at the highest elevation point on each sandbar, so if one was inadvertently removed, resurveying from known elevations would still be possible.

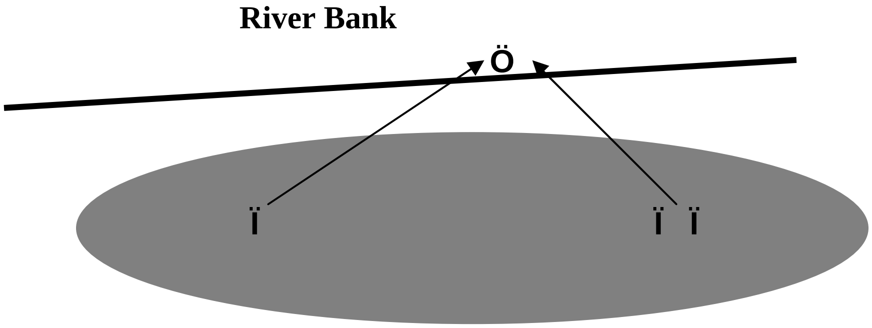


Figure 2.3 Example of the placement of associated sandbar and shoreline benchmarks, where **Ö** represents the shoreline benchmark and **Ï** represents the sandbar benchmarks. Number of sandbar benchmarks on each sandbar varied depending on the size of the sandbar.

For large sandbars, setting distinct transects for surveying was not logistically feasible. Instead, surveying began at either the upstream point of the sandbar (head) or downstream point (tail). The rod-person walked from one end of the sandbar to the other while they traversed from one side of the sandbar to the other (right bank/left bank). The rod-person used their discretion as they traversed with the objective of making rough transects and capturing important elevation changes and slope breaks. If a steep slope or cutback feature was identified, points were captured at the top, bottom and along the waters edge within that feature. For small sandbars and sandbars with minimal sloping topography surveys attempted to keep points close to transect lines and at even spatial intervals across and down the sandbar. Distance between transects was approximately 50 m for point sandbars and 10 m for wing-dike sandbars. While traversing from bank to bank, spacing was dependent on the width of the sandbar. Data points along the waters edge were always collected to quantify perimeter, total area, and water surface elevation.

Total station ground surveys collected x, y, and z coordinates in an arbitrary coordinate system. These data were transformed into real-world coordinates (northing, easting, and elevation) using the RTK system and I consistently used or transferred data according to the geoid99 model. Vertical and horizontal accuracy for the RTK is recorded as overall RMS, a formal statistical root mean-square error of the solution in meters, which averaged 2 to 3 centimeters. The calculated error associated with correcting elevations of topographic surveys (converting ground surveys to real world coordinates) averaged 3 centimeters.

Sandbars were mapped over a range of river discharges between 2002 and 2005 to develop empirical discharge-morphometric relations. Some sandbars were discarded from the dataset because frequent inundation prevented thorough surveys or an insufficient range of flows was surveyed. Of the 19 originally selected, 13 (six point and seven wing-dike sandbars) provided sufficient data to meet our quality standards and were retained for further analysis.

Discharges were obtained from USGS (http://water.usgs.gov/mo/nwis/rt) for days that sandbars were mapped. I used the nearest gage station relative to major tributaries for the location of each sandbar. Discharge values were adjusted to the location of the sandbar by river mile using straight line interpolation between gages to provide a more accurate value of discharge at the sandbar location. Hourly changes of discharge were reviewed after each survey. Data from surveys were not used for analysis if discharge changed more than 5% during the survey period. Three hours was the average length of time for surveys to be completed and discharge tended not to vary greatly within this interval.

Data Processing

Data processing involved the production of a series of topographic grids from sandbar survey data used to develop discharge-morphometric relations. Data processing involved many steps (Fig. 2.4) and multiple software programs (Table 2.1). Upon returning from the field, total station surveys were downloaded and corrected for errors. To manage multiple surveys, each survey was kept in a hierarchical filing structure according to sandbar, year, and date. Each survey was then processed individually. Coordinates (arbitrary x and y) of each survey were transformed into real world coordinates by applying the RTK data of each sandbar’s benchmarks. Total station elevation data (z) was transformed to RTK elevations based on RTK benchmark elevations from respective benchmarks. The final corrected files were saved as text files to import into ArcGIS. ArcView GIS (3.3) and ArcGIS (9.0) were used to develop topographic elevation grids for each complete topographic survey. Ground surveys consisting of perimeter and water surface elevation data only, could not be used to create topographic grids, but still provided information on other physical parameters such as emergent area, wetted perimeter, and water-surface slope.

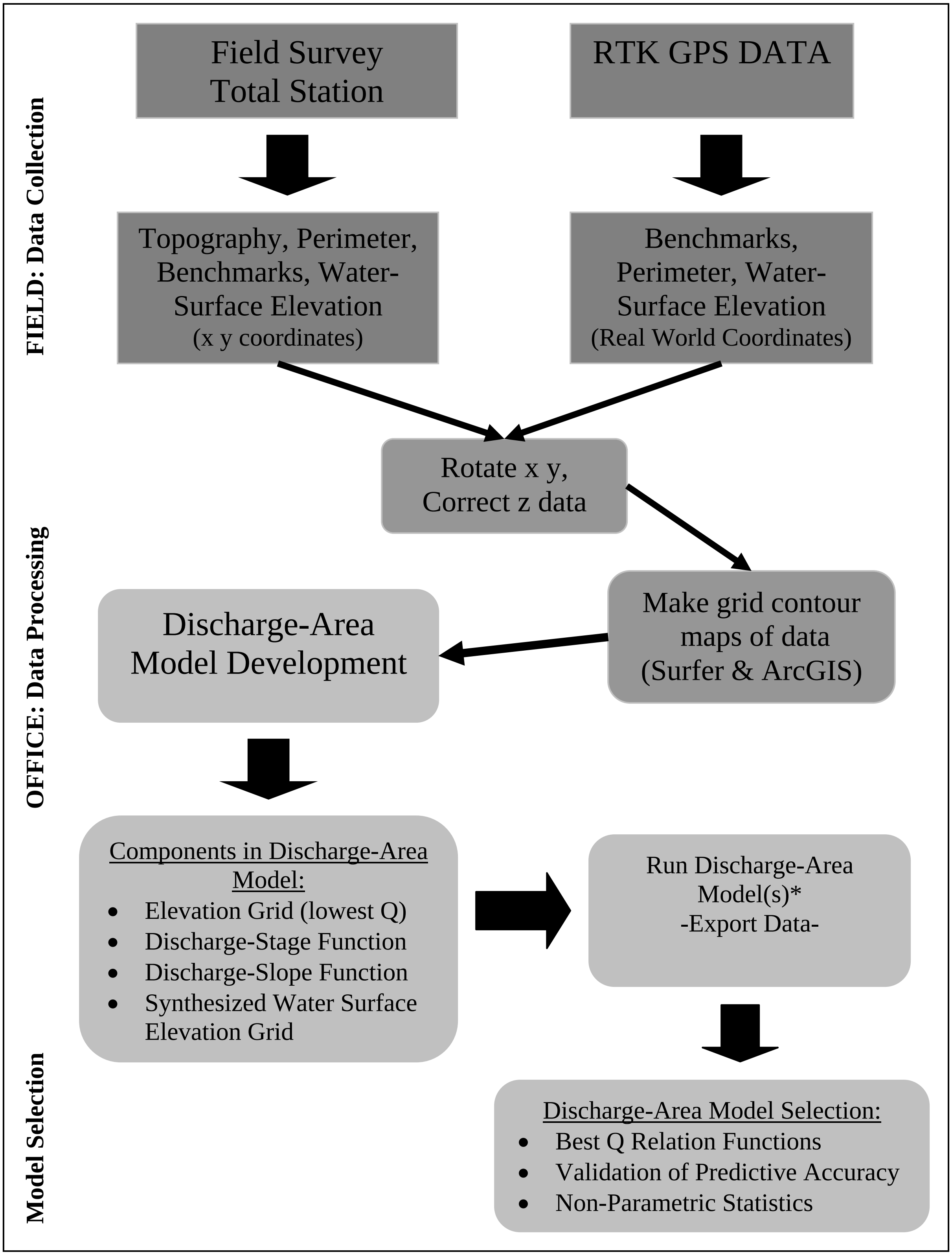


Figure 2.4. Flow chart of data collection, processing, and discharge-area model development and criteria for selection. * Multiple discharge-area models were run if more than one discharge-slope function was identified for a sandbar.

Table 2.1. Procedures, programs, and steps involved in editing and processing of sandbar topographic survey data for the development of predictive discharge-area models.

Procedure	Program(s)	Steps
Rotate x, y coordinates	Trimble Geomatics Office	Import survey and use coordinate transformation tool to transform current easting (x) and northing(y) to known x and y using RTK coordinates.
Correct Elevation (z)	Excel	Elevation differences are calculated between RTK and survey measurements at Sandbar Benchmarks (Head, back-sight, Tail, and shore) for each individual sandbar topographic survey. The average of the differences is added to elevation data in spreadsheet to correct for elevation. Subtracting the differences between the results of the corrections is the associated error (see table 2) for each grid.
Elevation Grids	ArcView (3.2)	Table of data is imported to create blanking files needed to “blank” out no value grid files in Surfer. Also used to digitize perimeter of each survey for use in area and perimeter analysis.
Uniform Elevation Grid	Surfer	Surfer is used for interpolation between data points so a uniform grid of elevation can be created. Surfer uses the krigging method to interpolate continuous grids with chosen spacing. We used 8 sectors for search.
Elevation Grids	ArcGIS/Arc Map (9.0)	Converts grid data created in Surfer to Raster Data at specified grid spacing (5-m for large sandbars and 1m spacing for small sandbars) to produce final output grid.
Distance Ratio Grid	ArcGIS & ArcView	Take a line feature them that defines center line of sandbar and cross section lines and convert to a point theme such that each point has an attribute that represents distance along the sandbar. Calculate the ratio of the distance along the channel from this. Then, use the point to make a TIN, and use the TIN to make a grid.
Model Script	Perl Command Line Interpreter	Used to create an aml file that is used to run the grid operations in Arc GIS.
Depth Grids	Arc Info Workstation – Arc	Used to run aml to produce depth grids from synthesized water surface elevations and know bathymetric surface for a range of discharges 10,000 – 100,000 cfs (283 – 2,832 $m^3 \cdot s^{-1}$) at 2,000 cfs (56 $m^3 \cdot s^{-1}$) increments.
Export Final Depth Grid Data	ArcView GIS 3.2	Used to apply specific legend of depth and elevation gradients to depth grids. Data was exported for each discharge increment using histograms and saving created temp file.

Discharge-Area Model Development

Part two of data processing involved development of predictive models of sandbar area at a specific discharge (Research Objective) using discharge as the independent variable and sandbar area as the dependent variable. Discharge-area model development required three assumptions: 1) sandbar topography (elevation) is stable, 2) sandbar areas are dependent on discharge, 3) sandbars studied are representative of those from the Grand River (km 402) to Osage River (km 209) segment. Our definition of sandbar stability adopts an ideal state where every particle of sand remains in more or less the same location over some defined period (Dexter and Cluer 1999). This strict definition of minimal sandbar flux was implemented by Dexter and Cluer (1999) working in a river system with limited sediment supply. Although the assumption of no sandbar flux is clearly unrealistic for the Lower Missouri River, it is a standard used in instream flow analysis when sediment movement associated with sandbars is unknown or difficult to quantify. My approach provides an initial estimate of how sandbar morphometry may respond to discharge fluctuations and can be further refined as we learn more about Missouri River sediment dynamics.

Components of each discharge-area model included: a discharge-stage function, a discharge-slope function, topographic elevation grid at lowest discharge recorded during mapping, and synthesized water surface elevation grid for each discharge in the model (sandbar ratio grid * length of sandbar * slope function). All components are combined to build a predictive discharge-area model for each sandbar to produce a series of depth and elevation grids for a discharge range of 10 kcfs to 100 kcfs (0.3 kcms to 2.8 kcms) at 2 kcfs (0.06 kcms) increments.

Discharge-Stage Function

Regression analysis was used to develop the discharge-stage function. For each survey, the discharge-stage function was determined by first calculating water-surface slope over the length of the sandbar. Water-surface slope of a river changes with discharge, and slope changes may be substantial for larger sandbars. Sandbar water-surface slope was calculated using the equation slope = Δelevation (rise)/Δ horizontal distance (run). Points of elevation were identified at the water's edge at the uppermost (head) and lowermost (tail) of each sandbar and horizontal distance was measured down the center of the sandbar, always following the horizontal curvature of the sandbar. The downstream elevation point represented the stage of that sandbar at a specific discharge. I first interpolated the stage for each survey outward to the downstream stage location of the largest survey (lowest discharge), referred to as the anchor point for that sandbar. ArcView GIS was used to measure the distance between downstream stage points. Elevation change was normalized to the anchor point at the downstream most survey by multiplying the slope for each survey by the distance between the downstream stage points. This elevation change was then subtracted from the known downstream stage point for that survey. This normalized interpolated stage value was used to produce the discharge-stage function for that sandbar. Within the range of discharges acquired, a linear function best represented the discharge-stage function for all sandbars, with R^2 values ≥ 0.95.

Discharge-Slope Function

Regression analysis also was used to develop the discharge-slope function. To evaluate the effect of changes in water-surface slope with discharge, I applied multiple discharge-slope functions to discharge-area models. Discharge-slope functions with the highest R^2 values were retained for use in the discharge-area models. All wing-dike sandbars had a minimal sandbar water-surface slope, meaning each survey had either zero or nearly zero slope. For two wing-dike sandbars a zero discharge-slope function was most appropriate and no additional discharge-area models were run. For the remaining five wing-dike sandbars I applied both a zero discharge-slope function and an average discharge-slope function. Up to four discharge-slope functions were evaluated for some point sandbars. The discharge-slope functions evaluated for point sandbars consisted of an average slope, zero slope and either a logarithmic, or exponential function, or both.

Discharge-Area Model Selection

Each discharge-area model is referred to by its specified discharge-slope function (e.g., Model 1 = Logarithmic, Model 2 = Average, Model 3 = Zero, Model 4 = Exponential). I evaluated predictive accuracy of each discharge-area model to select the model that best fit empirical field data. Area of emergent sand from survey data was compared to that of predicted sandbar area at a similar discharge (Table A.1). Validation analysis concluded that wing-dike sandbars may not be sensitive to slope for the discharge range observed in this study, so all seven wing dike sandbars in the study retained a zero discharge-slope function. Validation analysis concluded that an exponential discharge-area model was appropriate for one point sandbar (km 343, Model 4) and was further used to reduce the discharge-area models for the five remaining point sandbars to two discharge-area models per sandbar (10 total). True validation data may not be attained because there may be erosion and deposition taking place that was not quantifiable and thus not included in our models. Increases in sandbar area with increasing discharge exhibited in some of our surveys, suggests this is likely a missing component in the models.

The nonparametric Kolmogorov-Smirnov two-sample test was used to determine if the distributions of predicted area were different between discharge-area models for the five point sandbars. Data for analyses were selected at 10 kcfs flow increments and discharges that coincided with validation data (Table 2.2). The Kolmogorov-Smirnov two-sample test is sensitive to differences of all types that may exist between two distributions (Daniel 1990). So, if a statistical difference is found between the distribution of X and Y, the test provides no insight as to what caused the difference.

I failed to reject the null hypothesis that distributions were equal ($P > 0.05$) for all point sandbar discharge-area model comparisons (Table 2.2). Since the distributions were not statistically different, validation data were used to compare area inundated and patterns in shape between predictive models and observed data to select one discharge-area model that best fit empirical field data for each of the remaining five point sandbars. Arc GIS was used to overlay the survey data points with the predicted data points along with their respective elevation and depth grids at similar discharges. Discharge-area model selection resulted in a total of 13 (six point and seven wing-dike) predictive discharge-area models (Table 2.3).

Table 2.2. Results of analysis for five sandbar discharge-area models at specified discharges. Shapiro-Wilk (univariate procedure) tests whether the data are normally distributed and Kolmogorov-Smirnov (non-parametric, m = n) two sample tests evaluate differences in distributions of area between discharge-area models. Model numbers represent the discharge-slope function for each: Model 1 = Logarithmic, Model 2 = Average, Model 3 = Zero, Model 4 = Exponential. P values ≤0.05 indicate distributions were significantly different.

Sandbar River Kilometer	Discharges Analyzed (kcfs)	Shapiro-Wilk Statistic	Kolmogorov-Smirnov Test
Jefferson City 234 Model 2 vs. 3	20, 30, 36, 40, 50, 60, 64, 70, 80, and 90	P <0.0001	P >0.05
Marion 253 Model 2 vs. 3	22, 36, 40, 52, 60, 66, 80, and 90	P <0.0001	P >0.05
Hartsburg 254 Model 3 vs. 4	22, 36, 40, 48, 60, 66, 70, 80, and 90	P <0.0001	P >0.05
Petite Saline 285 Model 2 vs. 4	20, 28, 34, 40, 50, 60, 70, 78, and 96	P <0.0001	P >0.05
Tadpole 288 Model 2 vs. 3	28, 36, 40, 50, 58, 60, 70, 78, 80, 90, and 96	P <0.0001	P >0.05

Morphometric Parameters

Once the final discharge-area models were selected (Table 2.3), morphometric parameters including area and wetted perimeter were extracted from gridded discharge-area model results. To evaluate how point and wing-dike sandbar types differ in area relative to their frequency of occurrence, I first quantified how changes in discharge affected areas of evenly divided *morphometric classes* of depth (-) and elevation (above water level) (+), (i.e., ±0 to 0.5 m, ±0.51 to 1.0 m, and ±1.01 to 1.5 m). The range of

Table 2.3. List of final 13 discharge-area models associated with each sandbar (six point and seven wing-dike) on the Lower Missouri River within the Grand to Osage River Segment evaluated for the effect of discharge (Q) on morphometry (intensive dataset). Components for each discharge-area model included: specific discharge-stage function, discharge-slope function, topographic elevation grid at lowest discharge recorded during mapping, and synthesized water-surface elevation grid for each discharge in model. (Sandbar type: PT = point sandbar, WD = wing-dike sandbar). Model numbers represent the discharge-slope function for each: Model 1 = Logarithmic, Model 2 = Average, Model 3 = Zero, Model 4 = Exponential.

River Kilometer Sandbar Type	Final model selected	Specific linear discharge-stage function	Specific discharge-slope function	Total sandbar area (m^2) at lowest discharge (cfs) from ground surveyed data
234 PT	Model 2	159.06 + (0.0000415*Q)	0.0001739	160,175 Q = 41,000
253 WD	Model 2	160.95 + (0.0000679*Q)	0.0003073	294,700 Q = 23,000
254 PT	Model 4	161.66 + (0.0000624*Q)	0.000130*2.72^(0.0000187*Q)	278,575 Q = 23,000
275a WD	Model 3	165.70 + (0.0000537*Q)	Slope = 0	8,550 Q = 26,000
275b WD	Model 3	165.83 + (0.0000494*Q)	Slope = 0	36,475 Q = 26,000
284a WD	Model 3	167.03 + (0.0000516*Q)	Slope = 0	9,575 Q = 22,000
284b WD	Model 3	166.88 + (0.0000532*Q)	Slope = 0	9,450 Q = 25,000
285 PT	Model 2	167.10 + (0.0000486*Q)	0.0002607	443,300 Q = 28,000
288 PT	Model 2	167.45 + (0.0000520*Q)	0.0001475	280,350 Q = 28,000
320 WD	Model 3	172.45 + (0.0000675*Q)	Slope = 0	31,525 Q = 25,000
334 WD	Model 3	172.87 + (0.0000537*Q)	Slope = 0	6,000 Q = 26,000
343 PT	Model 4	176.68 + (0.0000473*Q)	$3.6817*10^{-9}$ *2.72^(0.000163*Q)	230,250 Q = 34,000
381 WD	Model 3	182.12 + (0.0000582*Q)	Slope = 0	8,875 Q = 26,000

depths and elevations is intended to evaluate areas of habitat that might be used differentially by biota. Mean area by sandbar type (six point, seven wing-dike sandbars) was calculated for each of three morphometric depth and elevation classes versus discharge. I compared mean area among morphometric depth and elevation classes at 2 kcfs (0.06 kcms) increments to determine at what discharge (or range of discharges) morphometric area was maximized within these depth and elevation classes. To compare the shape (distribution) of the discharge-area relationships between sandbar types (Kolmogorov-Smirnov test), area was first normalized based on maximum area for each morphometric class for each sandbar type.

ArcView GIS was used to calculate wetted perimeter and total area (m^2) for each predicted sandbar discharge-area model of emergent sand (+) across a range of discharges of 10 kcfs to 100 kcfs (0.3 kcms to 2.8 kcms) at 2 kcfs (0.06 kcms) increments. Wetted perimeter was calculated by first creating a new grid theme, differentiating the areas inundated as zeros and areas of exposed sand as ones. The new grid was saved as a shapefile and the areas classified with a number one (emergent sand) were summed. Perimeter and area calculations were automated with a script developed for Arc View. I calculated perimeter and associated area in order to calculate the shoreline development index (SDI) which allows evaluation of complexity by normalizing perimeter. The equation for calculating SDI is:

$$SDI = \frac{L}{2\sqrt{\pi A}}$$

When SDI is 1.95, L is 3,475 m, and A is 251,579 m^2.

The shoreline complexity as measured by SDI will relate to the range of microhabitats available and inshore retention capabilities. The SDI is a comparative index used in limnological studies that calculates the degree of irregularity of shoreline margins as the ratio of the shore length to the circumference of a circle of area equal to that of a pond or lake (Goldman and Horne 1983). This index is the relative perimeter of a shape, in our case the water's edge of a sandbar. The smallest index is 1.0, and the longer or more irregular (complex) the shoreline the greater the SDI (Goldman and Horne 1983). I have applied SDI using our perimeter and area calculations of emergent sandbar area (+) to evaluate the variability of shoreline between sandbar types over a range of discharges. Mean SDI, or degree of shoreline heterogeneity, was calculated using area (m^2) and perimeter (m) of emergent sandbar area for six point sandbars and seven wing-dike sandbars.

Measured length of sandbar perimeter depends on the resolution of data. The representation of irregularities in shoreline structure changes with changing scale: as resolution increases (smaller scale) more detail is added thereby increasing the length of the perimeter. Analysis of perimeter at the micro habitat scale is limited by the density of field points collected and the density of grid spacing. The gridding procedure I used interpolates transect data points to create a uniform grid and my selected 5 m grid cell spacing allows a limited look at scales of perimeter that are multiples of 5. The dependence of perimeter (length) measurements on the scale of measurement may limit use of these data for some biological questions.

Statistical Analysis

The Kolmogorov-Smirnov two-sample test statistic was used to determine if the distributions of discharge-area curves for each morphometirc depth (-) and elevation (+)

class and distributions of discharge-shoreline development index curves were different between sandbar types. This test is sensitive to differences in the general shapes of the distributions in the two samples (such as range and skewness) (Kolmogorov et al. 1941). If the calculated D statistic is greater than the quantile of the Smirnov test statistic for two samples of equal n or if the p-value is less than the 0.05 significance level, I reject the null hypothesis of equal distributions and conclude that the two distributions differ significantly. The Kruskal-Wallis test statistic was used to check for differences in means of SDI between two sandbar types at individual discharge values. This test is a non-parametric alternative to one-way analysis of variance as it makes no assumptions about the distribution of the data (e.g., normality). This post hoc test uses the ranks of the data rather than their raw values to calculate the statistic and tests the null hypothesis that the samples do not differ in mean rank for the selected variable. The Kruskal-Wallis test approximates a P value from the chi-square distribution; if the p-value is less than the 0.05 significance level I reject the null hypothesis of equal means.

RESULTS

Sandbar Types

The extensive dataset shows sandbars on the Lower Missouri River that form off navigation structures (i.e. spur and L-dikes) composed 83% of all sandbars (Chapter 1, Table 1.1). Islands and point sandbars are remnants of naturally-formed sandbars/islands, and composed >50 % of total area, but less than 5% of total number of bars and islands (Chapter 1, Table 1.1). The Grand River to Osage River Segment (km 402 to 209) included the greatest number of point sandbars, whereas the Osage River to Mississippi River Segment (km 209 to 0) had the greatest area of emergent sandbar compared to all five designated segments (Chapter 1, Table 1.2).

At the resolution of the intensive dataset each of the 13 (six point, seven wing-dike) sandbar study sites was distinct in its location and proximity to varying navigation structures (Table 2.4). As with size, elevation ranges also differed between sandbar types. Topographic elevation grids of emergent sandbar area collected at lowest discharge indicated point sandbar elevations ranged from 160.5 to 181.2 m and wing-dike sandbars ranged from 166.9 to 187.4 m (Fig. B.2) over a discharge range of 22 kcfs to 41 kcfs (Table 2.3). For example, point sandbar km 253 (23 kcfs) elevation range was 6.78 m whereas, the range for wing-dike sandbar at km 381 (26 kcfs) was 4.05 m (Fig. 2.5).

Discharge

Median Missouri River discharge at km 317 was 35.5 kcfs (range: 20.5 to109 kcfs) during 2003 and was higher during 2004 at 42.5 kcfs (range: 22.5 to 156 kcfs) (Fig. 2.6). Median discharge during my study (2002 – 2004, 37.5 kcfs) was lower than the previous decade's median (1991 – 2001, 67.5 kcfs), which included the record floods of the 1990s.

Table 2.4. Description and location of associated navigation structures for six point and seven wing-dike sandbars within the Lower Missouri River, Grand River to Osage River segment used to develop discharge-area models and evaluate effects of discharge on sandbar morphometry. Orthophotographs of each sandbar are located in Appendix B.1. Bank designation is facing downriver. See text for definitions of navigation structures.

Sandbar Name River Kilometer	Classification	Location and associated navigation structures
Jefferson City 234	Point	Left bank, two upstream spur dikes Three downstream spur dikes
Marion 253	Point	Left bank across from Marion boat ramp Two upstream spur dikes and one spur dike contained within sandbar area
Hartsburg 254	Point	Right bank across Hartsburg boat ramp Two upstream spur dikes; one directly at head of sandbar another further upstream Multiple L-dikes on left bank
Perche A 275	Wing-dike	Right bank, upstream from Perche Creek outlet Upstream from Perche B sandbar Formed behind fifth L-dike in six L-dike complex
Perche B 275	Wing-dike	Right bank, upstream from Perche Creek outlet Downstream from Perche A sandbar Behind last L-dike in a six L-dike complex Unrooted spur dike downstream and becoming part of sandbar at tail
Powerline A 284	Wing-dike	Right bank, upstream from Powerline B Three upstream L-dikes and two downstream kick-back dikes
Powerline B 284	Wing-dike	Right bank, downstream from Powerline A Downstream from kick-back dike (≈375m) Three upstream L-dikes and one downstream kick-back dike
Petite Saline 285	Point	Left bank, kick-back dike upstream Two spur dikes within sandbar area (≈ 600 meters apart) one at head of sandbar with notch Five L-dikes on right bank
Tadpole Island 288	Point	Right bank, across from Huntsdale boat ramp

		Three upstream spur dikes; closest is notched, next is angled downstream Revetment and multiple L-dikes on left bank
Booneville 320	Wing-dike	Left bank, one spur dike upstream and three L-dikes further upstream Two downstream spur dikes
Jameson Wing-Dike 334	Wing-dike	Left bank, two upstream L-dikes Downstream kick-back dikes Kick-back, spur, and L-dikes on right bank
Jameson Island 343	Point	Right bank, two upstream navigation structures (≈ 180m apart); one is part of sandbar area at head, spur-dike within sandbar area near tail Multiple navigation structures on left bank
Chariton 381	Wing-dike	Left bank Two upstream kick-back dikes (≈350m apart) One unrooted spur downstream

Morphometric Area

Modeled mean area at any time for the six point sandbars was as much as 24 times greater than the mean area of the seven wing-dikes sandbars for morphometric depth classes (hereafter indicated by – preceding value) and elevation (hereafter indicated by + preceding value), (i.e. ±0 to 0.5, ±0.51 to 1.0, and ±1.01 to 1.5) (Tables C.1 and C.2). The shape of the relation of mean area to discharge for morphometric depth classes was unimodal for point and bimodal for wing-dike sandbars with peaks shifting to the right as depth classes increased (Fig. 2.7). Depth class 0.0 to-0.5 m had the greatest peak in area for both point and wing-dike sandbars (Fig. 2.7). The shape of the mean area relation curve for morphometric elevation classes was unimodal for point and unimodal or bimodal for wing-dike sandbars with peaks shifting to the left as elevation

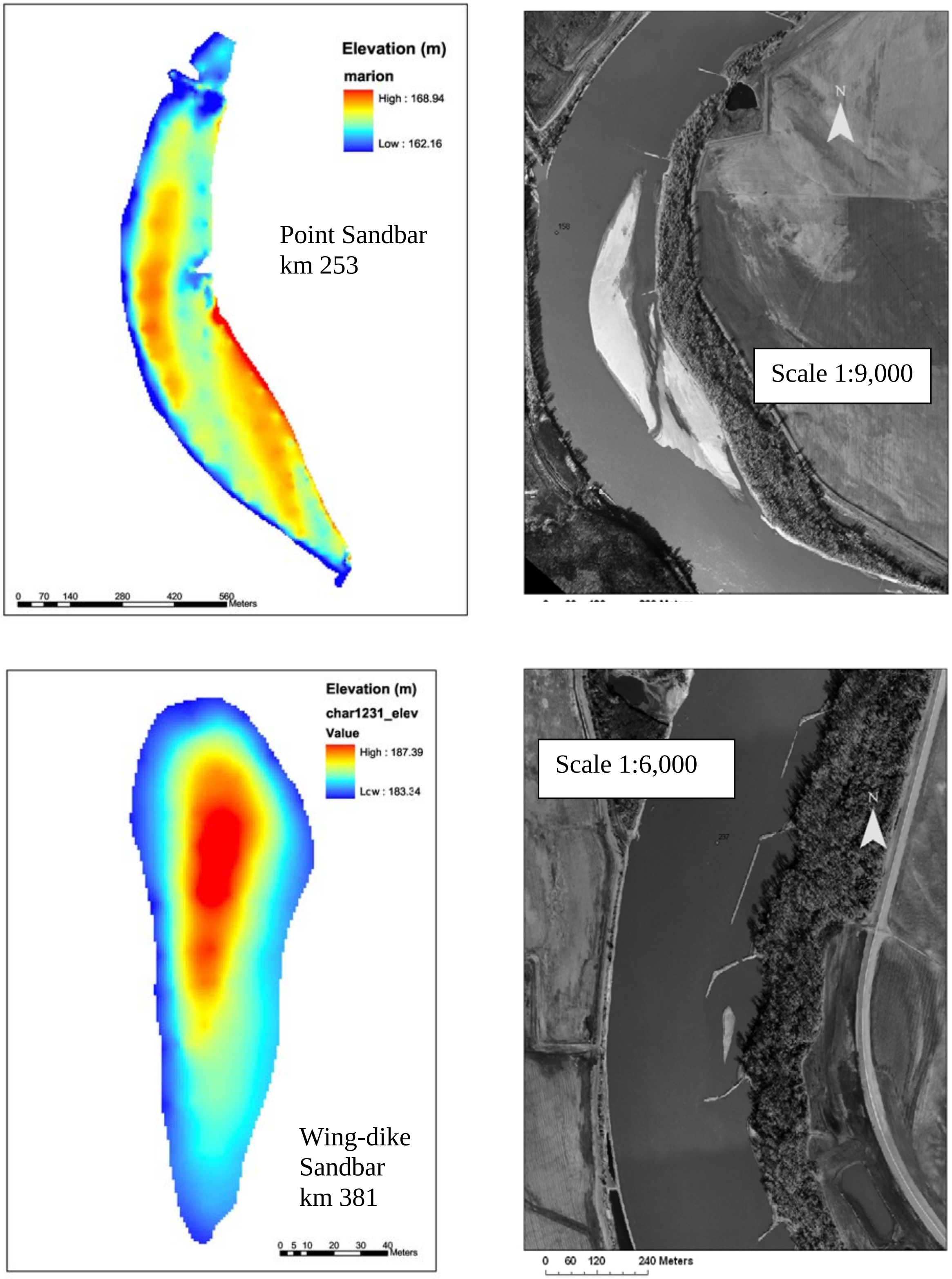


Figure 2.5. Representative elevation grids and orthophotographs for a point sandbar at km 253 (at 23 kcfs) and a wing-dike sandbar at km 381 (at 26 kcfs) within the Grand River to Osage River segment of the Missouri River, Missouri.

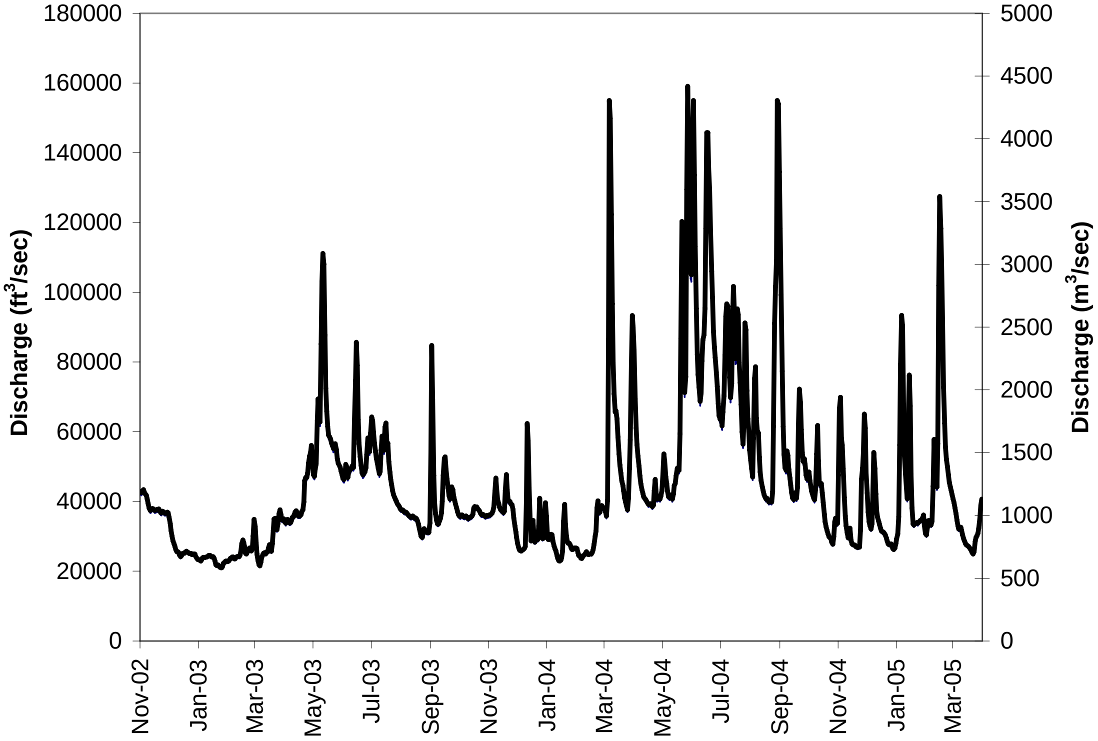


Figure 2.6 Missouri River daily mean discharge within the sandbar mapping period, autumn 2002 through spring 2005. Gage at Boonville, MO (km 317).

classes increased (Fig. 2.8). Mean area (± 1SD) for six point sandbars and seven wing-dike sandbars for morphometric elevation class 0.0 to +0.5 m at the summer (June-August) median discharge during the combined 2003 – 2004 study period (54 kcfs) was 5.4 ± 2.3 hectares for point sandbars and 0.3 ± 0.4 hectares for wing-dike sandbars. Mean area at morphometric depth class 0.0 to -0.5 m was 6.7 ± 2.2 hectares for point sandbars and 0.3 ± 0.3 hectares for wing-dike sandbars. In addition to evaluating area relations between sandbar types, analysis included differences in shape (distribution) of discharge-area relations for normalized mean area between sandbar types. The shape (distribution) of discharge relation curves of mean area between the six point and seven wing-dike sandbars for each morphometric depth and elevation class were not significantly different (Kolmogorov-Smirnov, P <0.05, Table 2.5).

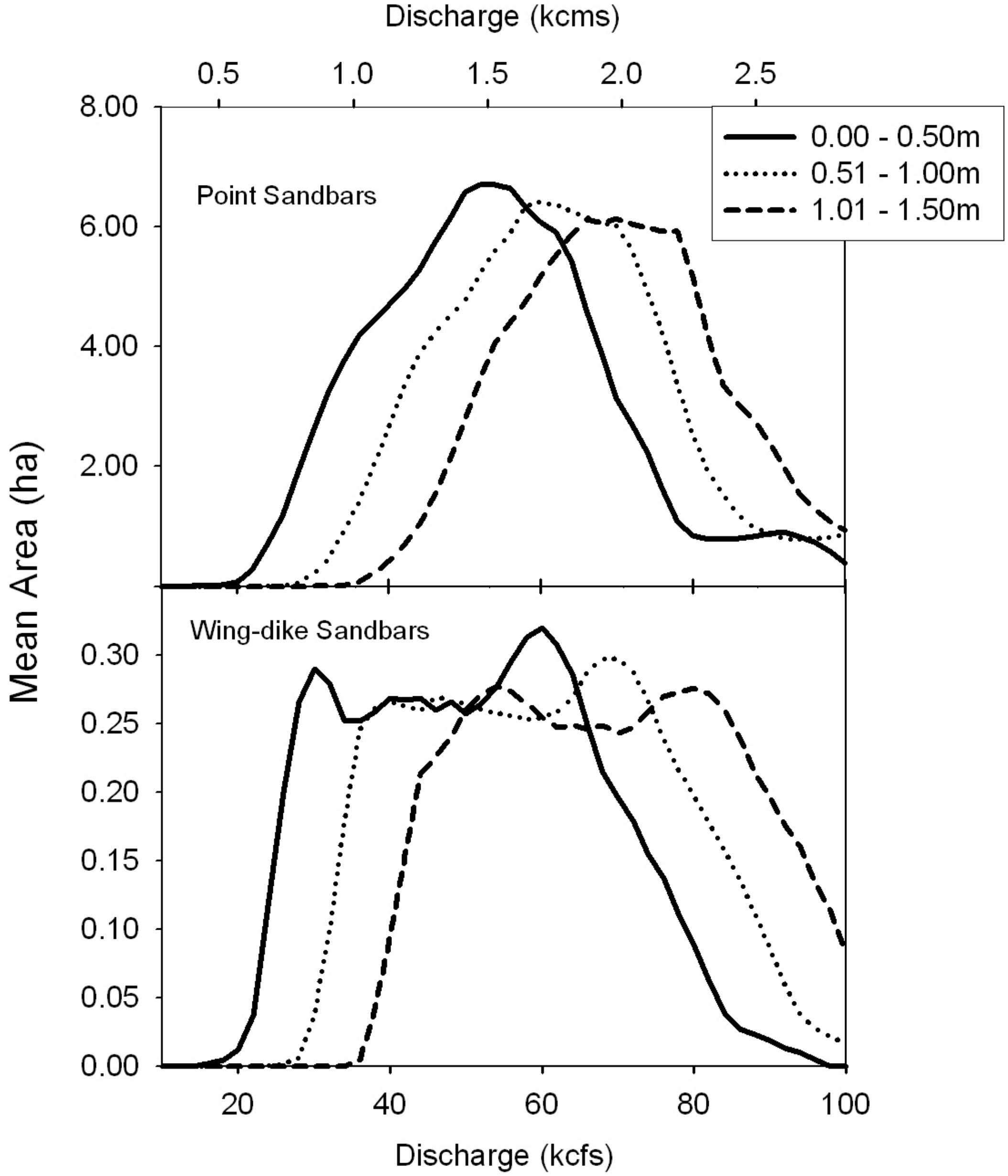


Figure 2.7. Modeled mean sandbar area for three morphometric depth classes (-) over discharges ranging between 10 and 100 kcfs for six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment (km 402 – 209), Missouri River, Missouri.

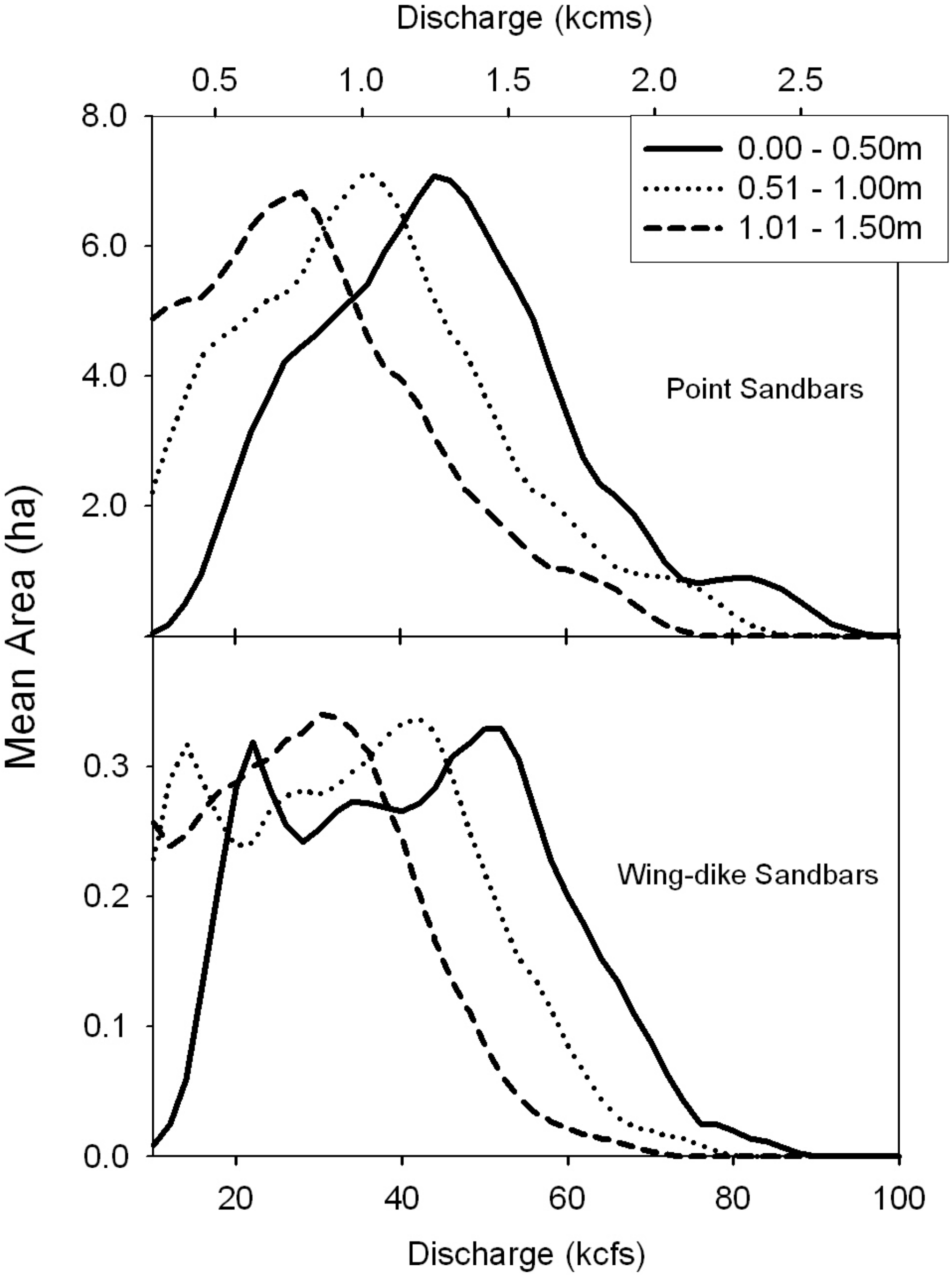


Figure 2.8. Modeled mean sandbar area for three morphometric elevation classes (+) over discharges ranging between 10 and 100 kcfs for six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment (km 402 – 209), Missouri River, Missouri.

Table 2.5. Results of Kolmogorov-Smirnov test statistics on the differences in the shape (distribution) of discharge-relation curves between six point sandbars and seven wing-dike sandbars for three morphometric depth (-) and elevation (+) classifications in meters and the shoreline development index (SDI). P values ≤0.05 indicate distributions were significantly different.

		Morphometric Depth (-)			Morphometric Elevation (+)		
	SDI	0.0 to 0.5	0.51 to 1.0	1.01 to 1.5	0.0 to 0.5	0.51 to 1.0	1.01 to 1.5
D-statistic	0.48	0.2	0.22	0.24	0.2	0.2	0.13
P-value	>0.001	0.3	0.2	0.1	0.3	0.3	0.8

Shoreline Development Index (SDI)

Mean SDI for point sandbars increased from 1.8 with increasing discharge from about 24 kcfs to about 2.6 at 44 kcfs; SDI decreased gradually from 2.6 at 50 kcfs to 1.4 at 92 kcfs (Fig. 2.9). Mean SDI was more uniform for wing-dike sandbars (range: 1.6 to 1.9) over discharges ranging from 10 kcfs to 74 kcfs (Fig. 2.9). The shape (distribution) of discharge-area relation curves of mean SDI over the full range of discharges differed significantly between the two sandbar types (Kolmogorov-Smirnov, $P < 0.0001$, Table 2.5). Furthermore, based on computed Kruskal-Wallis test statistics, at select discharges (42 kcfs – 54 kcfs, 58 kcfs, 76 kcfs and 84 kcfs) mean SDI also differed significantly between sandbar types ($P < 0.05$, Fig. 2.9).

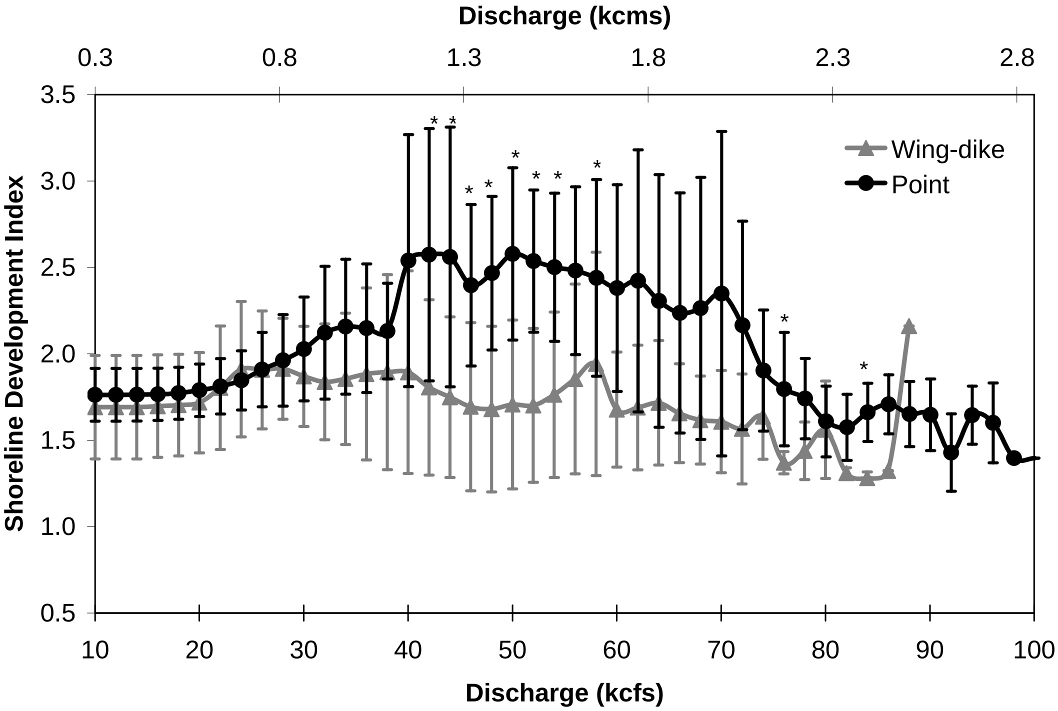


Figure 2.9. Mean sandbar shoreline development index (SDI) for point and wing-dike sandbars over a range of discharges. SDI was calculated using area (m^2) and perimeter (m) of emergent sandbar area for six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment (km 402 – 209), Missouri River, Missouri. Ninety-five percent confidence intervals are represented by vertical lines. Asterisks (*) indicate p-value less than 0.05 level of significance derived from a chi-square distribution computed using the non-parametric Kruskal-Wallis test statistic.

DISCUSSION

Riverine Habitat Complexity

Dynamic river-floodplain systems exhibit high levels of complexity and habitat heterogeneity across a range of spatial and temporal scales that influence biodiversity of the system (Schlosser 1991, Ward et al. 1999, Amoros and Bornette 2002, Robinson et al.

2002, Ward et al. 2002). Fluvial dynamics maintain successional processes and high levels of connectivity across the river-floodplain system that help structure habitat patch heterogeneity (Ward et al. 1999, Ward et al. 2002). Complex gradients of habitat conditions and hydrologic connectivity result in high diversity of river-floodplain systems and the duration and timing of connectivity affects ecosystem productivity and species recruitment (Amoros and Bornette 2002). Small-scale spatial heterogeneity across the river channel is associated with variable conditions of depth, current velocity, and substrate size (Schlosser 1991) and these conditions influence fish abundance and distribution (Rabeni and Jacobson 1993). The spatial distribution of habitat patches within the river-floodplain system permits segregation of species and size classes, thus reducing interspecific competition and predation risk (Schlosser 1991, Bowen et al. 2003). The complex life cycles of riverine biota require different habitat conditions to be available at different times for different uses (e.g. refugia, feeding, breeding, rearing, spawning, nesting) (Schlosser 1991, Robinson et al. 2002).

Disturbances create conditions under which coexistence of species can occur (Townsend 1989, Ward et al. 2002) as floods do not affect patches uniformly, an increased age diversity of patches will support more species with similar ecological requirements (Bretschko 1995) and a diversity of disturbance regimes will provide habitat conditions for a greater variety of biota (Ward et al. 1999). The ATTZs of river-floodplain systems are ecologically significant in that they provide heterogeneous habitat conditions across time and space. Although channel-margin ATTZ is an important component within nonregulated rivers, in regulated rivers where flow modifications or channel-floodplain disconnection has occurred, the channel-margin ATTZ increases in ecological importance relative to the floodplain ATTZ by providing a mosaic of habitat patches for a variety of biological uses.

Sandbars as Habitat Patches

Examination of channel-margin ATTZ patches, interactions among patches (e.g. dispersal of organic matter and organisms), and the mechanisms behind their structure and function provide empirical information to river ecologists to better understand the dynamic nature of habitat patches and enable quantitative comparisons between other river systems. Patchiness of sandbar ATTZ varies among sandbar types and within sandbar sites due to differences in morphometric parameters of area, perimeter, and water-surface slope; and the distribution of woody debris; substrate type; vegetation; and organic matter. The occurrence of varying forms and sizes of vegetation and wood debris on islands and sandbars provides a complex hydrological and geomorphological environment for use by biota (Gurnell et al. 2001).

Point sandbars in the current channel provide a few large patches of sandbar-ATTZ habitat, whereas wing-dike sandbars provide many small patches. An obvious question is, is it better to have a few big (point) versus many small (wing-dike) patches for ecological benefits? Patch size and edge effect influence habitat use of many species (Bender et al. 1998). Small patch size increases the risk of predation for nesting birds (Hoover et al. 1995, Keyser et al. 1998) and patch size can influence the distribution and persistence of native fishes (Rieman and McIntyre 1995). In some cases size may not be as important as the arrangement and function of habitat patches (McIntyre and Wiens 1999).

Habitat size is utilized differently by different species. Migrating shorebirds frequent of the Missouri River are highly mobile and travel great distances between arctic and subarctic breeding grounds to Central and South American nonbreeding areas (Skagen and Knopf 1992). They tend to be opportunistic during migration because the occurrence of mudflats and shallow-water habitat is highly variable (Skagen and Knopf 1992). Consequently, they are able to stop along their migration route wherever suitable habitat conditions are found. These migration stopovers can be 100's of km apart. In contrast, age-0 fishes have more restricted mobility, and can only select suitable habitat conditions present in smaller areas within individual sandbars. Restoration emphasis on point (few large) or wing-dike (many small) sandbars should take into account what species are targeted as both types provide a variety of ATTZ habitat conditions.

Sandbar ATTZ

The differences in peaks of area between sandbar types indicated that targeted flows to provide variability of sandbar ATTZ depth and elevation classes within the current channel geomorphology can be obtained over a select range of discharges that would differ between sandbar types. Though wing-dike sandbars were much smaller in area than point sandbars, their high occurrence throughout the Lower Missouri River means they provide additional sources of habitat heterogeneity and make up a high proportion of channel-margin ATTZ. Point sandbars are larger in area and consequently can be comprised of a variety of habitat patches. However, point-sandbar ATTZ is maximized over a smaller range of discharges compared to wing-dike sandbars. Flows that maximize point sandbar ATTZ will likely maximize wing-dike sandbar ATTZ as well because of the greater range of discharges. Also because point sandbars are greater in size they can provide a large proportion of sandbar ATTZ even at flows below their maximum potential. River discharges <50 kcfs would provide a variety of emergent and submergent ATTZ among both sandbar types. Spatial proximity of wing-dike sandbars to one another and to point sandbars may increase exchange of organic matter, woody debris, and biota between patches. Taken together, point and wing-dike sandbars increase spatial heterogeneity and diversity of channel-margin ATTZ habitat conditions within the main channel of the Lower Missouri River. Knowing the discharge ranges that sandbar-ATTZ area is maximized for both sandbar types provides the information necessary to manage river flows that will increase the amount of channel-margin ATTZ across the entire river corridor.

Shoreline Complexity

Perimeter analysis was highly scale dependent. Although field observations indicated sandbar perimeters were often highly dissected, my perimeter analysis provided only a coarse estimate of how the shoreline (edge) changed with discharge, because over a majority of discharges shoreline complexity (SDI) was similar between sandbar types. The degree of shoreline complexity is important for inshore retention of water, organic matter, and other microhabitat conditions, with greater complexity increasing availability of riverine fish nursery areas (Schiemer et al. 2001a, Winemiller 2004). Significant differences in mean SDI occurred within a range of flows managed for navigation (≈ 40 – 80 kcfs; Fig. 2.9). Hence, flow regulation could result in differences in shoreline complexity and result in different retention capabilities and subsequent productivity of inshore areas between the two sandbar types. My perimeter analysis indicates a need for further research to adequately quantify shoreline complexity between sandbar types, and also for sandbar ATTZ and channel-margin ATTZ.

Sandbar-ATTZ Rehabilitation

The pre-1900's lower Missouri River channel contained numerous islands and sandbars of multiple sizes and at various juxtapositions within the river channel. The current constrained channel of the Lower Missouri River has lost nearly all islands, and the size and number of sandbars has substantially decreased (Funk and Robinson 1974, Hallberg et al. 1979). The contemporary channel and contemporary flows of the Lower Missouri River, though substantially different from pre-regulation conditions, still retain ecologically important areas of channel-margin ATTZ. Sandbars with their complex shorelines and variable morphometric areas of depth and elevation compose potentially important areas of channel-margin ATTZ. Managing for both point and wing-dike sandbars would provide a diversity of habitat conditions and ecological benefits over a wide range of flows. Understanding of the relations of discharge and sandbar-ATTZ characteristics can contribute to improved rehabilitation design that benefits a multitude of riverine biota.

Hydrologic Variability and Geomorphic Processes

Variable flows will help maintain heterogeneous sandbar ATTZs by providing a variety of habitat patches in which the distribution within the river-floodplain system changes spatially and over time through flooding, cut-and-fill processes, and regeneration of riparian vegetation (Stanford et al. 2005). Reductions of the frequency and magnitude of floods can cause infilling of side channels and increase of vegetation growth until eventually islands become connected to the adjacent floodplain (Ham and Church 2002). Development of Missouri River navigation constrained the channel with rock revetment to prevent the natural cutting action of river flow. It confined the once wide channel to a narrow fixed channel using dikes to divert the force of river flow and deepen the channel (Ferrell 1996). The constricted channel's increase in depth and flow velocity may impede sandbar and island development because of the reduction of deposited fine sediments and removal of existing deposits that are essential for vegetation to become established (Ham and Church 2002). Vegetation is fundamental to island development and the succession of sandbars to islands as vegetation increases accumulation of fine sediments (Ham and Church 2002).

Riparian vegetation on islands increases habitat heterogeneity for benthic invertebrate production (Thorp 1992) that also may constitute an important food source for fish larvae (Coutant 2004). Research has identified small fishes to be correlated with the presence of vegetation (Lobb and Orth 1991, Johnson and Jennings 1998, Jurajda 1999), while Coutant (2004) proposed that inundation of riparian vegetation may serve as important spawning sites for sturgeon. Submerged vegetation and wood along river shorelines (channel-margin ATTZ) provide microhabitat diversity for riverine fishes throughout many life stages (Zalewski et al. 2003). Woody debris in rivers provides habitat structure, shelter, and increased food resources for birds, turtles, mammals, fishes (Steel et al. 2003, Wondzell and Bisson 2003), and stable substrate (relative to sand) for invertebrate colonization (Drury and Kelso 2000).

The National Research Council recommended that key physical processes including a high degree of hydrologic variability and cut-and-fill processes need to be restored to improve the ecology of the Missouri River (National Research Council 2002). Niebur (2001) examined effects of the 1993 Missouri River flood and the subsequent revegetation of the Missouri River floodplain within the Big Muddy National Fish and Wildlife Refuge. The flood breached levees reconnecting floodplain habitats to the main channel and deposited large amounts of sand followed by accumulated silt and clay due to moderate recurrent floods (Niebur 2001). These areas became increasingly vegetated up to the chute borders, until placement of control structures reduced connectivity to main channel flows. The absence of flooding in late 1999 throughout 2000 further removed the river's access to the chutes, allowing vegetation to encroach and a continued lack of flooding resulted in a static uniform forested floodplain surrounded by an immobile channel (Niebur 2001). Niebur's study illustrated the importance of floods for both creating and maintaining habitat diversity and the importance of hydrologic variability to initiate cut and fill processes.

There has been a substantial effort on the Missouri River to remediate some of the effects of engineering structures. Sediment collected behind wing-dikes when they were originally installed on the Missouri River in the 1930's resulted in land accretion and forest colonization of the accreted land. Notching of dike structures began in the 1970's to halt the accretion process and to enhance in-channel shallow-water habitat (SWH) (U.S. Army Corps of Engineers 2004b). The notching effort has expanded recently to include wider and deeper notches of banks, dikes, and revetments to create SWH in accordance with the Biological Opinion (U.S. Army Corps of Engineers 2004b).

Notching has been engineered to increase the time flow occurs through the section of the dike and is intended to create SWH over a broader range of flows (U.S. Army Corps of Engineers 2004b). Notching efforts have been attributed with improving depth and velocity diversity downstream of the notches (U.S. Army Corps of Engineers 2004b) thereby creating a diversity of aquatic habitats important to pallid sturgeon and other riverine fishes. Notching may also help maintain clean substrates important for nesting softshell turtles.

Jacobson and Galat (2006) evaluated the interaction between flow and form and the influence on availability of shallow-water habitat on the Lower Missouri River by comparing modeled combinations of modern and historical channel morphology and modern and historical flow regimes. Engineering structures on the Lower Missouri River have effectively decoupled form and flow (Jacobson and Galat 2006) and made possible management strategies to increase SWH through rehabilitation of channel morphology independent of flow. Rehabilitation of channel form to a more historical condition having a diversity of channel elevations will increase SWH over a greater range of flows (Jacobson and Galat 2006). However, flow is a necessary function that controls the timing of habitat availability for many life stages of many riverine biotas (Jacobson and Galat 2006). Changes in channel form and the creation of physical habitat along the Lower Missouri River will increase channel-margin ATTZ within the bounds of maintaining navigation flows. Dike modifications implemented by the COE have been designed to create SWH at or near full-service flows in order to meet all project purposes (U.S. Army Corps of Engineers 2004b). Maintaining navigation flows, especially higher flows in mid to late summer months reduces availability of emergent sandbar habitat for nesting softshells and SWH for fish nursery (Tracy-Smith 2006). My discharge-area models indicated that area of sandbar ATTZ was maximized over a wider range of discharges than the imposed minimum (around 34 kcfs) and full service (around 41 kcfs) navigation flows at Boonville, Missouri.

Overtime, if cut-and-fill processes are not implemented there will be a reduction in the diversity of sandbar-ATTZ habitats. Field observations revealed the extremely rapid rate that vegetation is capable of colonizing sandbars. Which would suggest flow regulation and reduction of flood flows may result in persistent vegetation growth with recurrent low flows possibly creating a more static sandbar ATTZ. Flooding resets vegetation growth and deposits nutrient-rich sediment thus maintaining a diversity of sandbar-ATTZ conditions and promoting colonization of invertebrates (Drury and Kelso 2000). My study was during a drought cycle where sandbars that exhibited more silt and clay substrates became heavily vegetated. The drought during this study alone resulted in sandbars connecting to nearby shorelines and encroachment of vegetation. Without high flows it is likely that the secondary channels of many sandbars will fill in with sediment and vegetation will continue to encroach until the sandbar becomes attached to the riverbank. Other authors have speculated that the natural flow regime is needed to improve habitat diversity within the main channel of the Lower Missouri River and similarly regulated rivers worldwide. My results suggest that there are functions of the natural hydrograph that need to be restored on the engineered Lower Missouri River. Higher flows whether natural or unnatural are needed to scour sandbars. Notching of wing dikes has been shown to increase habitat heterogeneity according to U.S. Army Corps of Engineers (U.S. Army Corps of Engineers 2004b). However, notching is a recent phenomenon that we do not know the effects of over the long term and may be insufficient to recreate natural patterns of water and sediment transport that create and maintain heterogeneous sandbar ATTZs (National Research Council 1992). Some combination between flow and design that maintain sandbar formations are necessary to increase channel-margin ATTZ and subsequent habitat diversity within the main channel of the Lower Missouri River and similarly regulated rivers worldwide.

CHAPTER III

EFFECTS OF DISCHARGE ON THE AQUATIC-TERRESTRIAL TRANSITION ZONE (ATTZ) OF LOWER MISSOURI RIVER SANDBARS AND THEIR USE BY SELECTED BIOTA

INTRODUCTION

Missouri River

Channelization and levees have effectively uncoupled the lower Missouri River from its floodplain and disrupted its annual flood pulse (Galat et al. 1997). Dams and channelization have concurrently altered the natural hydrograph, sediment transport dynamics, organic matter cycling, and fish migration patterns (Hesse et al. 1989, Hesse and Mestl 1993). Discharge patterns currently do not mimic the natural (historical) flows having a bimodal hydrograph with the first peak or "spring rise" in March-April and a second "June rise" as a result of regional precipitation and mountain snowmelt (Hesse and Mestl 1993, Galat and Lipkin 2000). The pre-regulation spring rise is thought to serve as a spawning cue to native fishes, and low flows during summer provided shallow-water habitat for native larval fishes (Galat and Lipkin 2000). A comparison of the historical or predevelopment hydrograph (1925-1952) with the modern/post-development hydrograph (1967-1999) for Boonville, Missouri [River Kilometer (km) 317] illustrates the changes in timing and magnitude of peak flows, and the volume of low flows (Chapter 1, Fig. 1.3; Jacobson et al. 2001).

Restoration activities on the Lower Missouri River need some direction and quantification of biological linkages. After the flood of 1993 created floodplain aquatic habitat along the lower Missouri River, ecologists suggested restoration of a functioning river-floodplain ecosystem through acquisition of damaged floodplain habitat, selective removal or modification of flow-control structures, and restoration of a more natural hydrograph (Galat et al. 1997). This study aims at providing the linkages between ATTZ habitat and biological use by quantifying the changes of habitat with varying flow regimes.

Biological Significance of Sandbars

Habitat conditions associated with sandbars are important for many species and many life cycles. Due to the timing of historical summer-early autumn low flows, the margins of sandbars previously contained abundant shallow-water shoals, which served as low-velocity and high-production habitats for riverine fishes (Galat et al. 1998, Galat 1999). It has been documented that these “sand islands” are valuable as nursery areas for fishes on the lower Missouri River (Gale et al. 1985), and that the low velocities are important to larval fish feeding because of the higher success rate in capturing food particles (Flore 2001). According to Ward and Stanford (1995), the growth rates of young fishes are optimized in shallow-water habitats with their associated high temperatures. The few sand islands and associated shoals that remain along the lower Missouri River are now flooded or their surface area reduced during much of the reproductive season (July-September) for many riverine fishes, birds, and turtles (Galat et al. 1998) that use these habitats. Extended periods of high water in late summer and early autumn tend to keep sandbars submerged, preventing their use by post-breeding herons, migrating shorebirds, and waterfowl (McColpin 2002). Sandbars that remain emergent for long periods provide high-elevation habitat conditions important to nesting riverine turtles that require bare substrate, clear of vegetation, in order to nest successfully. Seasonally variable flows are necessary to provide such conditions. High flows submerge sandbars and scour them of existing vegetation, while low flows during the nesting period leave high elevation nesting sites dry. In its natural state, Missouri River sandbars would be scoured of vegetation by winter ice flows and high spring runoff, but they are no longer scoured, primarily because flows are regulated by main stem dams (U.S. Army Corp of Engineers 1995).

Aquatic-Terrestrial Transition Zone (ATTZ)

Channel-margin ATTZ is the area that is alternatively inundated and exposed within the annual hydroperiod (Chapter 1). Sandbars were identified as important sources of ATTZ habitat (sandbar ATTZ) within the main channel of the Lower Missouri River, because they represent a biologically useful interface between aquatic and terrestrial environments. As discharge increases and decreases, sandbar ATTZ is constantly changing relative to the location of the water’s edge (defined herein as 0.0 m elevation). The ATTZ is a dynamic zone that includes areas in depth and elevation associated with sandbars. Sandbar ATTZs are classified herein to quantify area at any point in time as *submergent sandbar ATTZ* (ATTZ-S) (depth below the water’s edge 0.0) and *emergent sandbar ATTZ* (ATTZ-E) (elevation above the water’s edge 0.0) (Fig. 3.1).

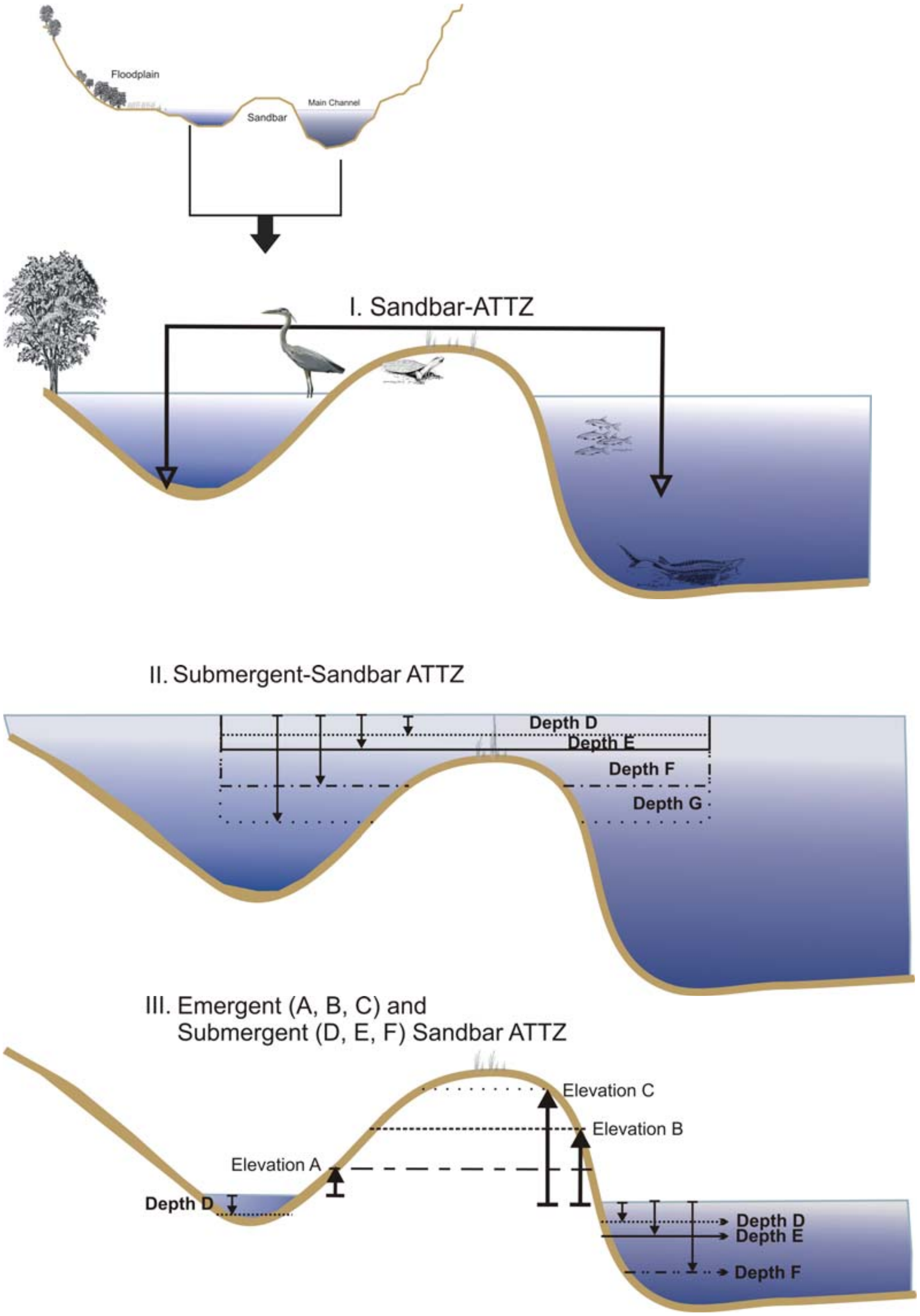


Figure 3.1. Diagram of the aquatic-terrestrial transition zone within the river corridor associated with sandbars (I) and the dynamic zone that is alternatively inundated (II. and III. submergent-sandbar ATTZ) and exposed (III. emergent-sandbar ATTZ) within the annual hydroperiod. Areas in depth and elevation associated with sandbars change relative to the location of the water's edge (0.0 m) as discharge increases and decreases.

Shallow-water habitat, as defined by others, includes: <0.28 m (Gelwick et al. 1997), <0.3 m (Plummer 1977a, Ehrhardt 1996), <0.4 m (Barko et al. 2004), <1.3 m (Scheidegger and Bain 1995), ≤1.0 m (Reeves 2006), and <1.5 m (U.S. Fish and Wildlife Service 2000). Definitions of shallow-water habitat are integrated into the submergent-sandbar ATTZ classifications. Shallow-water habitat (SWH) is contained within ATTZ and rather than pinpointing one depth as critical SWH for all biota, the ATTZ provides a more realistic depiction of the diversity and dynamic nature of habitats associated with sandbars.

Goals and Objectives

Flow regulation and channelization of the Lower Missouri River have reduced the more naturally occurring point sandbars while increasing the amount of sandbar ATTZ associated with navigation structures (see Chapter 2). My goal was to evaluate the effect different Missouri River flow regimes have on sandbar ATTZ between point and wing-dike sandbars, and integrate timing of sandbar ATTZ availability with life-history activities of riverine biota that represent a wide range of sandbar ATTZ uses.

Objective 1 – Apply classifications of submergent (-) and emergent (+) sandbar ATTZ to my predictive models of sandbar morphometry (area, wetted perimeter, elevation, and water-surface slope) from river discharge for selected point and wing-dike sandbars to:

1.1. Determine how discharge-area curves vary between sandbar types for several submergent and emergent-sandbar ATTZ classifications.

1.2. Evaluate differences in predicted area of submergent-and emergent-sandbar ATTZ relative to minimum-and full-service navigation flows.

Objective 2 – Evaluate timing and duration of predicted submergent (ATTZ-S) and emergent (ATTZ-E) sandbar ATTZs in association with modeled daily flows (using long-term data) for two modeled flow-management alternatives and two reference alternatives to:

- 2.1. Determine if area of submergent and emergent-sandbar ATTZ varies seasonally and among alternatives within the channelized river segment.
- 2.2. Explore the effect on targeted life-cycle events:
    - 2.2.1. Foraging of migratory shorebirds and wading birds
    - 2.2.2. Nesting of smooth (*Apalone muticus*) and spiny (*Apalone spiniferus*) softshell turtles
    - 2.2.3. Nursery of riverine fishes

Biota Background

The biota chosen for analysis represent a wide range of sandbar-ATTZ habitat uses: softshell turtles, shorebirds, wading birds, and riverine fishes.

Freshwater Turtles

The semi-aquatic behavior of turtles makes them especially useful for understanding the link between aquatic and terrestrial habitats. Freshwater turtle species typically inhabit both lentic and lotic habitats (Bodie and Semlitsch 2000, Moll and Moll 2000) using them for basking, feeding, mating and overwintering (Ernst et al. 1994, Bodie and Semlitsch 2000). All turtles use terrestrial habitats for some aspects of their life cycle, and many riverine genera [e.g. *Graptemys* spp (map turtles) and *Apalone* spp. (softshells)] are tied to specific aquatic conditions (Ernst et al. 1994, Lamb et al. 1994, Bodie and Semlitsch 2000). For nesting, many riverine turtles also require large, easily accessible, open expanses of well-drained substrates, such as sandbars, islands, and beaches (Moll and Moll 2000). Juveniles may choose shallow habitats to avoid predation and being displaced by flooding (Moll and Legler 1971, Bodie and Semlitsch 2000).

The timing of flow pulses is also important to the success of turtle nesting. Floods during the nesting season can destroy part or all of the annual reproductive output of a river turtle population (Moll and Moll 2000). Most species of river turtles can tolerate only short periods of nest submergence (Plummer 1976, Moll and Moll 2000). River turtles are often habitat specialists that respond poorly to change (Moll and Moll 2000). Direct alterations to rivers and their banks, such as channelization, damming, and sand and gravel mining, can negatively affect river turtle populations (Moll and Moll 2000). Declines of softshells has been attributed to the straightening of rivers in Iowa (Williams and Christiansen 1981, Christiansen and Bailey 1988, Moll and Moll 2000), and due to the loss of islands and sandbars in the lower Missouri River (Johnson 1992, Bodie 2001).

The smooth (*Apalone muticus*) and spiny (*Apalone spiniferus*) softshell turtle species were selected for analysis because they reside in many large rivers throughout the United States and are known to use sandbar-ATTZ habitats throughout their life cycle.

Smooth Softshell

The smooth softshell ranges from the Ohio River drainage, the upper Mississippi watershed, and the Missouri River from the Dakotas south to western Florida and Texas (Ernst et al. 1994). Along the Kansas River, smooth softshells were most associated with sand and swift current and activity was concentrated where sandbars were shelving off into deep and swift water (Fitch and Plummer 1975). Hatchlings prefer small, shallow (<0.3m), warm puddles created by the highly dissected shoreline of sandbars (sandbar-ATTZ) (Plummer 1977a). Male smooth softshells frequently bask on sandbars and mud banks, usually within one meter of the water, and have exhibited foraging behavior on sandbars (Plummer and Shirer 1975) at the shallow interface between terrestrial and aquatic environments (ATTZ) feeding on a greater proportion of terrestrial prey than females (Plummer and Farrar 1981). Whereas female softshells forage primarily in stable microhabitats in deep water (Plummer and Farrar 1981).

Most annual activity of smooth softshells occurs from May through September (Plummer and Shirer 1975, Plummer 1977a) and nesting extends from late May through July (Fitch and Plummer 1975). Incubation ranges between 65 – 77 days and emergence generally occurs in August and September (Ernst et al. 1994). Smooth softshells typically produce two clutches each year (Plummer 1977b). Individuals can range several kilometers over a given season, not confining their activities to small areas over long periods, and smooth softshells do not show a high degree of home range fidelity after nesting (Plummer and Shirer 1975).

Spiny Softshell

The spiny softshell turtle is more widely distributed than the smooth softshell, ranging from western New York, South Dakota, and south to the Gulf coastal states (Ernst et al. 1994). The spiny softshell is a habitat generalist, (Webb 1962, Moll and Moll 2000), capable of using a variety of prey (Cochran and McConville 1983), and thriving in the altered environment (Moll 1980).

Mating occurs April through May and spiny softshells typically produce two clutches each year (Robinson and Murphy 1978). Nesting season for the spiny softshell begins late May and extends through August, though June and July are the primary months for nesting (Ernst et al. 1994). Incubation ranges over 52 to 95 days and varies as a function of temperature; warmer temperatures result in faster incubation (Ernst et al. 1994). Emergence of hatchlings occurs late August through October, while some hatchlings may overwinter in the nest (Minton 1972).

Softshell Nesting Habitat

Female smooth softshells prefer sandbars relatively free from vegetation as nesting areas to lay their eggs (Fitch and Plummer 1975, Ernst et al. 1994). Plummer (1976) found ninety percent of smooth softshell nests were constructed on open sandbars free of vegetation and reported that turtles were able to see and select the highest areas of the sandbar while in the water. Female smooth softshells build nests close to water but can wander 90 – 100m from the river in search of suitable nesting sites (Fitch and Plummer 1975). A study on the Kansas River found smooth softshell nests averaged a distance of 38 m from the water’s edge and averaged 1.3 m above water level with the highest number of nests at 1 m above water level (Fitch and Plummer 1975). In a comparative nesting study between smooth and spiny softshell species on the Comite River in south central Louisiana, Doody (1995) concluded that smooth softshells nested in sites with significantly steeper slopes and significantly closer to water than did spiny softshells. Height above water was the most important variable for nest site selection, with a mean height of 2.7 m above water level for both smooth and spiny softshells (Doody 1995). Nest site selection (height and distance from water) will vary between river systems due to the flooding tendency of rivers and relative sandbar size.

Plasticity in selection of a general nesting area may exist in both species of softshells (Doody 1995). Spiny softshells are known to nest in a variety of seemingly suboptimal areas, especially when sandbars are lacking (Doody 1995) and smooth softshells were found to nest in small sandy patches among dense vegetation during periods of high water (Goldsmith 1944, Plummer 1976).

Inundation of Sandbars

Softshells are affected by changes in the physical structure of their environment, ranging from subtle daily changes of contours to extreme changes in shape and physical composition (Plummer and Shirer 1975). Some sandbars have unstable conditions for nesting turtles in that periodic flooding during nesting inundates their nests. Sandbars that sustain high elevations ($\geq$1.0 m) throughout the nesting season provide the greatest chance of egg survival. Maintaining high summer flows for navigation on the Lower Missouri River reduces or eliminates emergent sandbar habitat during the nesting season of softshells. Plummer (1976) found the single most important factor in the Kansas River determining nest success was length of time of nest inundation. Eggs in early embryonic stages submerged for over 24 hours had decreased survivorship, and those submerged for over four days had little chance of surviving (Plummer 1976). The risk of flooding and consequently mortality may create an advantage for nesting earlier in the season (Doody 1995). Hatching earlier could provide more time to feed and reach an optimal size before winter hibernation. Little to no growth occurred in late September and October for 100 hatchlings measured (Fitch and Plummer 1975). This indicated possible incentive for earlier nesting and emergence to utilize the most time for growth before hibernation.

Shorebirds

Interior populations of shorebirds (e.g., sandpipers, plovers, oystercatchers, snipes, and stilts) that migrate through Midcontinental North America between breeding grounds and wintering areas are dependent on freshwater wetlands throughout for stopover resources (Skagen and Knopf 1994, Skagen et al. 1999). Stopover areas allow shorebirds to accumulate energy (fat) reserves essential for continued migratory flight and also additional reserves that may be important for successful reproduction upon arrival at the breeding grounds (Ricklefs 1974, Myers 1983, Myers et al. 1987, Farmer and Parent 1997). Interior-migrating shorebirds have evolved with unpredictable stopover resources, and are able to find suitable microhabitats in a temporally dynamic and spatially complex landscape (Skagen and Knopf 1992, Skagen et al. 1999).

Dietary flexibility allows for exploitation of variable resources, and is highly advantageous to many shorebirds that migrate across vast landscapes (Skagen and Oman 1996). Shorebirds are known to prey on whatever invertebrate resource is available

(McColpin 2003). Hands (1988) found shorebird foraging habitat ranged from saturated mud to water <6 cm deep. Most shorebird species forage in water <15 cm deep (Rundle and Fredrickson 1981, Hands et al. 1991, Isola et al. 2000, Plauny 2000) with diets consisting of insects, aquatic invertebrates, mollusks and small fishes (Plauny 2000). Rundle and Fredrickson (1981) found that 73% of shorebirds identified were located within 15 cm of the water's edge (i.e., ATTZ). The amount of vegetative cover present at foraging areas is important, as most shorebirds favor areas with bare substrate or with vegetation cover <10 cm (Rottenborn 1996).

Timing of Shorebird Migration

Missouri lies within a migration corridor used extensively by shorebirds, waterfowl, and other migrating waterbirds that move through the interior of North America (Ehrhardt 1996). About thirty-five species of shorebirds migrate through Missouri each year, with peak migrations occurring from late April through early May (spring) and mid-August through early September (autumn) (Jacobs 2001). A study on the lower Missouri River floodplain identified nearly 62,000 waterbirds during 16 Mar – 15 Oct, 1996 – 1997, shorebirds arrived early spring from April to May and were the first autumn migrants to return from mid-July through mid-October (McColpin 2002). Most migrating shorebird species occur in Missouri later in spring (April – May), however in another study that evaluated the use of habitats along the Missouri River by waterbirds, killdeer migration occurred earlier in the spring beginning in March (Raedeke et al. 2003).

Wading Birds

Wading birds (i.e., Ciconiiformes; herons, egrets, bitterns, rails, and ibis) are relatively large birds ranging in size from 28 to 140 cm long (Kushlan 1981). Wading birds forage alone (Kushlan 1981) or aggregate in groups of varying size when prey availability is high (Kushlan 1976). Wading birds are seasonal migrants; following nesting, juveniles and adults disperse to areas with increased food resources (Kushlan 1981). Bill morphology, diet, and feeding behavior differentiate wading bird species and the habitats they use (Lifjeld 1984). Large wading bird species are capable of consuming a variety of prey sizes; for example a heron can seize and hold a fish at least 25% longer than its bill (Recher and Recher 1969). Compared to shorebirds, rails and herons can forage over a wider range of habitat conditions including water up to 60 cm deep (Rundle 1980, Fredrickson and Reid 1986, Hands 1988). Water depth use varies within wading bird species. Foraging depth for great blue herons (*Ardea herodias*) on Missouri River floodplain habitats was found to range from 3 to 80 cm (Ehrhardt 1996). Maximum foraging depth of Florida Bay wading bird species ranged from 16 cm for small wading bird species [(e.g., little blue heron (*Egretta caerulea*) and snowy egret (*Egretta thula*)] to a maximum depth of 39 cm for large wading birds species [(e.g., great blue heron (*Ardea herodias*)] (Powell 1987).

Wading birds are distributed throughout almost all wetlands and depend on critical wetland habitats that are decreasing worldwide (Hafner 1997). Extended periods of high water levels prevent wading birds access to foraging sites and force them to disperse or shift to other habitats in the area (Powell 1987). Periods of high water during the breeding season and a decrease in availability of alternate habitats limit the size of wading bird populations (Powell 1987). Missouri wetlands provide breeding or post breeding habitat for several species of herons and least bittern (Ehrhardt 1996, McColpin 2002). Ehrhardt (1996) concluded that Missouri River wetlands and shallow areas adjacent to deep water provide optimal habitat for great blue herons, and found heron density, flock size, and number of adult and immature herons to be positively correlated with shallow-water area and percent shallow-water area ($\leq$30 cm).

Ehrhardt (1996) identified early spring (April) migrants to include four heron species, while late spring (May) migrants included cattle egrets (*Bubulcus ibis*) and American (*Botaurus lentiginosus*) and least bitterns (*Ixobrychus exilis*). Post-breeding (fledgling) wading birds were found to occur from late July to September (Raedeke et al. 2003) or mid-June to September (Ehrhardt 1996). Autumn migration (mid-July through mid-October) included herons, which were the largest group of resident birds (Ehrhardt 1996). McColpin (2002) concluded herons had the highest, but variable, richness during late spring through early autumn.

Sandbar Use

Sandbars on the Lower Missouri River and the shallow-water habitat surrounding them are used by migratory shorebirds and wading birds if sandbars are available. The Missouri Department of Conservation (MDC) compared the contribution of different habitat types to migrating waterbirds within the entire cross section of the Missouri River floodplain between Hartsburg, Missouri and Kansas City, Missouri using helicopter surveys (Raedeke et al. 2003). The Missouri River corridor hosted 32 species of water birds and 22 species were recorded at sandbars (Raedeke et al. 2003). Their study noted that the amount of sandbar habitat available complimented that of the floodplain and birds used available sandbar habitat more extensively during dry conditions (Raedeke et al. 2003).

Riverine Fishes

Riverine fishes can be characterized into generalized habitat-use guilds (Kinsolving and Bain 1993; Galat and Zweimüller 2001, Galat et al. 2005). *Fluvial specialists* are restricted to streams and rivers for all life stages, *fluvial dependents* require riverine habitats for part of their life cycle, and *macrohabitat generalists* are capable of completing their life cycle in lentic systems (Kinsolving and Bain 1993). Classification of the fish assemblages of a representative group of eight large rivers revealed that nearly half of native fish species richness was composed of fluvial dependent and fluvial specialist fishes (Galat and Zweimüller 2001). Fluvial specialists use flood pulses as a cue for feeding and reproduction (Barko et al. 2004). Morphology characteristics of fluvial fish species can include a streamlined anterior body, a narrow caudal peduncle, and a large anterior body depth (Webb 1985).

Riverine fishes shift habitat and resource use during ontogeny, from early life stages (egg, larvae, and juvenile) to adult. Habitat use is size-specific with many larval and juvenile fishes using shallow-water habitats and adults or larger fishes using deeper habitats (Kneib 1987). Many riverine fishes also exhibit diel and seasonal (winter and summer) shifts in habitat use (Wolter and Freyhof 2004). Shallow inshore areas are used by many small-bodied species and juveniles of larger-bodied riverine fishes as they migrate in-shore at night for refuge and feeding (Copp and Jurajda 1993). During daytime these near-shore areas also provide refuge to juvenile fishes from predation (Copp 1992). Many large river fishes shift to inshore habitats at night to minimize energetic costs of swimming and to forage on high densities of zooplankton (Wolter and Freyhof 2004). Shallow, near-shore waters are important larval fish nursery habitats that can be easily disrupted by artificial flow regulation (Scheidegger and Bain 1995, Schiemer et al. 2001b, Keckeis and Schiemer 2002).

Great rivers support a distinct assemblage of fishes categorized by Pflieger (1997) as the ‘Big River Faunal Group’ or “Big River” fishes (Simon and Emery 1995, Galat et al. 2005). The main channel is an important habitat for these fishes (Dettmers et al. 2001, Galat and Zweimüller 2001). Fifty-four percent of Missouri River fishes reside primarily in the main channel (73 species) and about one-half (68 species) requires flowing water for some life-stage activity (Galat et al. 2005). All fluvial specialists in the Missouri River are native fishes (Galat et al. 2005). The temperature range over which most Missouri River fishes spawn is between 15 and 25˚C, which occurs between late April and late June (Gelwicks 1995, Galat et al. 1998). Sandbars and associated shallow-water habitat on the lower Missouri River are used by riverine fishes for spawning and nursery (Galat and Lipkin 2000). The decline in Missouri River’s native fluvial fishes is likely associated with reduced summer-autumn high flows and in-channel habitat loss (Galat and Lipkin 2000).

METHODS

Data Collection and Model Development

To evaluate the potential effect submergent and emergent-sandbar ATTZ availability has on use by softshell turtles, migratory shorebirds, wading birds, and riverine fishes, I applied data on species' use of sandbar habitats to predicted discharge-area relations from chapter two. My hypothesis was that area of available sandbar ATTZ, which is dependent on river discharge, will influence potential use of sandbars by softshell turtles, migratory shorebirds, wading birds, and riverine fishes.

Nineteen sandbars representing two sandbar types (nine point and ten wing-dike) were selected for analysis within the Grand River (km 402) to Osage River (km 209) segment of the Lower Missouri River, Missouri. Morphometric variables (total area, elevation, wetted perimeter, and water-surface slope) were measured on each sandbar using several instruments. Sandbars were mapped over a range of river discharges between 2002 and 2005 to develop empirical discharge-morphometric relations. Exposed sandbars were mapped using both an electronic Total Station (SOKKIA-SET5W) and Real Time Kinematic system (Trimble Unit 5700/5800) to produce detailed topographic maps. Morphometric data from 13 (six point and seven wing-dike sandbars) provided sufficient data meeting quality standards and were retained for further analysis. Discharge data were obtained from USGS (http://water.usgs.gov/mo/nwis/rt) for the days that sandbars were mapped, using the nearest gage station relative to major tributaries for the location of each sandbar. Discharge values were adjusted to the location of the sandbar by river mile by interpolating between gages. The rate of water discharge is presented primarily in units of thousand of cubic feet per second (ft^3/s, or kcfs) because it is the common unit used by researchers and agencies on the Lower Missouri River and I have converted these measurements to thousand of cubic meter per second (kcms). See chapter two for further details on site selection and data collection.

Data processing involved production of a series of topographic grids from sandbar survey data used to develop a discharge-morphometric relation (Chapter 2). I developed predictive models of sandbar area at specific discharges using discharge as the independent variable and sandbar area as the dependent variable. Components of each discharge-area model included; a discharge-stage function, a discharge-slope function, topographic elevation grid at lowest discharge recorded during mapping, and synthesized water surface elevation grid for each discharge in model (sandbar ratio grid * length of sandbar * slope function) (Chapter 2, Fig. 2.4). A predictive discharge-area model was created for each sandbar, following specified assumptions (Chapter 2). Multiple discharge-area models were developed for each sandbar based on individual discharge-slope functions. Each sandbar model produced 46 grids (elevation and depth) at a specified discharge range of 10 kcfs to 100 kcfs (0.3 kcms to 2.8 kcms). A series of statistical tests (Kolmogorov-Smirnov) and validation techniques were used to select one discharge-area model for each sandbar that best fit empirical field data. Model selection and validation resulted in a total of 13 predictive discharge-area models (six point and seven wing-dike sandbars); Chapter 2, Table 2.3.

Sandbar ATTZ Classes

Physical parameters including area and perimeter were extracted from the final 13 predictive model results. To evaluate how discharge affects changes in sandbar area for potential biota use, results from each model were grouped into ecologically guided sandbar-ATTZ classes based on life-history information and criteria defined by others. Submergent ATTZ (-) includes four depth classes and emergent ATTZ (+) includes two elevation classes. Each ATTZ class was defined according to biological criteria of species use for: riverine fishes, migrating shorebirds, wading birds, and softshell turtle species (Table 3.1).

The ATTZ classes relevant to selected riverine biota are emergent ATTZ 0.0 to 0.3 m, which include the wet soil-water interface that shorebirds use (0.15 m) (Rundle and Fredrickson 1981). Emergent-ATTZ class >1.0 m is the height above water level that Fitch and Plummer (1975) found softshell nesting to peak. Submergent-ATTZ class 0.0 to -0.3 m is the smallest depth designation defined for shorebird foraging, ranging from small shorebird species [e.g., least sandpiper (*Calidris minutilla*), that use water depths <-0.025 m] to large shorebird species [e.g., greater yellowlegs (*Tringa melanoleuca*) that use water depths >0.14 m] (Hands 1988). Submergent-ATTZ class 0.0 to -0.3 m also integrates two definitions of shallow-water habitat used by fishes, <0.28m (Gelwick et al. 1997) and <0.4m (Barko et al. 2004), that we include as one definition of larval fish nursery habitat and also includes the shallow water at sandbar shorelines that is used by softshell turtle hatchlings (Plummer 1977a). Submergent-ATTZ class 0.0 to -0.5 m coincided with Ridenour's (2005) study on juvenile and small-bodied fish use of shallow-water habitats associated with sandbars and is also inclusive of the depth range

Table 3.1. Classification of sandbar ATTZ into submergent ATTZ (depth from water's edge 0.0 m) and emergent-ATTZ (elevation from water's edge 0.0 m) classes. Each ATTZ class was defined according to biological criteria of species use and life-history information (See text for details). Sandbar ATTZ is a dynamic zone that is alternatively inundated and exposed within the annual hydroperiod (Fig. 3.1).

	Submergent-Sandbar ATTZ				Emergent-Sandbar ATTZ	
	0.0 to -0.3 m	0.0 to -0.5 m	0.0 to -1.0 m	0.0 to -1.5 m	0.0 to 0.3 m	>1.0 m
Biological Significance	larval fish nursery habitat, shorebird and wading bird foraging, softshell foraging	juvenile fish foraging/ refugia, wading bird foraging	riverine fish foraging/ refugia	riverine fish foraging/ refugia	Shorebird foraging	Softshell nesting

that rails and herons can use (0.6 m; Rundle 1980, Fredrickson and Reid 1986). Submergent-ATTZ class 0.0 to -1.0 m is the depth interval selected by Reeves (2005) for his study on larval fish nursery that is based on other studies, physical equipment constraints, and the objective to ensure inclusion of as much habitat as possible that larvae were using. Submergent-ATTZ class 0.0 to -1.5 m corresponds to the U.S. Fish and Wildlife Service's definition of the depth range of shallow water for the Missouri River (U.S. Fish and Wildlife Service 2000). The submergent-ATTZ classes are inclusive of multiple depths, because as young-of-year (age 0) fishes grow they occupy deeper water (Kneib 1987).

I first quantified how changes in discharge affected area of submergent ATTZ (0.0 to -0.3, 0.0 to -0.5, 0.0 to -1.0, and 0.0 to -1.5 m) and emergent ATTZ (0.0 to 0.3 and >1.0 m) classes to evaluate how point and wing-dike sandbar types differ in area relative to their frequency of occurrence. Mean area by sandbar type (seven wing-dike, six point sandbars) was calculated for each ATTZ class versus discharge. I compared mean area among ATTZ classes at 10 kcfs (0.3 kcms) increments to determine at what discharge (or range of discharges) areas were maximized. I also analyzed discharge-area curves in relation to discharges required to maintain minimum and full service navigation at Kansas City, Missouri. Peaks in mean area and percent area available in relation to minimum (35 kcfs, 0.99 kcms) and full (41 kcfs, 1.20 kcms) service navigation flows were compared among defined submergent ATTZ and emergent-ATTZ classes. Percent area for the six point and seven wing-dike sandbars was calculated to evaluate how much each sandbar type contributed to the total area for each sandbar-ATTZ class. I calculated wetted perimeter of emergent sand across a range of discharges of 10 kcfs to 100 kcfs

(0.3 kcms to 2.8 kcms) to evaluate amount of edge habitat available to migrating shorebirds and wading birds that are known to use this interface.

Navigation Flows

Morphological and hydrological management necessary to maintain navigation on the Lower Missouri River will likely continue; therefore it is prudent to evaluate dynamics of sandbar ATTZ in relation to minimum and full-service navigation flows. Full-service navigation designation is 35 kcfs and minimum navigation service is 29 kcfs (U.S. Army Corps of Engineers 2004a). At Kansas City, Missouri the full-service navigation flow target is 41 kcfs and minimum service is 35 kcfs (U.S. Army Corps of Engineers 2004a). Since minimum and full-service target flows have not been defined for Boonville, Missouri, target flows at Kansas City, MO were used, as the closest upstream site.

Modeled Flow-Management Alternatives

A Biological Opinion (BiOp) was completed by the U.S. Fish and Wildlife Service (USFWS) concerning operational management of the Missouri River by the U.S. Army Corps of Engineers (U.S. Fish and Wildlife Service 2000). The BiOp included implementation of "reasonable and prudent alternatives" (RPAs) composed of the following elements: adaptive management, flow enhancements below Ft. Peck and Gavins Point Dams, unbalanced storage among upper three reservoirs, and habitat restoration/creation/acquisition (U.S. Army Corps of Engineers 2004a). Five alternatives to the current water control plan (CWCP) were developed by the COE in their "Final

Environmental Impact Statement" (FEIS) including four flow-alternatives that evaluate the relative effects of high and low flow from Gavins Point Dam (U.S. Army Corps of Engineers 2004a). The flow-management alternatives have been simulated by the COE using the Missouri River system Daily Routing Model (U.S. Army Corps of Engineers 1998). The modeled flows for each alternative were generated by the COE by incorporating historical tributary inflows, climatic variability, and a uniform set of operating rules including: operation of the reservoirs, flood control, and navigation. Development of these models allows for comparison between recommended flow alternatives using long-term data.

Predicted-discharge area models of ATTZ classes for each sandbar type and total area of all 13 sandbars were applied to four alternative flow-management scenarios to estimate habitat availability under various flow regimes. Modeled flow data for two modeled flow-management alternatives (GP1528 and GP2021) and two reference alternatives ROR (run-of-river) and CWCP (current water control plan) were obtained from the U.S. Army Corps of Engineers for the Boonville, MO streamflow-gaging station. I used the full range of modeled data available for the period 1898 – 1997.

Two flow-management alternatives, GP1528 and GP2021, incorporate the relative effects of high and low flow releases from Gavins Point dam (Jacobson and Heuser 2001). The flow-management alternative GP1528 has the lowest spring rise and highest summer flows (U.S. Army Corps of Engineers 2004a). The GP1528 alternative includes a 15 kcfs spring rise (high) (mid-May to mid-June) above full-service navigation releases (35 kcfs) from Gavins Point Dam, followed by a minimum service flat release of 28.5 kcfs (low) (6.5 kcfs < full-service navigation) ending September 1 (U.S. Army Corps of

Engineers 2004a). The GP2021 flow-management alternative has the highest spring rise and lowest summer flows of the four scenarios (U.S. Army Corps of Engineers 2004a). The GP2021 alternative has a 20 kcfs spring rise (high) followed by a split navigation season with two low-flow periods during the summer of 21 and 25 kcfs (Jacobson and Heuser 2001). Two modeled reference alternatives include the Current Water Control Plan (CWCP) and a run-of-river scenario (ROR). The ROR (run-of-river) is a model of flows that would occur in the absence of reservoirs and regulation, and is an estimate of the natural state of the lower Missouri River’s flow conditions (Jacobson and Heuser 2001). All modeled flows remain within the confines of the current river channel and will not inundate historical floodplain habitat.

Surface-water statistics (SWSTAT) software was used to analyze daily streamflow data for the modeled flow of each alternative to compute duration hydrographs. Duration hydrographs are plots of selected percentiles of daily flows a year over a specified period of record. SWSTAT was originally developed for streamflow data, but can be used to analyze any time-series data. Predicted mean area of ATTZ classes for each sandbar type and total area of all 13 sandbars were applied to the daily modeled flow for each alternative and then SWSTAT was used to compute duration hydrographs. In this way, the duration hydrographs represent the area of ATTZ available for each modeled alternative.

Mean area-duration curves by sandbar type were produced by calculating the percent time mean area was exceeded for each ATTZ classification between sandbar types (six point and seven wing-dike sandbars) and then comparing the duration curves among each modeled alternative. Total area (combined six point and seven wing-dike sandbars) from modeled discharge-area relations for each ATTZ classification was applied to the modeled daily flows (1898 – 1997) of each flow alternative to determine when during the year ATTZ classes were available and the frequency of availability. SWSTAT outputs duration hydrographs of area at defined percentiles for each day of the selected year (January-December). Median area (50%) was selected for analysis on the availability of submergent and emergent-ATTZ habitats during targeted life stages of riverine biota.

Frequency of inundation of softshell turtle nests was calculated during the time period May through October that covers the entire range of nesting and hatchling emergence documented for both smooth and spiny softshell species. The days that flows were ≥60 kcfs were identified for each flow management and reference alternative at the median (50%) modeled discharge. I selected 60 kcfs as the cutoff based on Figure 3.2 which illustrated little to no emergent ATTZ >1.0 m was available at discharges greater than 60 kcfs.

Data Collection: Biota

Life history information for softshell turtles, shorebirds, wading birds, and riverine fishes was compiled from studies conducted on a portion of the Lower Missouri River and used to determine when sandbar ATTZs met the targeted life-history criteria listed in Table 3.1. Information collected on the life histories of softshells included timing of the nesting season, location of nests, and timing of hatchling emergence. Similar information on life history of shorebirds and wading birds included timing of autumn and spring migrations and post fledgling activity.

Spawning chronologies for three taxa groups of Missouri River fishes were compiled to identify timing of spawning period. I used results from Reeves (K. Reeves, personal meeting, 2006) on use of sandbars by larval fish from a sample of 10 (five point and five wing-dike) sandbars that included 10 of the 13 sandbars in this study. Spawning temperature range and date of first collection of larval fishes were acquired from a synthesis of lower Missouri River studies compiled by Patton (2003). Identified spawning temperature range was compared with water temperature data (October 1937 – March 31, 2005) for the Boonville Water treatment plant to assign calendar dates to estimated spawning temperature ranges. These sources were used to determine the range of spawning for the three most abundant taxa collected by Reeves (2006): native carpsuckers and buffalo (*Carpiodes* spp./*Ictiobus* spp.), non-native silver and bighead carps (*Hypophthalmichthys molitrix*/*nobilus*), and native chubs (*Macrhybopsis* spp.). I then estimated the median temperature of spawning using data of temperature and date of first collection from previous Missouri River studies and from Reeves study (2002) and then linked with calendar date to designate timing of submergent ATTZ use thereafter as nursery. I used Reeves (2006) larval fish data of the three most abundant taxa as criteria to select a submergent-ATTZ class to focus on for analysis, submergent ATTZ 0.0 to -1.0 m.

Statistical Analysis

The Kolmogorov-Smirnov two-sample test statistic measures the maximum deviation of two cumulative distribution functions (SAS 2000). This test determined if any difference in the distributions, including shape, of mean area for each submergent

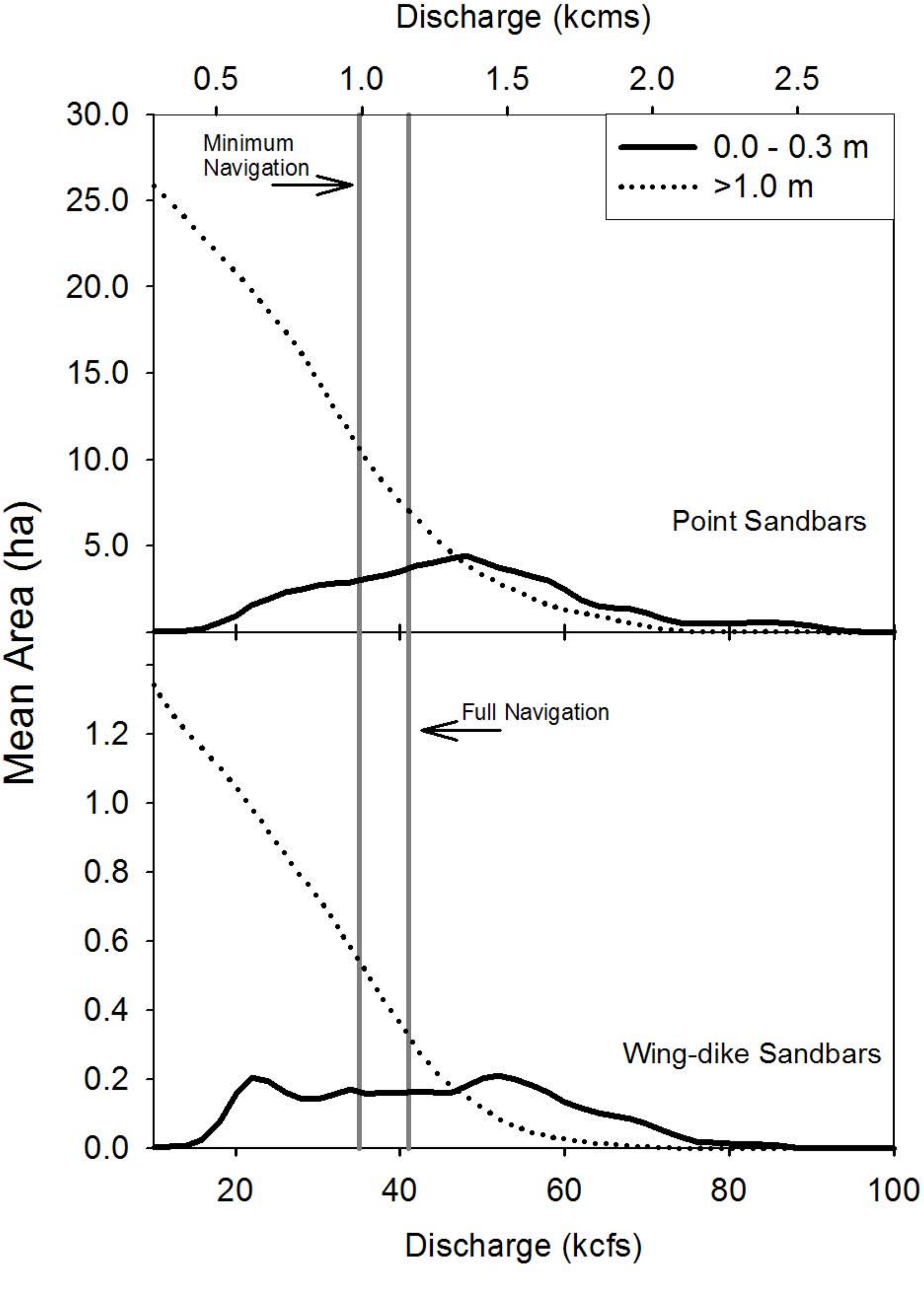


Figure 3.2. Modeled mean area for two emergent-ATTZ classes over discharges ranging between 10 and 100 kcfs (0.3 kcms to 2.8 kcms) for six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment of the Missouri River, Missouri. Vertical lines represent discharges required to maintain minimum and full-service navigation at Kansas City, Missouri (U.S. Army Corps of Engineers 2004).

ATTZ (n = 4) and emergent-ATTZ (n = 2) classes were significant between point and wing-dike sandbars. The Kolmogorov-Smirnov test statistic was used to determine if distributions of duration curves (percent exceedence) and duration hydrographs of median area for each submergent ATTZ and emergent-ATTZ class were different between selected flow management alternatives (GP1528, GP2021, ROR, and CWCP). Pairs of distribution curves were compared among all alternatives both within each sandbar type and for all sandbars combined. I binned the duration hydrograph data based on the timing of life-history activities of selected biota for the ATTZ class designated for use by each, to further analyze if distributions were different between flow-management alternatives during the critical time periods of species use. This was done because the Kolmogorov-Smirnov two-sample test statistic is sensitive to any differences in the distributions in the two samples (Kolmogorov et al. 1941) and would include all time periods, including those not used by species of interest. If the two-sample Kolmogorov-statistic (D) is greater than the quantile of the Smirnov test statistic or if the asymptotic p-value for the Kolmogorov-Smirnov test is <0.05 significance level, I would reject the null hypothesis and conclude that the two distributions are not identical for the two groups (SAS Institute 2000).

RESULTS

Sandbar ATTZ (Objective 1)

Modeled mean area for the six point sandbars was as much as 22 times greater than the mean for the seven wing-dike sandbars for both submergent-ATTZ classes (0.0 to -0.3, 0.0 to -0.5, 0.0 to -1.0, and 0.0 to -1.5 m) and emergent-ATTZ classes (0.0 to 0.3 and >1.0 m) (Objective 1.1.; Tables D.1, D.2, and D.3). Differences in percent area between six point sandbars (≈169 ha) and seven wing-dike sandbars (≈11 ha) for all ATTZ classes ranged from 0 to 11% (Table D.4). The shape of the mean area relation for submergent-ATTZ classes was unimodal for point and unimodal or somewhat bimodal for wing-dike sandbars with peaks shifting to the right as depth of submergent ATTZ increased (Fig. 3.3). Emergent-ATTZ area >1.0 m was negatively correlated and appeared linear from 10 to 40 kcfs for both point and wing-dike sandbars (Fig. 3.2). The shape of the mean area distribution for emergent ATTZ 0.0 to 0.3 m was unimodal for point sandbars peaking at 48 kcfs and weakly bimodal for wing-dike sandbars peaking at 22 and 52 kcfs (Fig. 3.2, Table 3.2). Distribution of discharge-relation curves of mean area for each submergent and emergent-ATTZ class were not significantly different between point and wing-dike sandbars (Kolmogorov-Smirnov, $P \leq 0.05$, Table 3.3).

Sandbar ATTZ and Navigation Flows

Discharges were compared at minimum (35 kcfs) and full-service (41 kcfs) navigation flows, to illustrate patterns of sandbar-ATTZ area (Objective 1.2.). Maximum submergent-ATTZ area occurred at discharges greater than minimum-navigation flows for all classes of point sandbars, but only at the 0.0 to -1.5 m class for wing-dike sandbars (Fig. 3.3). Once flows reached minimum navigation there was not much change in available mean area for wing-dike sandbars at submergent-ATTZ classes 0.0 to -0.3, 0.0 to -0.5, and 0.0 to -1.0 m; Fig. 3.3). Area of emergent-ATTZ class 0.0 to 0.3 m for wing-dike sandbars peaked both below (22 kcfs) and above (52 kcfs) navigation flows, but the actual area differences between these flows were small (0.21 ha versus 0.16 ha). Maximum emergent-sandbar ATTZ area for point sandbars occurred above minimum and full-service navigation flows at 48 kcfs with a 0.7 and 1.4 ha difference in area between these flows, respectively. Area of emergent-ATTZ class >1.0 m was highest at 20 kcfs for both sandbar types (Fig. 3.2). A decrease in mean area occurred for both point and wing-dike sandbars at minimum and full-service navigation flows for emergent-ATTZ class >1.0 m (Fig. 3.2).

Modeled Flow-Management Alternatives (Objective 2.1.)

The modeled daily discharges for the Missouri River at Boonville, MO for 100 years of record illustrated seasonal (range of Q over months) and interannual (range of Q between 25th and 75th percentiles) variability under unregulated (ROR) and regulated (CWCP, GP1528, and GP2021) flow conditions within the contemporary channel geomorphology (Fig. 3.4). Modeled flow-management alternatives (GP1528, GP2021) exhibited a similar pattern of seasonal variation as the CWCP, with a few exceptions in July-August when GP2021 and GP1528 exhibited lower discharges. Modeled flow-management alternatives (GP1528 and GP2021) and the representative contemporary

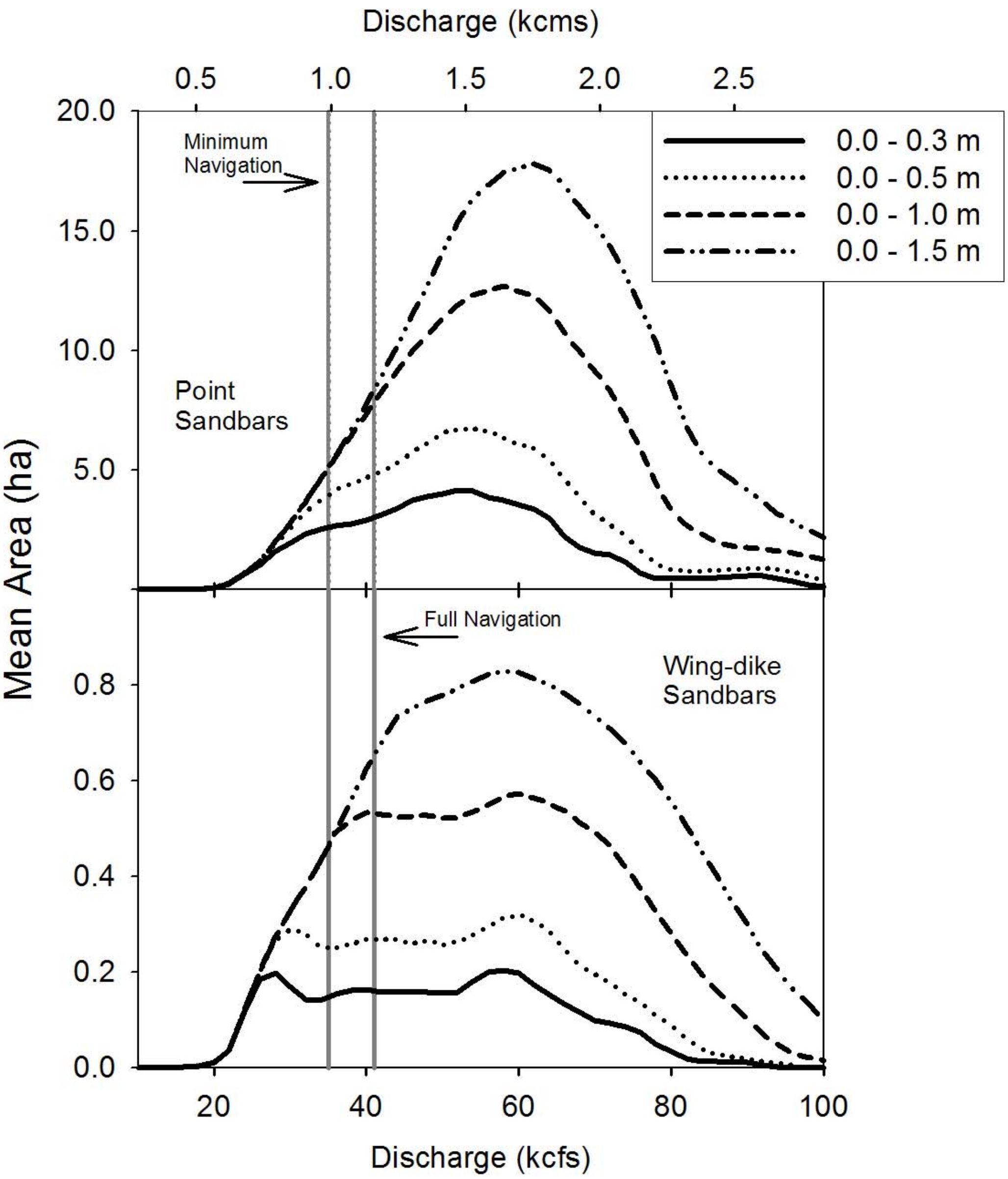


Figure 3.3. Modeled mean area for four submergent-ATTZ classes over discharges ranging between 10 and 100 kcfs (0.3 kcms to 2.8 kcms) for six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment of the Missouri River, Missouri. Vertical lines represent discharges required to maintain minimum and full-service navigation at Kansas City, Missouri (U.S. Army Corps of Engineers 2004).

Table 3.2. Peaks in mean area at corresponding discharge for emergent ATTZ (ATTZ-E) and submergent-ATTZ (ATTZ-S) classes and percent mean area within each ATTZ classification associated with minimum (35 kcfs) and full-service navigation flows (41 kcfs) (Kansas City, MO) for six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment of the Lower Missouri River, MO km 402 to 209.

	ATTZ Classification (m)	Discharge (kcfs) of peaks in area		Maximum mean area (ha) available at corresponding discharge ± SD		Percent of mean area during minimum navigation flows 35kcfs		Percent of mean area during maximum navigation flows 41 kcfs	
		Point	Wing-dike	Point	Wing-dike	Point	Wing-dike	Point	Wing-dike
ATTZ-S	0.0 to -0.3	52	28 56-60	4.2 ± 1.6	0.2 ± 0.2 0.2 ± 0.3	3.3	3.4	4.1	3.7
	0.0 to -0.5	54	30 60	6.7 ± 2.2	0.3 ± 0.3 0.3 ± 0.4	3.0	3.5	3.8	3.8
	0.0 to -1.0	58	58-60	12.7 ± 3.1	0.6 ± 0.6	2.1	3.2	3.1	3.7
	0.0 to -1.5	62	58-60	17.8 ± 4.7	0.8 ± 0.8	1.5	2.2	2.4	3.1
ATTZ-E	0.0 to 0.3	48	22 52	4.4 ± 1.7	0.2 ± 0.2 0.2 ± 0.3	4.0	3.7	4.5	3.7
	>1.0	10	10	25.8 ± 7.2	1.3 ± 1.1	3.5	3.6	2.4	2.3

Table 3.3. Results of Kolmogorov-Smirnov test statistics for the distribution curves of mean area for submergent ATTZ (ATTZ-S) and emergent-ATTZ (ATTZ-E) classifications between six point sandbars and seven wing-dike sandbars. P values $\leq$0.05 indicate distributions were significantly different.

	ATTZ-S 0.0 to -0.3	ATTZ-S 0.0 to -0.5	ATTZ-S 0.0 to -1.0	ATTZ-S 0.0 to -1.5	ATTZ-E 0.0 to 0.3	ATTZ-E >1.0
D-statistic	0.17	0.20	0.22	0.20	0.17	0.11
P-value	0.5	0.3	0.2	0.3	0.5	1.0

CWCP flow pattern are characterized by lower flow pulses in spring and higher flows in the summer and autumn months compared to the run-of-the river (ROR) reference alternative.

Two submergent-ATTZ classes (0.0 to -0.3 and 0.0 to -1.0 m) and one emergent-ATTZ class >1.0 m were used for duration analysis of flow-management alternatives (Objective 2.1.) to illustrate availability compared to timing of biota use (Objective 2.2.). Submergent ATTZ 0.0 to -1.0 m is includes shallow water for riverine fishes, and submergent ATTZ 0.0 to -0.3 m includes larval fish nursery habitat, and foraging habitat for shorebirds, wading birds, and softshell turtles (Table 3.1). Emergent ATTZ >1.0 m represents nesting habitat for softshell turtles.

Mean area for point sandbar submergent-ATTZ classes 0.0 to -0.3 and 0.0 to -1.0 m under the ROR, GP1528 and GP2021 modeled flows (1898 –1997) are exceeded by present conditions of the CWCP (Fig. 3.5, Table 3.4). Mean area for wing-dike sandbars for submergent ATTZ 0.0 to -1.0 m under ROR, GP1528, and GP2021 modeled flows were also exceeded by the CWCP (Fig. 3.5, Table 3.4). The shape (distribution) of discharge-area relation curves of mean area for both submergent-ATTZ class 0.0 to -0.3 and 0.0 to -1.0 m were not significantly different among all flow-management alternatives for both point and wing-dike sandbars (Kolmogorov-Smirnov, P = 1.0; Tables 3.5 and 3.6). Additionally, there was no significant difference in distribution of mean area over the 20% to 60% exceedance levels for GP1528 and GP2021 versus ROR for point sandbars (Kolmogorov-Smirnov, D = 0.22, P = 1.0). Mean area for point and wing-dike sandbars emergent-ATTZ class >1.0 m exhibited more area a greater percent of time under the ROR alternative than under present conditions of the CWCP and alternatives GP1528 and GP2021 (Fig. 3.6). Distributions of mean area among alternatives were not significantly different for emergent ATTZ >1.0 m for point and wing-dike sandbars (Kolmogorov-Smirnov, P = 1.0) (Tables 3.5 and 3.6). The Current Water Control Plan (CWCP) had the greatest area 25, 50 and 75% of the time for submergent ATTZ 0.0 to -1.0 m for point sandbars, whereas ROR had the greatest area 25, 50, and 75% of the time for emergent ATTZ >1.0 m for point and wing-dike sandbars (Table 3.4).

Median area for submergent-ATTZ class 0.0 to -0.3 m, for the combined six point and seven wing-dike sandbars, available from mid-March through November was greater under the CWCP than under the ROR and there was little difference in area between GP1528 and GP2021 (Fig. 3.7). Median area for 0.0 to -0.3 m under flow alternatives GP1528 and GP2021 was less throughout the season than the CWCP and was greater than ROR except for periods within August, September and November when ROR was greater than the alternatives GP1528 and GP2021 (Fig. 3.7). Distributions of median area were significantly different for submergent ATTZ 0.0 to -0.3 m among all alternatives

(Kolmogorov-Smirnov, P = <0.0001) except between GP1528 and GP2021 (Kolmogorov-Smirnov, P = 0.6; Table 3.7).

Median area for submergent ATTZ 0.0 to -1.0 m increased similarly among alternatives CWCP, GP1528 and GP2021 from January through June as modeled discharge increased (Fig. 3.8). Alternatives GP1528 and GP2021 from June through August had the largest decrease compared to flows under the ROR and the CWCP (Fig. 3.8). Median area for 0.0 to -1.0 m available September through November was greater among the CWCP, GP1528, and GP2021 than under the ROR (Fig. 3.8). Distributions of median area were significantly different among all alternatives (Kolmogorov-Smirnov, P = <0.0001) for submergent-ATTZ class 0.0 to -1.0 m except between GP1528 and GP2021 (Kolmogorov-Smirnov, P = 1.0; Table 3.7).

Median area for emergent ATTZ >1.0 m decreased similarly among all alternatives from February through June as modeled discharge increased, and thereafter the alternatives varied (Fig. 3.9). Median area for emergent ATTZ >1.0 m increased as discharge decreased for alternatives GP1528 and GP2021 July through September, increased for ROR August steadily through December, and median area increased under the CWCP only slightly until December when all alternatives had a similar peak in area (Fig. 3.9). Distributions of median area under ROR for emergent-ATTZ class >1.0 m was significantly different from all other alternatives (Kolmogorov-Smirnov, P <0.0001; Table 3.7).

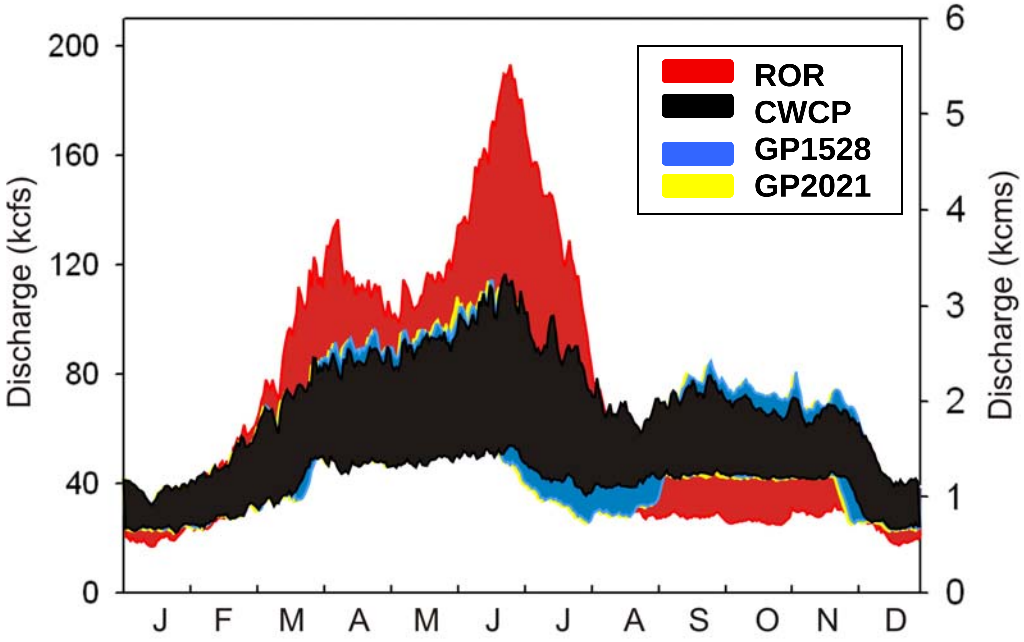


Figure 3.4. Duration hydrographs for the Missouri River at Boonville, Missouri for two modeled flow-management alternatives (GP1528, GP2021), and two reference alternatives: run-of-the-river (ROR) and the current water control plan (CWCP). Hydrographs present variability of flow during the year (horizontal axis) and over 100 years of modeled daily flows (1898-1997) (vertical axis). The shaded bands represent the 25th and 75th percentile flows each day of the year.

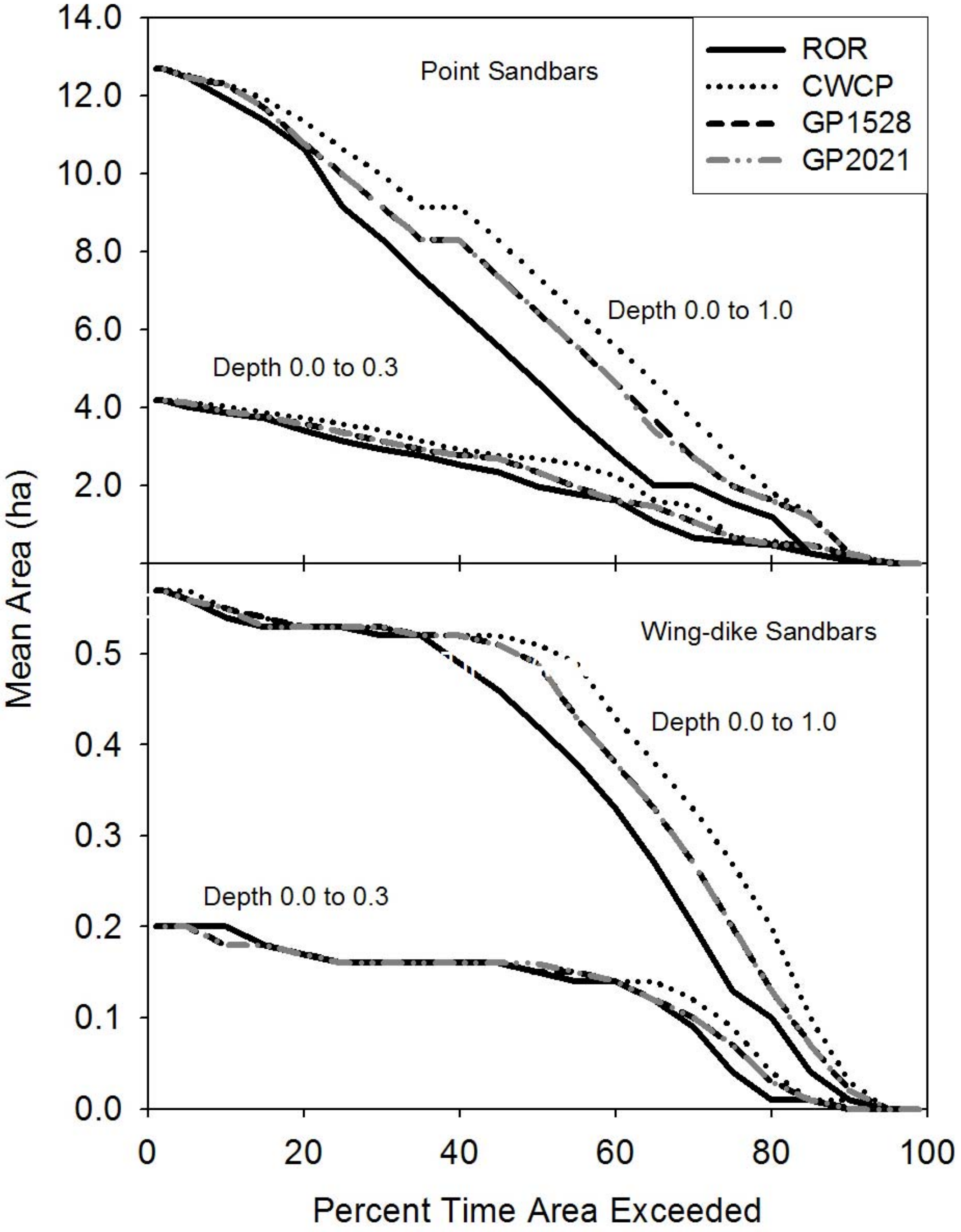


Figure 3.5. Mean area duration curves for submergent-ATTZ classes 0.0 to -0.3 m and 0.0 to -1.0 m for six point sandbars (top panel) and seven wing-dike sandbars (bottom panel) within the Grand River to Osage River segment at two modeled flow-management alternatives (GP1528, GP2021), and two reference alternatives: run-of-the-river (ROR) and the current water control plan (CWCP) for the Missouri River at Boonville, Missouri (1898-1997).

Table 3.4. Modeled mean (ha) ± 1 SD corresponding to percent time area is exceeded (%tile) for six point sandbars and seven wing-dike for two submergent-ATTZ classes and one emergent-ATTZ class at two modeled flow-management alternatives (GP1528, GP2021), and two reference alternatives: run-of-the-river (ROR) and the current water control plan (CWCP) in the channelized Lower Missouri River, km 402 to 209. See text for further explanation of flow alternatives.

Flow-management alternative percent time exceeded	Depth class (m) ATTZ-S				Elevation class (m) ATTZ-E	
	0.0 to -0.3		0.0 to -1.0		>1.0	
	Wing-dike	Point	Wing-dike	Point	Wing-dike	Point
ROR						
25th %tile	0.2 ± 0.0	3 ± 1	0.5 ± 0.1	9.1 ± 3.0	0.8 ± 0.0	16 ± 0
50th %tile	0.1 ± 0.1	2 ± 1	0.4 ± 0.4	4.6 ± 6.1	0.4 ± 0.1	8 ± 4
75th %tile	0.0 ± 0.1	0 ± 2	0.1 ± 0.3	1.5 ± 2.7	0.0 ± 0.7	2 ± 6
CWCP						
25th %tile	0.2 ± 0.1	4 ± 1	0.5 ± 0.7	10.6 ± 3.1	0.6 ± 0.0	11 ± 0
50th %tile	0.2 ± 0.1	3 ± 1	0.5 ± 0.4	7.3 ± 5.2	0.2 ± 0.1	5 ± 4
75th %tile	0.1 ± 0.1	1 ± 3	0.3 ± 0.4	2.7 ± 5.5	0.0 ± 0.5	1 ± 5
GP1528						
25th %tile	0.2 ± 0.1	3 ± 1	0.5 ± 0.6	10.0 ± 2.9	0.7 ± 0.0	13 ± 0
50th %tile	0.1 ± 0.1	2 ± 1	0.5 ± 0.4	6.4 ± 6.1	0.2 ± 0.1	6 ± 4
75th %tile	0.1 ± 0.1	1 ± 3	0.2 ± 0.4	2.0 ± 4.6	0.0 ± 0.6	1 ± 6
GP2021						
25th %tile	0.2 ± 0.1	3 ± 1	0.5 ± 0.6	10.0 ± 2.9	0.7 ± 0.0	13 ± 0
50th %tile	0.2 ± 0.1	2 ± 1	0.5 ± 0.4	6.4 ± 6.1	0.2 ± 0.1	6 ± 4
75th %tile	0.1 ± 0.1	1 ± 3	0.2 ± 0.4	2.0 ± 4.6	0.0 ± 0.6	1 ± 6

Table 3.5. Results of Kolmogorov-Smirnov test statistics on duration curves (percent exceedence) of mean area for six point sandbars for submergent ATTZ (ATTZ-S) and emergent-ATTZ (ATTZ-E) classifications. Results were modeled over the 1898 –1997 time period between selected flow-management alternatives percentiles (n=23). All P-values equaled 1.0, greater than α ≤ 0.05 selected for significance.

	ATTZ-S 0.0 to -0.3 m	ATTZ-S 0.0 to -1.0 m	ATTZ-E >1.0 m
WCP comparison	D-Statistic	D-Statistic	D-Statistic
ROR vs. CWCP	0.13	0.13	0.13
ROR vs. GP1528	0.09	0.09	0.13
ROR vs. GP2021	0.09	0.09	0.13
CWCP vs. GP1528	0.09	0.09	0.04
CWCP vs. GP2021	0.09	0.09	0.04
GP1528 vs. GP2021	0.04	0.04	0.04

Table 3.6. Results of Kolmogorov-Smirnov test statistics on duration curves (percent exceedence) of mean area for seven wing-dike sandbars for submergent ATTZ (ATTZ-S) and emergent-ATTZ (ATTZ-E) classifications. Results were modeled over the 1898 – 1997 time period between selected flow-management alternatives percentiles (n=23). All P-values equaled 1.0, greater than α ≤ 0.05 selected for significance.

	ATTZ-S 0.0 to -0.3 m	ATTZ-S 0.0 to -1.0 m	ATTZ-E >1.0
WCP comparison	D-Statistic	D-Statistic	D-Statistic
ROR vs. CWCP	0.04	0.13	0.13
ROR vs. GP1528	0.04	0.09	0.13
ROR vs. GP2021	0.04	0.09	0.13
CWCP vs. GP1528	0.04	0.04	0.04
CWCP vs. GP2021	0.04	0.04	0.04
GP1528 vs.GP2021	0.04	0.04	0.04

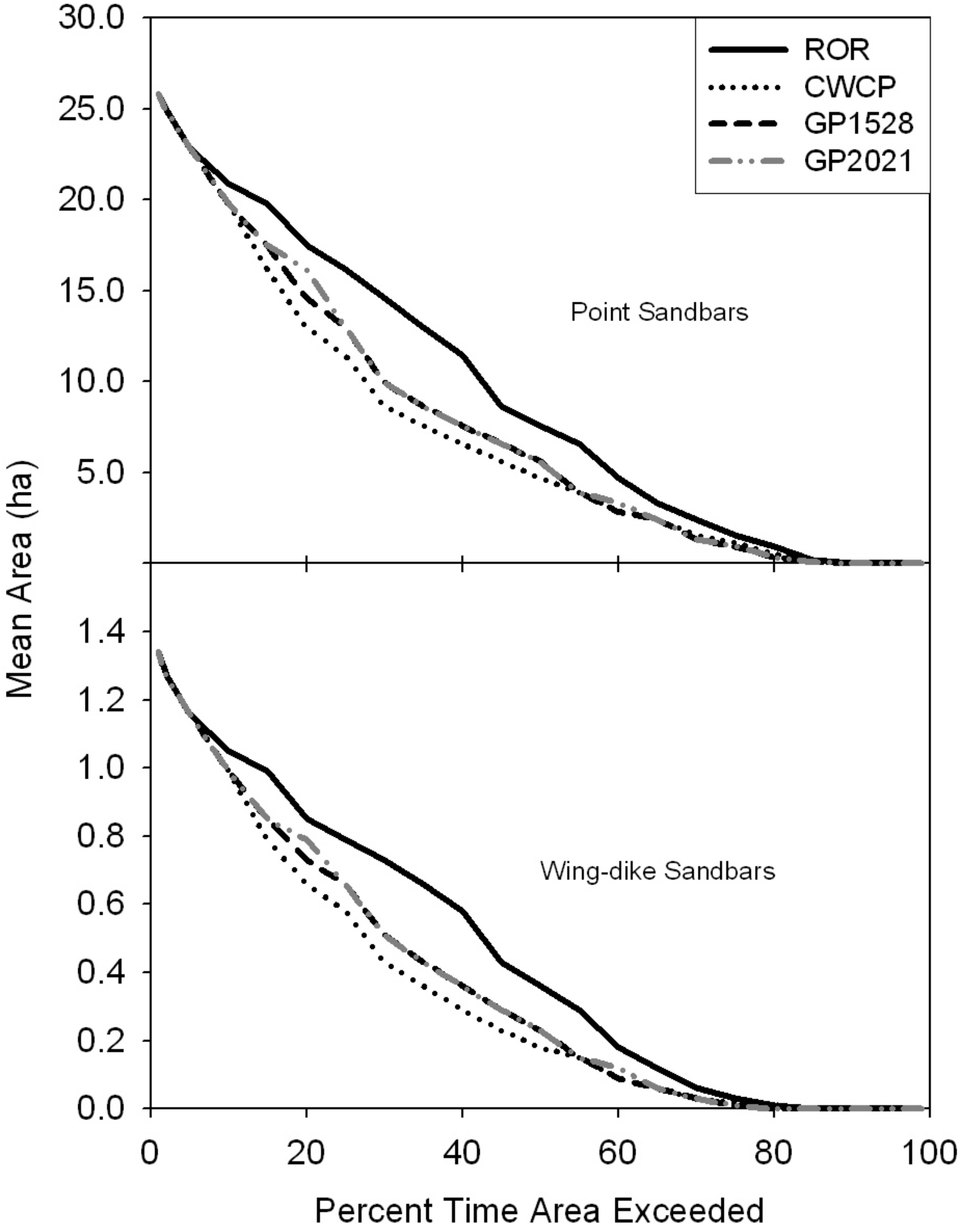


Figure 3.6. Mean area duration curves for emergent-ATTZ class >1.0m for six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment at two modeled flow-management alternatives (GP1528, GP2021), and two reference alternatives: run-of-the-river (ROR) and the current water control plan (CWCP) for the Missouri River at Boonville, Missouri (1898 –1997).

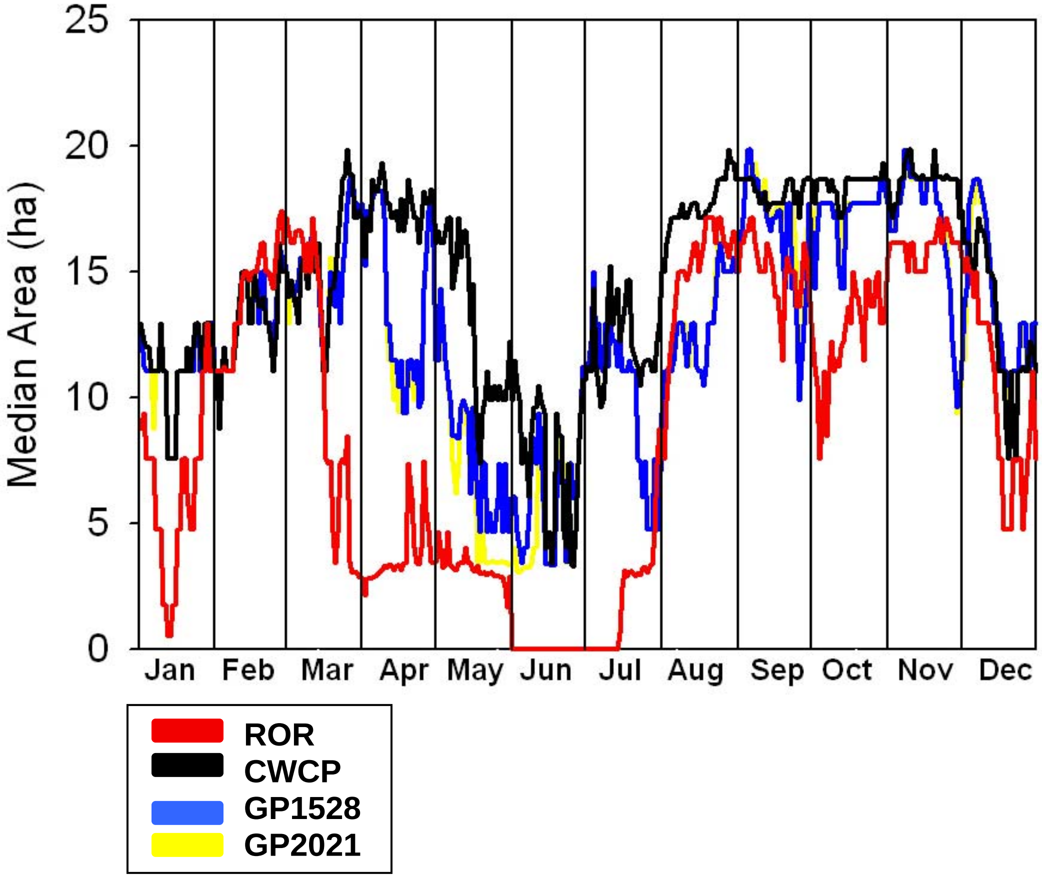


Figure 3.7. Median area for submergent-ATTZ class 0.0 to -0.3 m for six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment at two modeled flow-management alternatives (GP1528, GP2021), and two reference alternatives: run-of-the-river (ROR) and the current water control plan (CWCP) for the Missouri River at Boonville, Missouri (1898-1997).

Table 3.7. Results of Kolmogorov-Smirnov test statistics on median area of combined total hectares for six point and seven wing-dike sandbars for submergent ATTZ (ATTZ-S) and emergent-ATTZ (ATTZ-E) classifications modeled over the 1898 –1997 time period between selected flow-management alternatives. P-values $\leq$0.05 indicate distributions were significantly different.

	ATTZ-S 0.0 to -0.3 m		ATTZ-S 0.0 to -1.0 m		ATTZ-E >1.0	
WCP comparison	D-Statistic	P-value	D-Statistic	P-value	D-Statistic	P-value
ROR vs. CWCP	0.42	<0.0001	0.48	<0.0001	0.32	<0.0001
ROR vs. GP1528	0.33	<0.0001	0.34	<0.0001	0.30	<0.0001
ROR vs. GP2021	0.32	<0.0001	0.31	<0.0001	0.26	<0.0001
CWCP vs. GP1528	0.22	<0.0001	0.25	<0.0001	0.11	0.03
CWCP vs. GP2021	0.20	<0.0001	0.25	<0.0001	0.12	0.01
GP1528 vs. GP2021	0.06	0.6	0.04	1.0	0.05	0.6

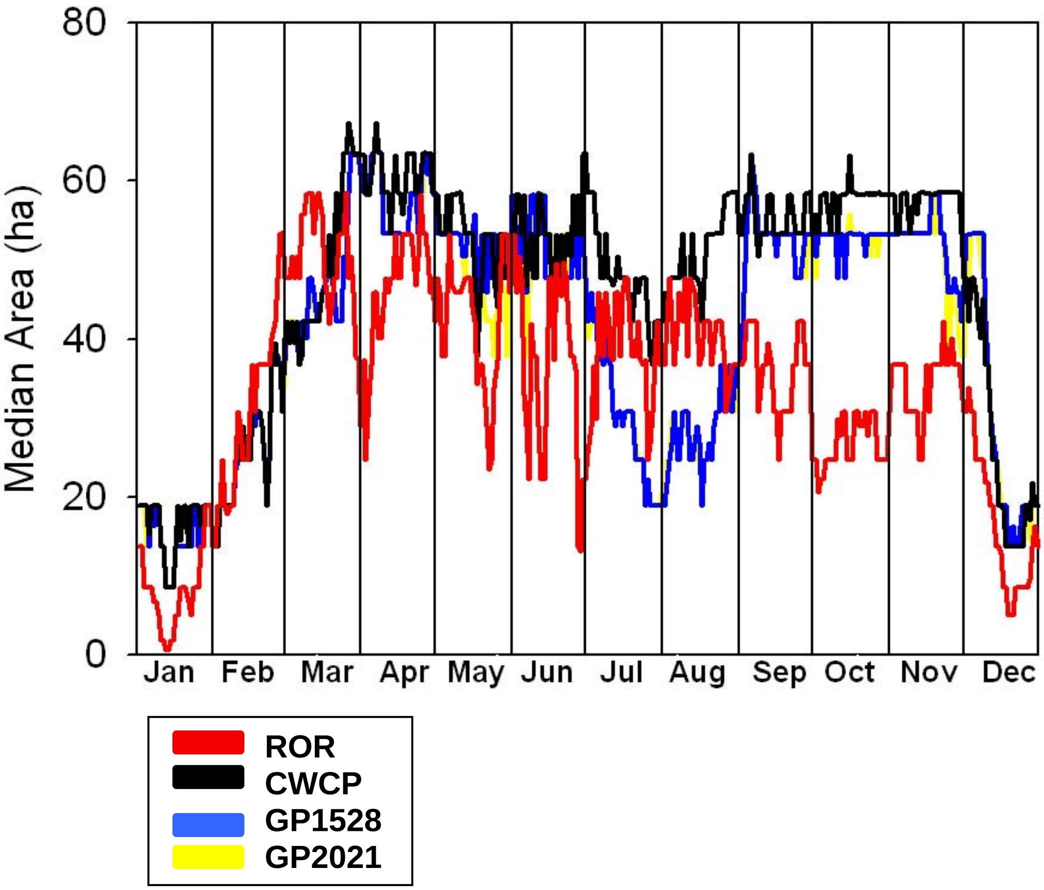


Figure 3.8. Median area for submergent-ATTZ class 0.0 to -1.0 m of six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment at two modeled flow-management alternatives (GP1528, GP2021), and two reference alternatives: run-of-the-river (ROR) and the current water control plan (CWCP) for the Missouri River at Boonville, Missouri (1898 – 1997).

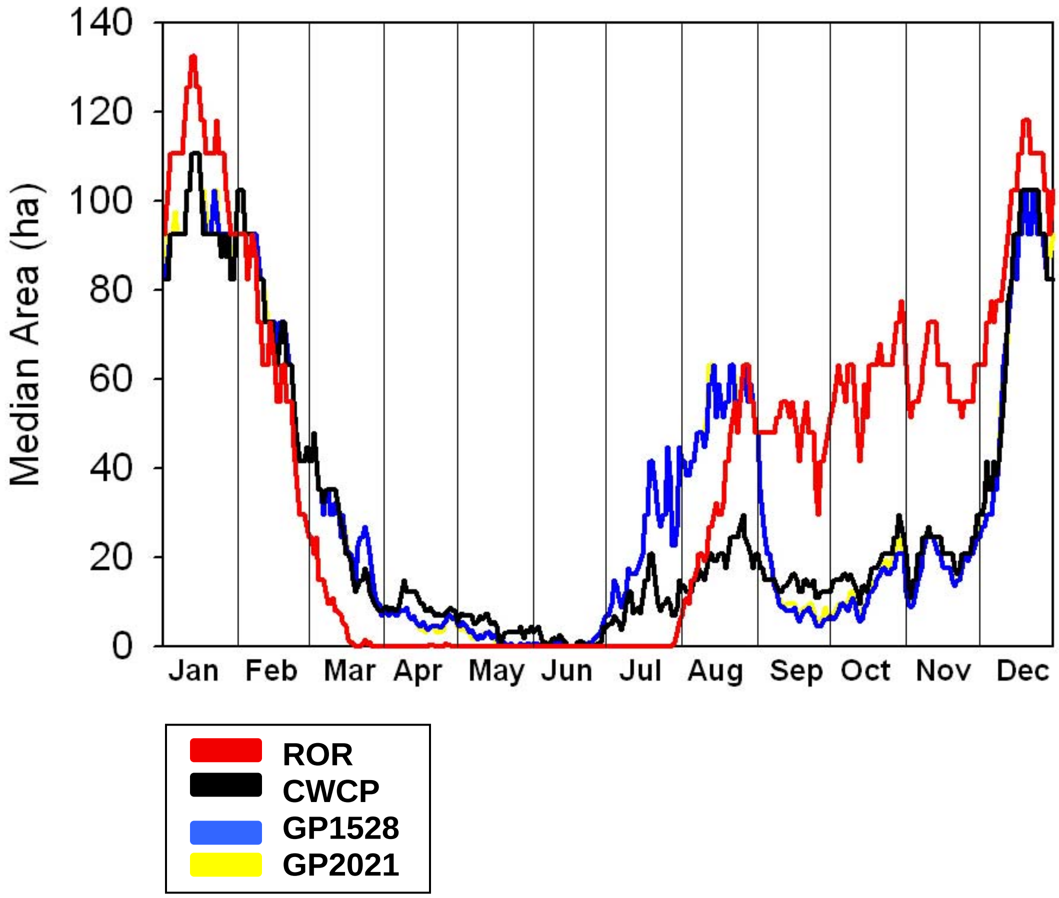


Figure 3.9. Median area for emergent-ATTZ class >1.0 m for six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment at two modeled flow-management alternatives (GP1528, GP2021), and two reference alternatives: run-of-the-river (ROR) and the current water control plan (CWCP) for the Missouri River at Boonville, Missouri (1898 – 1997).

Sandbar ATTZ Availability vs. Biota Use (Objective 2.2.)

Softshell Turtles

Median area for emergent ATTZ >1.0 m was lowest during the early months of softshell turtle nesting (May-June) and increased in July and August under the CWCP and GP1528 and GP2021 and did not increase until August under the ROR (Figs. 2.10

and 2.11). During the time period of both smooth and spiny softshell hatchling emergence, less than 30 hectares of median area for emergent-ATTZ >1.0 m was consistently available under the CWCP (Fig. 3.10). The distribution of median area during softshell turtle nesting and emergence was significantly different between the CWCP and all other alternatives (Kolmogorov-Smirnov, P = <0.0001). Median area for emergent ATTZ >1.0 was >30 hectares during the first month of smooth softshell hatchling emergence for GP1528 and GP2021 and declined to <30 hectares in late September (Fig. 3.11). During spiny softshell emergence both GP1528 and GP2021 had a peak in median area (≈ 60 ha) in April followed by a steep decline and <30 hectares available from mid-September to October. The distributions of median area during the nesting and emergence activity of both softshell species were identical between GP1528 and GP2021 (Kolmogorov-Smirnov, P = >0.05). Median area under the ROR increased from <20 hectares in the first month of smooth softshell emergence to >40 hectares of median area available throughout the period of spiny softshell emergence (Fig. 3.10).

Sandbar Inundation

During the nesting and emergence activity (May-October) of both softshell species I looked at the frequency of inundation of softshell nests associated with emergent ATTZ >1.0 m based on median modeled discharges $\geq$60 kcfs for management alternatives GP1528 and GP2021 and reference alternatives CWCP and ROR. Median discharge ranged between 60 and 79 kcfs during May and June for the CWCP which would increase inundation risk during early nesting softshells. Under the CWCP, July had minimal risk of nest inundation with only a few occurrences of days with discharges

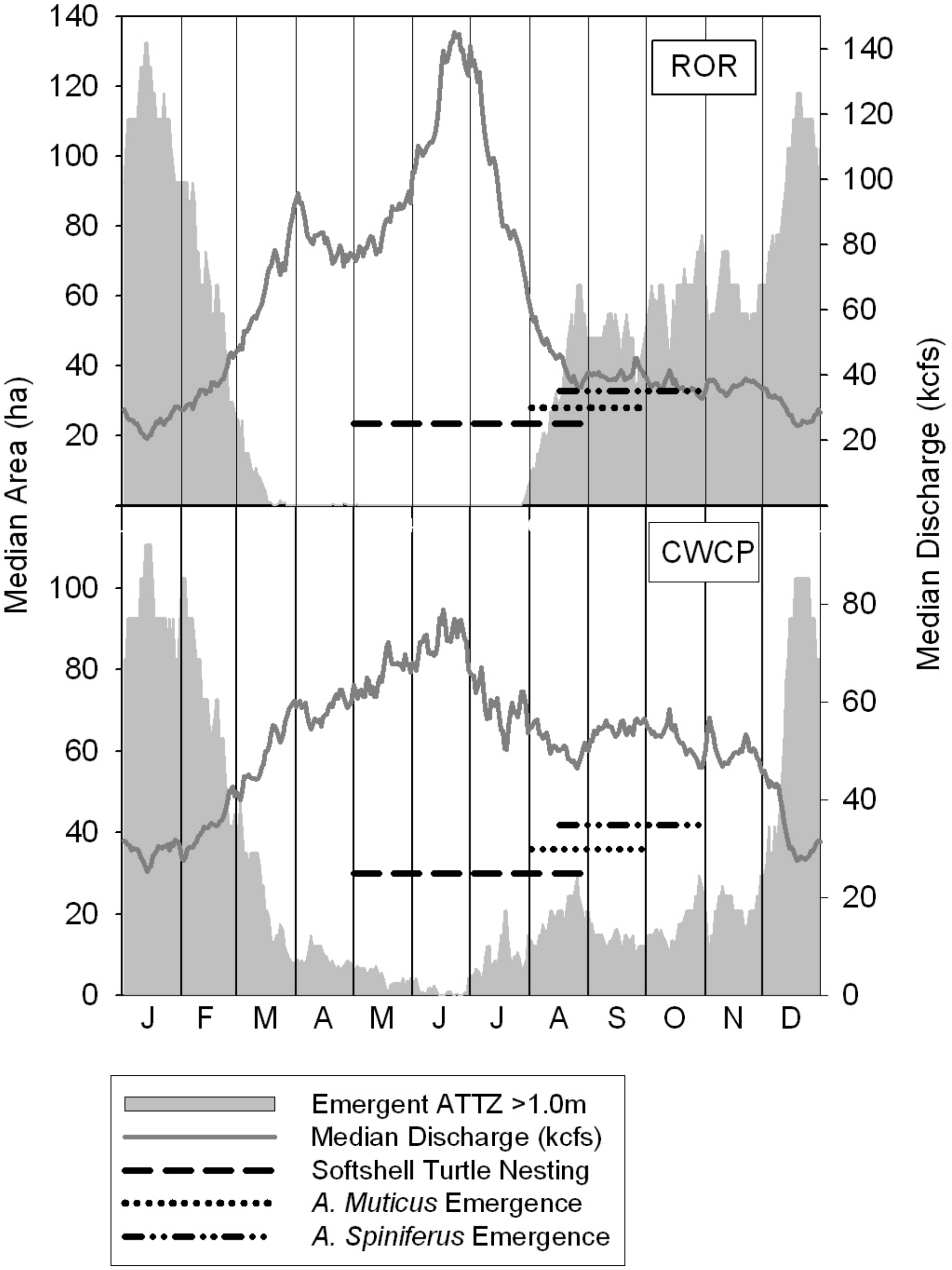


Figure 3.10. Timing of softshell turtle reproduction activity (nesting and hatchling emergence) versus median area of emergent-ATTZ class >1.0 m for six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment at two reference alternatives: run-of-the-river (ROR) and the current water control plan (CWCP) for the Missouri River at Boonville, Missouri (1898 – 1997).

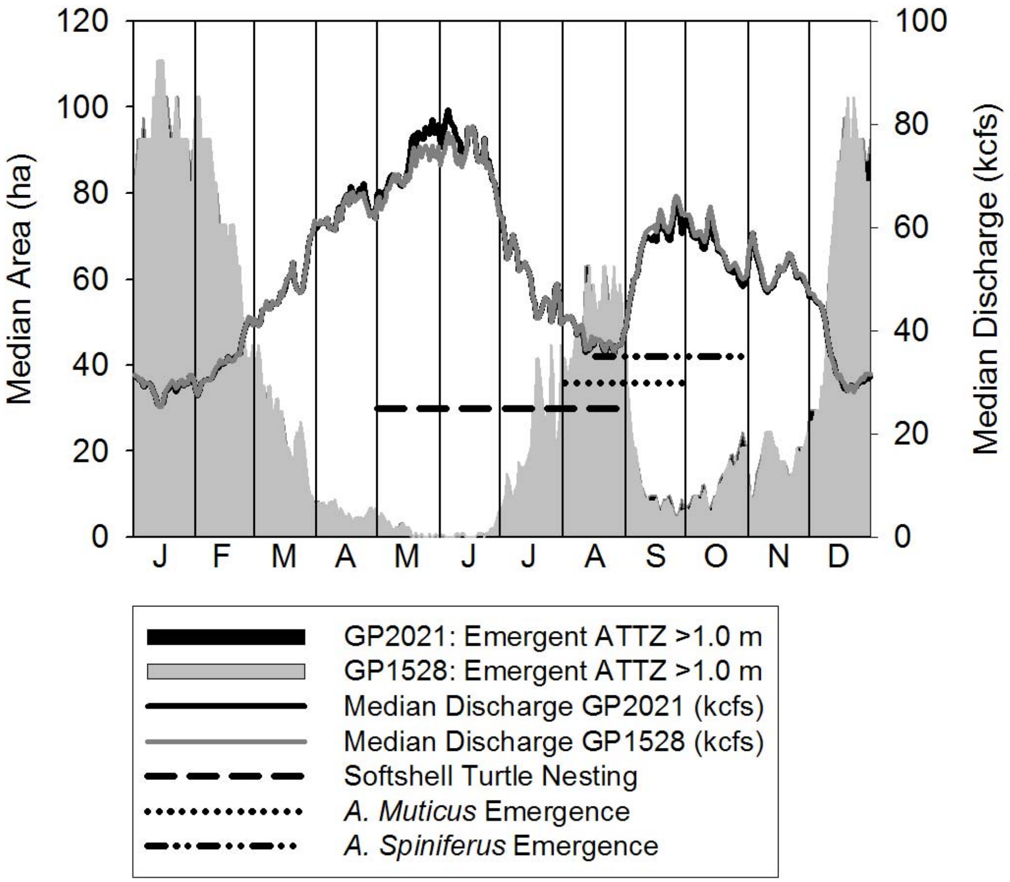


Figure 3.11. Timing of softshell turtle reproduction activity (nesting and hatchling emergence) versus median area of emergent-ATTZ class >1.0 m for six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment at two modeled flow management alternatives (GP1528, GP2021) for the Missouri River at Boonville, Missouri (1898 – 1997).

>60 kcfs. Late July and October had median discharges <60 kcfs allowing for more emergent-ATTZ under the CWCP for late nesting softshell turtles and low occurrence of inundation of high elevation nests (>1.0 m) to allow emergence of hatchlings for both softshell species. The ROR tends to have days of discharges ranging between 75 and 96 kcfs in May, 102 to 145 kcfs in June, and 61 to 137 kcfs in July which indicates a high risk of nest inundation during 75% of the softshell nesting period. August through

October had discharges ranging 32 to 58 kcfs, under the ROR alternative, indicating less inundation risk to late nesters and during the entirety of emergence for both softshell species.

All of May and June had multiple days of discharges ranging from 64 to 80 kcfs under GP1528 and GP2021 with minimal occurrence of median discharges >60 kcfs in July. Otherwise median discharges ranged between 41 and 59 kcfs for July and 35 to 43 kcfs in August for GP1528 and GP2021, indicating less inundation risk for late nesting softshells. Median discharges in September and October for GP1528 and GP2021 ranged from 40 to 66 kcfs with a few days of discharges >60 kcfs. A potential risk of nest inundation was predicted to occur before emergence of both softshell species with a slightly greater risk to spiny softshells under GP1528 and GP2021 modeled flows.

Shorebirds and Wading Birds

The ROR included the least amount of median perimeter and median area of submergent ATTZ 0.0 to -0.3 m available within the contemporary channel configuration among all modeled flow-management alternatives, during autumn and spring migration of shorebirds and the occurrence of post breeding wading birds. The distribution of median area for submergent-ATTZ class 0.0 to -0.3 m during spring shorebird migration was significantly different between CWCP and all other alternatives (Kolmogorov-Smirnov, P = <0.0001). The CWCP had up to 85% more area from March through May within the spring shorebird migration period than ROR (Fig. 3.12) and up to 62% more area than GP1528 and GP2021 (Fig. 3.13). Distributions of median area for submergent-ATTZ class 0.0 to -0.3 m during range of dates for post breeding wading bird use were significantly different between CWCP and all alternatives (Kolmogorov-Smirnov, P = <0.0001) with ROR exhibiting zero area until mid-July (Fig. 3.12). During autumn shorebird migration, median area for submergent-ATTZ class 0.0 to -0.3 m was always greater under CWCP than ROR having 33% to 81% more area for the days in July, with a significant difference between distributions of submergent-ATTZ area for the entire period of autumn migration (Kolmogorov-Smirnov, D = 0.70, P = <0.0001). The CWCP had 4% to 63% more area than alternatives GP1528 and GP2021 from mid-July through August during autumn shorebird migration, while GP1528 and GP2021 had up to 78% more area than ROR for the days in July and up to 35% less area than ROR in August. The distributions of median perimeter and area during spring and autumn shorebird migrations and the occurrence of post breeding wading birds were identical between GP1528 and GP2021 (Kolmogorov-Smirnov, P = >0.05).

Wetted perimeter was included in the analysis of timing of shorebird and wading bird use because submergent-sandbar ATTZ 0.0 to -0.3 m includes depths out of range of use for many shorebird species, as most shorebirds forage in water <15 cm deep (Rundle and Fredrickson 1981, Hands et al. 1991, Isola et al. 2000, Plauny 2000). Although the coarseness of perimeter measurements and scale of data collection inhibits absolute representation of the geomorphic complexities associated with sandbar shorelines, the wetted perimeter is an important habitat variable describing the aquatic-terrestrial interface highly used by shorebirds (Rundle and Fredrickson 1981).

Median perimeter of emergent-sandbar area was less under ROR than CWCP (Fig. 3.12) and GP1528 and GP2021 (Fig. 3.13) for the entire period of spring migration with a significant difference between their distributions (Kolmogorov-Smirnov, P =

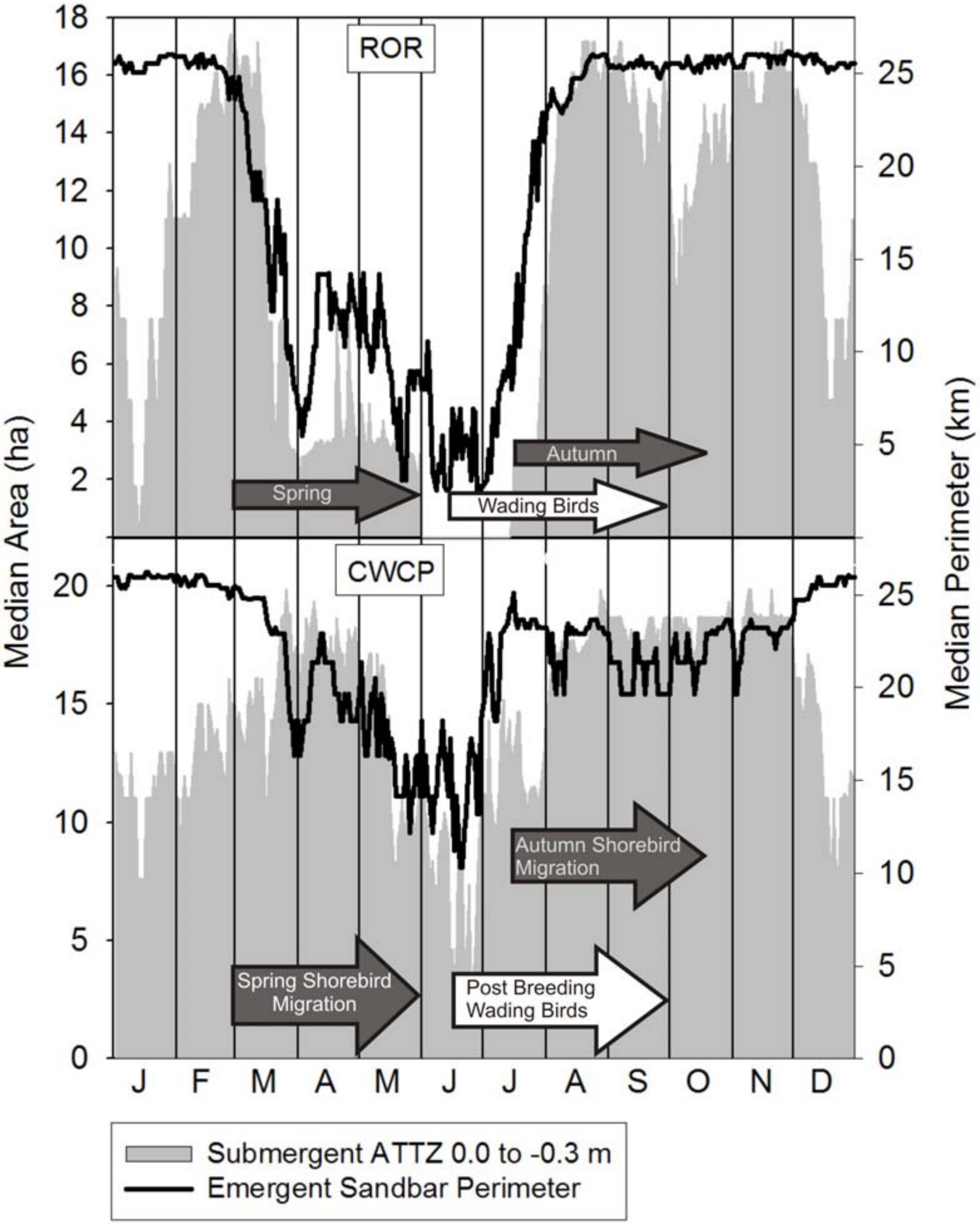


Figure 3.12. Timing of autumn and spring migration of shorebirds and of post breeding wading birds versus median area of submergent-ATTZ class 0.0 to -0.3 m and median emergent sandbar perimeter for six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment. Two reference alternatives were modeled: run-of-the-river (ROR) and the current water control plan (CWCP) for the Missouri River at Boonville, Missouri (1898 – 1997).

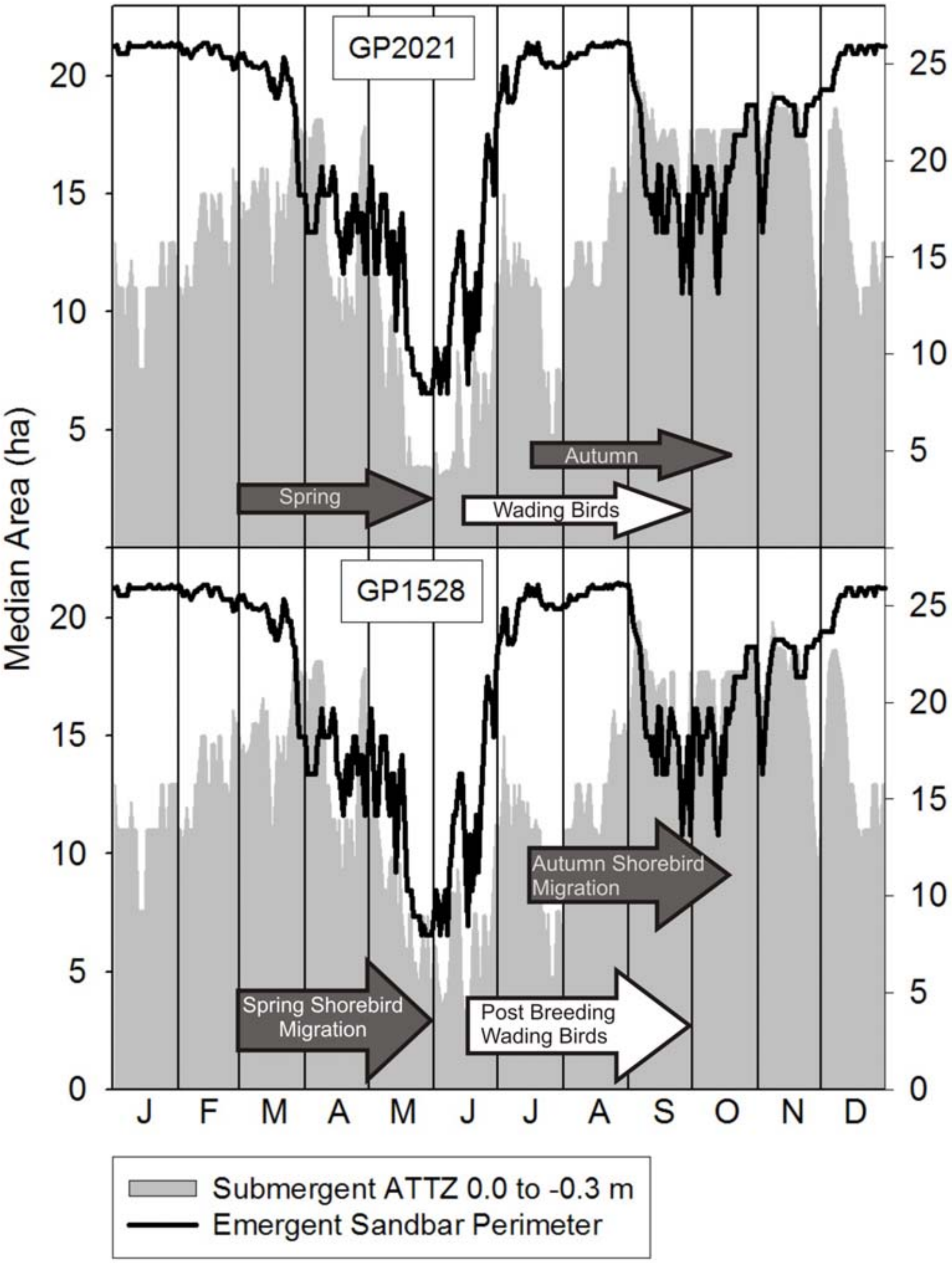


Figure 3.13 Timing of autumn and spring migration of shorebirds and of post breeding wading birds versus median area of submergent-ATTZ class 0.0 to -0.3 m and median emergent sandbar perimeter for six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment. Two flow management alternatives were modeled: GP2021 and GP1528 for the Missouri River at Boonville, Missouri (1898 – 1997).

<0.0001). Median perimeter of emergent-sandbar area was 33% to 86% greater under CWCP than ROR through mid-July of the post breeding wading bird time period. Median perimeter for modeled alternatives GP1528 and GP2021 was greater than CWCP (5% – 36%) July thru August and greater than ROR (1% – 90%) June thru August during the period of post breeding wading birds. Distributions of median perimeter of emergent-sandbar area during range of dates for post breeding wading bird use were significantly different between CWCP and all alternatives (Kolmogorov-Smirnov, P = <0.0001). Median perimeter of emergent-sandbar area remained >15 km during autumn shorebird migration for both ROR and CWCP and the distributions of perimeter between alternatives were significantly different (Kolmogorov-Smirnov, D = 0.69, P = <0.0001). Median perimeter was greater under GP1528 and GP2021 than CWCP and ROR during the days in July and August of autumn shorebird migration. Distributions of median perimeter were significantly different among alternatives (except between GP1528 and GP2021) for the entire autumn migration time period (Kolmogorov-Smirnov, P = <0.0001).

Riverine Fishes

Among all modeled flow management alternatives, ROR and CWCP represent the greatest and least amount of median area for submergent-ATTZ classes 0.0 to -0.3 and 0.0 to -1.0 m available during the timing of spawning and nursery habitat for three most abundant taxa collected by Reeves (2006): native carpsuckers and buffalo (*Carpiodes* spp./*Ictiobus* spp.), non-native silver and bighead carps (*Hypophthalmichthys molitrix*/*nobilus*), and native chubs (*Macrhybopsis* spp.). The distributions of median area for submergent-ATTZ class 0.0 to -0.3 m were significantly different between CWCP and all alternatives for the full range of fish spawning and the nursery time period (Kolmogorov-Smirnov, P = <0.0001). Median area of submergent ATTZ 0.0 to -0.3 m was greater for CWCP than under modeled ROR. Run-of-the river had no area from June through mid-July and CWCP had 39% to 95% more area than under ROR during the entire spawning period (Fig. 3.14). While distributions of median area for both submergent-ATTZ classes 0.0 to -0.3 and 0.0 to -1.0 m during the full range of spawning and the nursery time period were identical between GP1528 and GP2021 (Kolmogorov-Smirnov, P = >0.05), these modeled alternatives had 3% to 95% more area than under ROR during fish spawning and nursery. Median area of submergent ATTZ 0.0 to -0.3 m was greater under CWCP than alternatives GP1528 and GP2021 for >80% of fish spawning and the nursery time period (Fig. 3.15). Distributions of median area for submergent ATTZ 0.0 to -1.0 m were significantly different between CWCP and all other alternatives for the full range of fish spawning and the nursery time period (Kolmogorov-Smirnov, P = <0.0001). The CWCP had fewer occurrences of troughs, or steep declines in area, of submergent-sandbar ATTZ 0.0 to -1.0 m within the nursery time period than did ROR, which had declines in area by as much as 62% (Fig. 3.14). Modeled alternatives GP1528 and GP2021 had up to 62% more area of submergent-sandbar ATTZ 0.0 to -1.0 m than under ROR for the days in May and June during the nursery time period and up to 60% less area than CWCP for July thru September of the nursery time period.

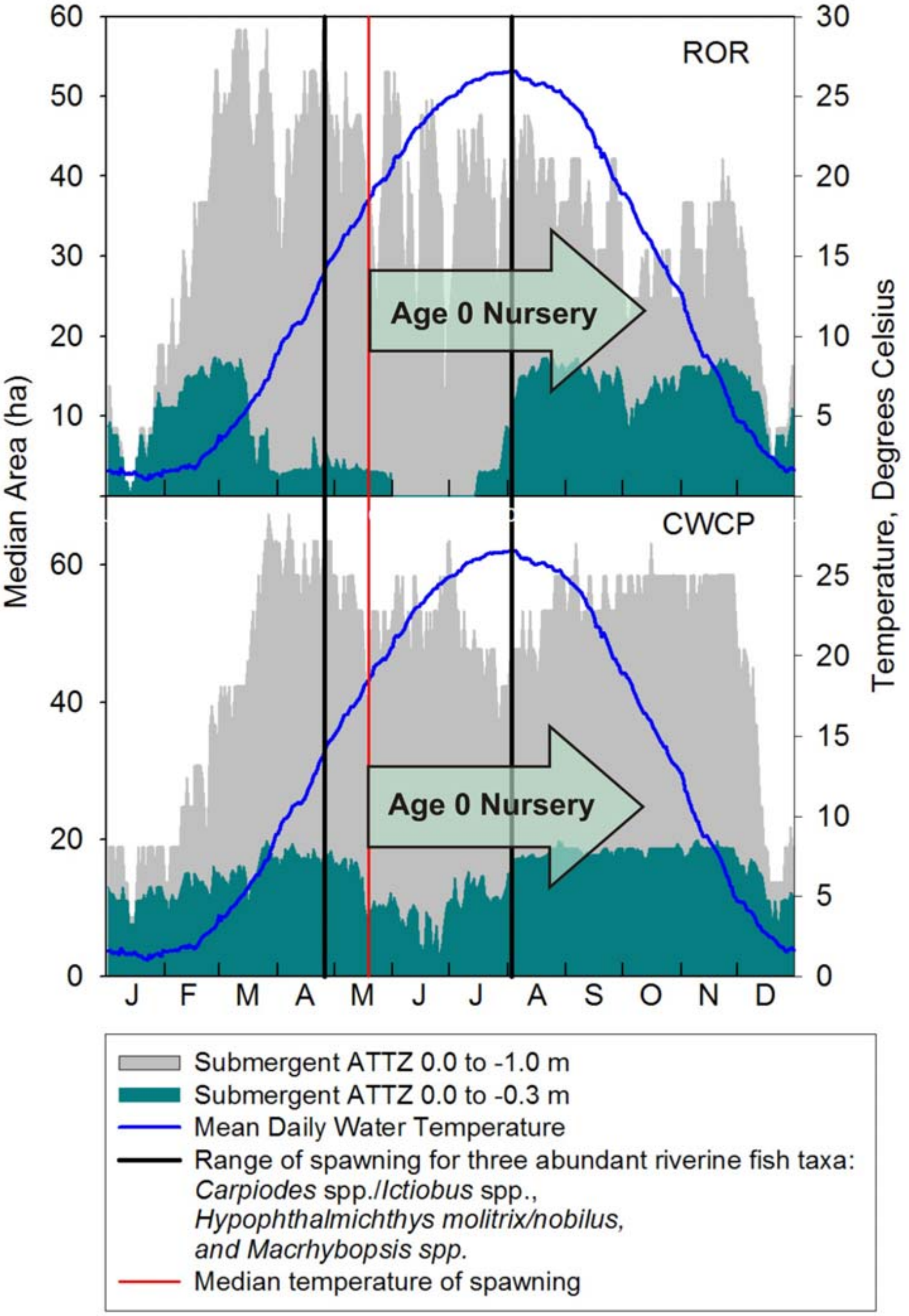


Figure 3.14. Timing of spawning for three abundant riverine fish taxa collected as larvae by Reeves (2006) versus median area of submergent-ATTZ class 0.0 to -0.3 m and 0.0 to -1.0 m for six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment. Two reference alternatives were modeled: run-of-the-river (ROR) and the current water control plan (CWCP) for the Missouri River at Boonville, Missouri (1898 – 1997). Spawning chronology is identified according to mean water temperature data for the Boonville Water treatment plant ~Boonville, Missouri (October 1937 – March 31 2005). Timing of age-0 nursery is based on the median temperature when spawning begins for the three taxa modeled.

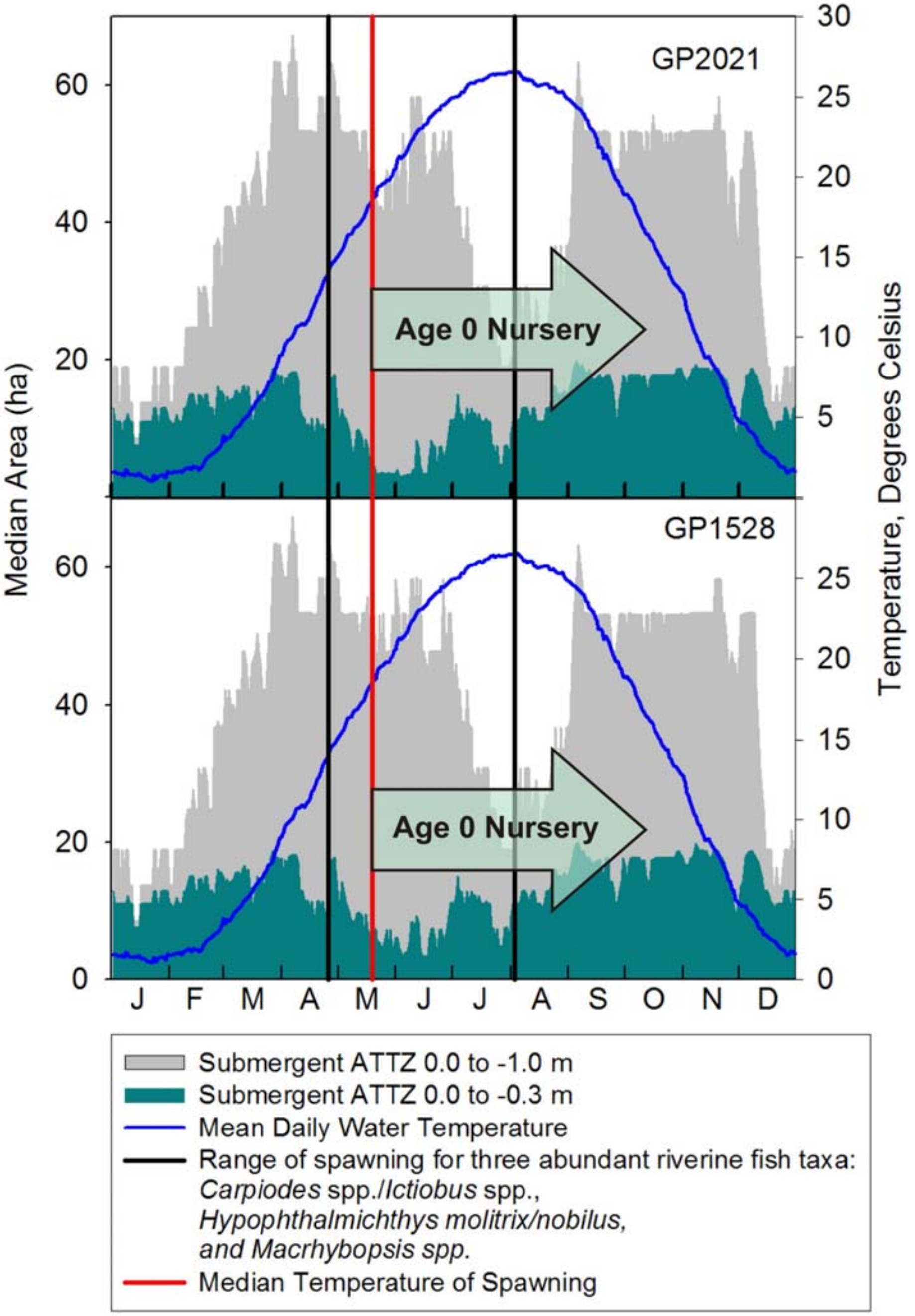


Figure 3.15. Timing of spawning for three abundant riverine fish taxa collected as larvae by Reeves (2006) versus median area of submergent-ATTZ class 0.0 to -0.3 m and 0.0 to -1.0 m for six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment. Two flow management alternatives were modeled: GP2021 and GP1528 for the Missouri River at Boonville, Missouri (1898 – 1997). Spawning chronology is identified according to mean water temperature data for the Boonville Water treatment plant ~Boonville, Missouri (October 1937 – March 31 2005). Timing of age-0 nursery is based on the median temperature when spawning begins for the three taxa modeled.

DISCUSSION

Restoring Flow and Habitat

The natural flow regime is considered the long-term pattern of a river's flow quantity, timing, and variability that make up its natural dynamic character (Poff et al. 1997). The natural flow regime in many rivers is thought to define the physical habitat of a river including sediment and channel and floodplain morphology (Poff et al. 1997). Moreover, it is important to provide floods that inundate the floodplain creating more shallow-water habitat, scouring sandbars of vegetation, and creating and reworking sandbars. The natural flow regime is not solely about quantity of flows, but also the timing, duration, and frequency of flows and includes movement of sediment within the channel and the floodplain and transporting materials such as woody debris (Poff et al. 1997). Results from applying the natural flow regime (ROR) to the constrained Lower Missouri River, where morphology of the river is no longer dependent on flow and the river is largely severed from its floodplain, indicate that flow alone cannot restore habitat (Jacobson and Galat 2006). According to the Natural Research Council (1992) restoration is a holistic process not achieved through the isolated manipulation of individual elements. Flow cannot be restored independent of habitat while maintaining a system that is self-regulating. Rehabilitation requires restoration of a river's natural flow variability and also the physical morphology that interacts to sustain ecosystem integrity.

Influence of Flow on Biota

Contemporary flows (CWCP) and flows under selected management alternatives (GP1528 and GP2021), within the current channel shape, provided more sandbar ATTZ to shorebirds and wading birds than under the natural flow regime in the contemporary channel. This result is not so surprising because of the extent of channel form changes that have occurred. Though habitat availability was better under managed flows, these flows may leave out other important processes. Variable flows of the natural flow regime create and maintain dynamic active-channel and floodplain habitat conditions (Poff et al. 1997). Low summer flows provide habitat and access to important food resources along sandbar-ATTZ margins. Higher spring flows redistribute organic matter and woody debris among sandbar-ATTZ habitat patches which provide suitable habitat conditions for invertebrate colonization (Drury and Kelso 2000) and zooplankton and larval fish retention (Schiemer et al. 2001a). These resources provide forage for shorebirds and wading birds. High flows also cause scour and sedimentation (cut-and-fill alluviation), thereby allowing the river to do the work of creating and destroying sandbars comparable to what occurs in natural rivers (National Research Council 1992).

Shorebirds and wading birds are highly vagile and opportunistic, taking advantage of available habitat from the range of habitat types (Raedeke et al. 2003). If floodplain wetlands and channel-margin ATTZ habitats have insufficient resources, it is likely that these interior-migration stopover habitats will not be used as refueling areas by shorebirds (Skagen and Knopf 1994) and will force wading birds to disperse to other habitats in the area (Powell 1987). The loss of floodplain habitats has reduced availability of important stopover sites for interior migrating shorebirds (Skagen and

Knopf 1994). Restoration of sandbar ATTZ habitats should complement available floodplain habitats and provide recurrent resources during the timing of shorebird and wading bird migrations.

Flow has many attributes that affect the lives of lotic fishes with critical life events linked to flow regime (e.g., phenology of reproduction, spawning behavior, larval survival, growth patterns and recruitment) (Welcomme 1985, Copp 1989, Junk et al. 1989, Copp 1990, Sparks 1995, Humphries et al. 1999, Bunn and Arthington 2002). Flow patterns directly influence and shape the life history patterns and reproductive cycle of riverine fishes. Changes in hydrologic regime are a cue for gonadal development of some fishes which initiates migration for reproduction (Robinson et al. 2002) and on the Missouri River, the pre-regulation spring rise is thought to have served as a spawning cue to native fishes (Galat and Lipkin 2000). The natural flow regime and successional processes within riverine-floodplain systems provide habitat diversity to riverine biota adapted to exploit the spatio-temporal heterogeneity of river-floodplain ecosystems (Ward et al. 1999, Robinson et al. 2002, Ward et al. 2002).

Many riverine fishes require a variety of habitat conditions for the completion of their life cycles. The availability of these habitats over time is regulated by the flow regime (Sparks 1995, Poff et al. 1997). Persistence of native fishes in flow-regulated systems depends, in part, on the seasonal occurrence of stable habitat conditions that facilitate reproduction and young-of-year survival (Freeman et al. 2001). Alteration of the hydrologic variation and disturbance functions of the natural flow regime changes the dynamic habitat conditions best suited for native biota where these specialized native species are typically replaced with generalist species (Poff et al. 1997). Variable flows characteristic of a more natural flow regime would promote heterogeneous habitat patch conditions associated with sandbar ATTZs, that in turn would generally support a greater variety of riverine fishes throughout their life cycle.

Sandbar ATTZ and Timing of Biota Use

Area of sandbar ATTZ exhibited seasonal differences among flow alternatives, due to differences in the timing, duration, magnitude, and frequency of modeled discharges. Management alternatives GP1528 and GP2021 had similar modeled discharges for the Missouri River at Boonville, Missouri, and consequently shared similar seasonal patterns in sandbar ATTZ availability. With differences being GP2021 having slightly higher modeled discharges than GP1528 April through June and lower discharges September and October. Modeled discharges under ROR showed greatest intra-annual variation among all four alternatives, having a greater magnitude and duration during the March-April and larger June flood pulses of the historical annual hydrograph (Galat et al. 1998, Galat et al. 2005) and lower summer flows.

Among all flow-management alternatives, not one provided the greatest sandbar-ATTZ area throughout all targeted activities for all selected riverine biota combined. Both contemporary flows (CWCP) and modeled flow alternatives (GP1528 and GP2021), within the current channel shape, generally yielded more suitable habitat for softshell nesting, shorebird and wading bird foraging, and age-0 fish nursery than under the natural flow regime (ROR).

The historical flow regime (ROR) in the current constrained channel would be unfavorable to softshell nesting, as the length of time of nest inundation determines hatching success of softshell nests (Plummer 1976). However, during hatchling emergence the characteristic low summer flows associated with a more natural flow regime provided the greatest amount of emergent-sandbar ATTZ habitat conditions. Likewise, the period of reduced summer flows under GP1528 and GP2021 provided an increase in emergent-sandbar ATTZ for July and August. These modeled flows, illustrate how reduced summer flows can benefit nesting softshells. The ROR exhibited less submergent-sandbar ATTZ 0.0 to -0.3 m and wetted perimeter than the CWCP and alternatives GP1528 and GP2021 over a majority of shorebird spring migration and the initial period of wading bird use. This period in spring is when historical peak flows occurred (Galat et al. 1998, Galat et al. 2005), consequently connecting the river to its floodplain and providing additional habitats for bird use. The steadily decreasing summer flows beginning in early July under ROR increased area of wetted perimeter and submergent sandbar ATTZ 0.0 to -0.3 m available for autumn migrating shorebirds and wading birds. Reduced summer flows associated with alternatives GP1528 and GP2021 also increased emergent sandbar perimeter in July and August for post breeding wading birds and the beginning of autumn shorebird migration.

The CWCP and alternatives GP1528 and GP2021 provided greater area of submergent ATTZ 0.0 to -0.3 m for the initial months of age-0 nursery and CWCP exhibited fewer troughs (gaps) in area available for submergent ATTZ 0.0 to -1.0 m throughout the nursery period compared to ROR flow conditions. Lack of available submergent-sandbar ATTZ, and the shallow-water, slow velocity habitat it provides reduces recruitment of riverine fishes and may result in a habitat-related bottleneck for many fish species (Bowen et al. 2003). Compared to the area available under managed flows, the amount of submergent-sandbar ATTZ area within the present channel configuration under the natural flow regime (ROR) during a large portion of age-0 nursery could limit age-0 recruitment of many riverine fishes. Though I illustrated that the current channel morphology and current flow regime provided riverine fish nursery habitat associated with sandbars, the historical channel and historical flow regime would have included inundated floodplain habitats (Galat et al. 1998) and numerous sandbars and active channel habitats used by riverine fishes for spawning and nursery (Funk and Robinson 1974, Latka et al. 1993, Galat and Lipkin 2000).

The historical flows under ROR yield the least area of ATTZ because flows are restricted to the contemporary channel geomorphology and will not inundate historical floodplain habitat. Within the historical channel, connection to floodplain habitats would have dissipated flood flows of the spring rise across the floodplain. Levees that were built on the Lower Missouri River for flood protection had the unintended consequence of increasing flood heights (Sparks 1995). The combination of levees that prevent channel-floodplain connectivity and channel constriction for navigation contribute to increased flood heights (Sparks 1995). An increase in stage for the same discharge causes flows that were once fully contained within the historical channel to now create floods in the contemporary channel (Pinter and Heine 2005).

Recommendations and ATTZ Rehabilitation

Results of my research identified a range of discharges where channel-margin ATTZ area was maximized between sandbar types and among sandbar-ATTZ classifications. Rehabilitation to increase both emergent and submergent-sandbar ATTZ area would depend on the targeted area of depth or elevation, whether it was associated with wing-dike or point sandbars, and the time period necessary for occurrence.

Maintaining navigation flows, especially higher flows in mid to late summer months reduces availability of emergent-sandbar ATTZ habitat for nesting softshells (Fig. 3.10). Within the contemporary channel, the COE could provide additional emergent-sandbar ATTZ habitat for softshell nesting by adjusting flows or by constructing sandbars at higher elevations. Discharge-area models revealed emergent sandbar ATTZ >1.0 m was greatest below navigation flows (Fig. 3.2) and that the summer low flow period under management alternatives GP1528 and GP2021 provided an increase in emergent-sandbar ATTZ for July and August (Fig. 3.11). I recommend adopting a flow-habitat rehabilitation program (applicable for Grand River to Osage River segment) by first extending the reduced summer flows associated with GP1528 and GP2021 through October. As modeled flows of ROR indicated, decreasing summer flows would also increase submergent-sandbar ATTZ 0.0 to -0.3 m for migrating shorebirds and wading birds (Fig. 3.12) and fish nursery (Fig. 3.14). While alternatives GP1528 and GP2021 showed that even a small reduction in summer flows can increase sandbar ATTZ, as decreasing summer flows increased emergent-sandbar ATTZ >1.0 m (Fig. 3.11) and emergent-sandbar perimeter (Fig. 3.13) during July and August.

The COE proposes to provide tern nesting (emergent ATTZ) and fish nursery (submergent ATTZ) by building sandbars that will be exposed at full-service navigation. Rehabilitation of this nature may reduce political strife and adversity to Missouri River habitat rehabilitation, but it may not replace the ecological values to be received from implementing reduced summer flows. Rehabilitation of sandbars through habitat programs that exclude incorporating some of the dynamic geomorphic processes associated with a variable flow regime would likely not achieve the goals set according to the Biological Opinion (U.S. Fish and Wildlife Service 2003). Eliminating key geomorphic processes would influence many functions of river-floodplain ecosystems that would also have consequences to long-term benefits to society. Restoration and maintenance of the processes and properties that support functional integrity of the Missouri River ecosystem requires consideration of the linkage between the production and function of river-floodplain ecosystems and the goods and services society derives from these systems.

The reduced (from full navigation service levels) Gavins Point summer releases of GP1528 represents a small change compared to releases under CWCP (-6 kfcs) while also providing full navigation service in a majority of years (U.S. Army Corps of Engineers 2004a). Since GP1528 and GP2021 function similarly according to modeled flows at Boonville, Missouri, reducing flows according to either of these alternatives would provide the same results for the Grand River to Osage River segment, but not necessarily for other river segments. If lower flows were maintained through October, it would reduce the risk of nest inundation and increase success of late nesting softshells while also providing shallow inshore areas (submergent ATTZ 0.0 to -0.3 m) suitable for young-of-year fish nursery and refugia, and habitat for foraging shorebirds, wading birds, and softshell hatchlings. Management of these low summer flows, because of the small change compared to CWCP, could have ecological benefits while also maintaining navigation.

The historical spring rise (ROR) and the spring flow pulses under CWCP and alternatives GP1528 and GP2021 in the contemporary channel exhibited reduced submergent and emergent-sandbar ATTZ. These flow pulses under CWCP limit the amount of submergent-sandbar ATTZ 0.0 to -0.3 m available during the initial period of age-0 fish nursery and post breeding wading bird use. Although submergent ATTZ 0.0 to -1.0 m exhibited less change in available area during fish nursery, for some fishes, this depth could be greater than the suitable range for nursery and refugia habitat conditions for successful larval development. This depth is also beyond the foraging capabilities of shorebirds and wading birds. Overall, my recommendation of decreasing summer flows would benefit many biota during targeted life-cycle events.

Sandbar Creation/Rehabilitation

Channel-margin ATTZ of the contemporary channelized, leveed, and flow-regulated Lower Missouri River could be increased by providing the range of flows identified where area was maximized for either or both sandbar types. Variability of elevations appeared greater for wing-dike sandbars as area of submergent ATTZ peaked over a wider range of discharges compared to point sandbars. The shorter duration of area peaks for submergent ATTZ of point sandbars provided maximum amount of area above minimum and full service navigation flows. Emergent-sandbar ATTZ for both sandbar types exhibited large declines in available area above navigation flows. Managing flows to maximize point sandbar-ATTZ habitat would likely maximize wing-dike sandbar-ATTZ habitat at the same time. However, managing flows to maximize wing-dike sandbar-ATTZ classes would not always optimize area for point sandbar ATTZs.

In addition to different discharge-area relations, point and wing-dike sandbars differ in that point sandbars are much larger in size and have larger substrate particle size than wing-dike sandbars (Reeves 2006). These large open expanses of emergent-sandbar ATTZ of point sandbars offer conditions favorable to nesting softshells. Wing-dike sandbars remain somewhat protected behind navigation structures allowing them to connect to parts of the shoreline at lower flows. Wing-dike sandbars have higher elevations and tend to foster more vegetation growth than lower elevation point sandbars. Vegetation on sandbars increases habitat heterogeneity for benthic invertebrate production (Thorp 1992) and microhabitat diversity for riverine fishes throughout many life stages (Zalewski et al. 2003). The ideal rehabilitation/restoration project would incorporate attributes from both sandbar types in order to provide diverse sandbar-ATTZ complexes within the current channel configuration of the Lower Missouri River.

Creation of sandbar habitats is a restoration goal (National Research Council 2002, U.S. Fish and Wildlife Service 2003), and given the observed discharge-habitat relationship, the approach should be to restore the flows necessary to restore the full range of ecological and geomorphic processes. The same philosophy would apply to the creation/restoration of shallow-water habitat. Each sandbar type and each ATTZ submergent (depth) and emergent (elevation) class has a discharge in which area was maximized. Point sandbars in my study demonstrated a tendency toward self-regulation by maintaining habitat clear of vegetation and constantly reworking the ATTZ area (Tracy-Smith, personal observation). Depending on the intended goal, wing-dike sandbars could require additional maintenance if vegetation encroachment were not desired, yet because they are formed behind navigation structures, they could be the easiest to recreate.

I recommend using a study design with emphasis on ATTZ categories and its relationship with discharge, to be implemented as part of the adaptive management component of the Biological Opinion (U.S. Fish and Wildlife Service 2003). This research could serve as a template to monitor shallow water and emergent-sandbar habitat to ensure that restoration goals of the USFWS are being met and to further understand the dynamic nature of sandbar structure and function on the channelized Lower Missouri River. I emphasized the importance of how the active-channel ATTZ functions in regards to discharge and provided a sound basis from which ATTZ can be optimized while still maintaining most navigation. The application of this research to current mitigation projects could help assess how and if discharge-area relations differ between newly created sites and already established sandbar sites.

My research identified a relationship between flow and area of channel-margin ATTZ associated with sandbars, but how persistent or unchanging that relationship is needs further investigation. Sediment transport, erosion and deposition, associated with sandbar dynamics is poorly understood on the Lower Missouri River. The assumption that sandbar topography is stable as discharge changes may be invalid, but was necessary due to our lack of information on erosion and deposition rates of sandbar habitats. Stabilization of the river channel has created a static environment for sandbar accretion and erosion as endurance of the 13 study sandbars over this two year study attests. The fact that the 13 sandbars have remained in place over a long period indicates that there may be a lack of dynamic equilibrium occurring. So, the assumption of sensitivity to discharge requires further research.

Historically, the channel of the Missouri River had continuous bank erosion, braiding and numerous sand islands and sandbars (Galat et al. 1996). The natural hydrograph provided variation in sediment loads for habitat rejuvenation. Sediment supply and transport have been reduced fourfold from the 1930's to the 1970's due to upstream impoundment (Galat et al. 1996) and reduction of high-energy floods that redistribute large amounts of sediment (Osterkamp 1998). Bankfull discharge occurred in only 2 of 33 years following closure of main-stem dams (1954-1986) (Galat et al. 1996). The armored channel, with rock revetment, limits bank erosion and lateral sediment supply and floodplain levees reduce connectivity to the floodplain. As a result bed erosion below Gavins Point dam and tributaries are the main source of limited sediment supply (Hesse et al. 1989).

Because of the constraints on sediment supply, the full geomorphic complexity of the Lower Missouri River will unlikely be restored to its pre-engineered condition. The current channel provides a control against which to evaluate rehabilitation efforts. If changes in channel geomorphology were implemented, my data on the relationships between discharge and sandbar-ATTZ area would change appreciably. In addition, the current understanding is that the routing of water movement through the channel has not been changed appreciably with the regulation of the main channel. If the channel is re-engineered it would change the dynamics of the river by changing the storage capacity for water and sediment.

I developed a discharge-area (ATTZ) relation based on a range of discharges (10 kcfs to 100 kcfs), but know little of what the relationship is outside these bounds. A more natural flow regime would include higher discharges that would incorporate sediment transport events that could change the discharge-area relationship developed. Investigation of the possible impact of individual flow events and the duration and sequences of flow events on sandbar ATTZs is also recommended.

Rehabilitation and Application to Other Rivers

Ecological conditions have been altered on the major temperate-zone rivers in Europe (e.g., Rhine, Danube, Drau, and Vistula Rivers) and the U.S.A (e.g. Mississippi, Missouri, Sacramento, and Kissimmee Rivers) through river regulation and engineered changes in morphology and hydrologic regimes of their river-floodplain landscapes (Jungwirth et al. 2002). Historically these dynamic river-floodplain systems contained vast amounts of ATTZ habitats including; floodplains, channel margins, and numerous sandbars and islands. There has been an increasing activity to rehabilitate these impaired river-floodplain systems, with an emphasis on improving their ecological conditions (National Research Council 1992, Henry and Amoros 1995, Sparks 1995, Jungwirth et al. 2002). It is essential that the appropriate steps be taken to further understand the structure and function of river-floodplains and the ecological consequences of river regulation. Restoring the once natural, full complexity, of these systems is likely impossible (Welcomme 1992, Stanford et al. 1996), so the goal of rehabilitation of these river-floodplain systems should focus on restoring their functional integrity and then ecological biodiversity of the system should follow (Ward et al. 1999).

The Missouri River has been severely modified over the past centuries and recent rehabilitation aims in restoring a small portion of the dynamic structure and function that once exemplified the natural (historic) state has met difficult challenges due to socio-political and economic concerns. The Missouri River is representative of other temperate, large river-floodplain systems that have incurred hydrologic and morphologic changes due to regulation (e.g., flow alteration, channelization, levee constructions) to produce a multiple-use system. Flow regime and channel morphology will differ between river systems, making direct comparisons or correlations difficult. However, the modeling framework presented here can be applied to other rivers including non-regulated rivers, to learn more about the natural structure and function of channel-margin ATTZ habitat, and aid in rehabilitation of large regulated rivers.

The Grand River to Osage River segment (402 – 209 km) of the Lower Missouri River may not be representative of the entire river, with inherent differences in channel shape and flows among segments. What is important and what transcends to other reaches and segments of the Lower Missouri River and other regulated and nonregulated river-floodplain systems throughout the world is the evident relationship between discharge and channel-margin ATTZ. This research highlighted the importance of dynamic, main-channel margin habitats, i.e., the channel-margin ATTZ, and the need for rehabilitation to consider habitat requirements of a variety of riverine biota during all life stages and the timing of their use. Adopting this holistic perspective will provide ecologically important habitat conditions to conserve and recover biological integrity of regulated large rivers.

Appendix A. Validation results for sandbar models.

Table A.1. Validation results for individual sandbar discharge-area models with area of emergent sand predicted based on each model and actual area calculated from topographic ground surveys with similar discharge. Components of each model included; topographic elevation grid at lowest discharge recorded during mapping, synthesized water surface elevation grid (sandbar ratio grid * length of sandbar * slope function), a discharge-stage function, and a discharge-slope function. The model numbers represent the discharge-slope function.

River Km Sandbar type Discharge (cfs)	Predicted emergent-sandbar area (m^2)				Surveyed area (m^2)
	Model 1 Logarithmic	Model 2 Average	Model 3 Zero	Model 4 Exponential	Discharge (Q) cfs if different from legend
234 Point					
40,000		146,125	157,800	148,800	160,175 Q = 40,700
64,000		7,650	6,650	5,700	11,082 Q = 63,700
253 Point					
22,000	292,975	294,450	294,725		294,700
36,000	268,150	265,475	276,300		300,625
52,000	142,525	129,425	151,775		146,288
66,000	3,400	3,475	2,575		6,573 Q = 67,000
68,000	2,125	2,250	2,225		
254 Point					
22,000	121,600	264,625	277,925	271,125	278,525
36,000	44,150	208,700	219,825	211,750	218,696
48,000	8,125	101,525	114,800	100,175	73,414
66,000	0	24,025	16,350	18,400	7,625 Q = 66,900
68,000			11,100	9,600	
275 Wing-dike					
26,000			7,775		8,590
40,000			4,200		4,490
58,000			2,250		2,320
82,000			400		805

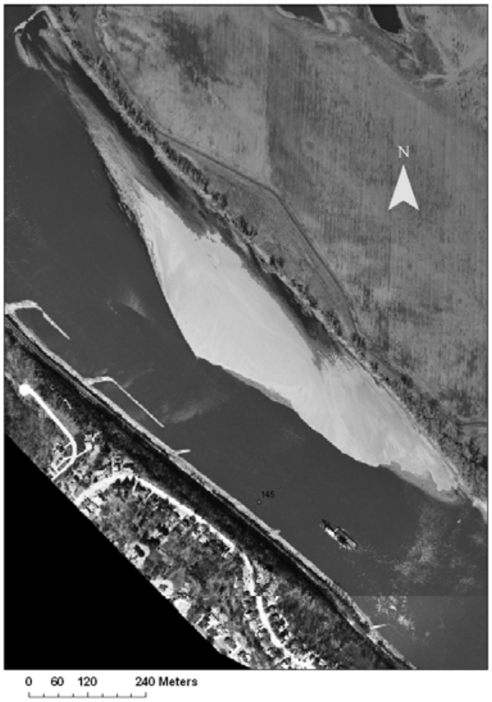
275 Wing-dike					
26,000		34,425	34,525		36,437
38,000		30,050	30,375		32,660
40,000		29,100	29,250		29,180
70,000		2,425	2,650		4,360
284 Wing-dike					
22,000				8,750	9,620
56,000				3,975	3,600
88,000				0	411
284 Wing-dike					
24,000		7,975	8,275		9,620
26,000		7,175	7,350		Q = 25,000
44,000		3,000	3,050		3,140
70,000		300	425		1,925
285 Point					
28,000	253,375	398,225	433,250	443,350	443,300
34,000	208,925	337,775	391,625	365,200	286,374
78,000	8,700	70,000	77,325	67,000	39,980 Q = 78,500
96,000	0	1,675	1,675	50	19,984 Q = 96,900
288 Point					
28,000	280,350	246,750	257,100		280,350
36,000	261,200	168,525	180,275		157,100
58,000	153,575	58,150	64,250		70,160
70,000	106,150	24,175	26,950		33,000
78,000	76,600	12,925	14,200		16,300
96,000	15,725	0	0		6,345
320 Wing-dike					
24,000			27,750		31,600 Q = 24,800

34,000			19,350			11,119
62,000			0			898 Q = 62,400
334 Wing-dike						
26,000		5,175	5,175			6,090
34,000		4,525	4,600			3,610 Q = 34,500
38,000		4,200	4,200			4,550
56,000		2,475	2,475			1,650
58,000		2,125	2,150			Q = 57,000
72,000		400	425			1,040 Q = 71,500
343 Point						
34,000		136,850		230,050		230,250
72,000		225		18,250		22,970
381 Wing-dike						
26,000			8,625	8,625		8,894
64,000			1,875	1,875		1,766
78,000			800	750		1,160
80,000			575	550		Q = 79,000

Appendix B. Sandbar orthophotographs and digital elevation grids.

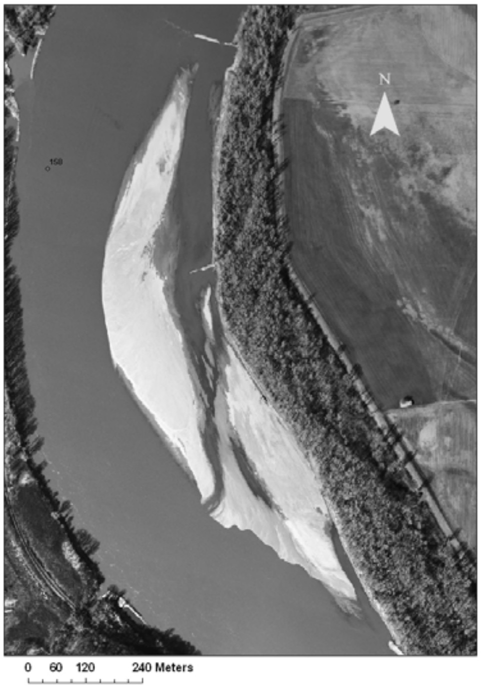
Figure B.1. Orthophotographs of 13 Lower Missouri River sandbars mapped and for which discharge-morphometric models were calculated from topographic surveys. Each sandbar is displayed at two scales (PT = point sandbar, WD = wing-dike sandbar) from the Grand River to Osage River segment, lower Missouri River, MO

km 234 (mile 145.5) (PT) Scale 1:9,000



km 234 (PT) Scale1:6,000

km 253 (mile 157) (PT) Scale 1:9,000



km 253 (PT) Scale 1:6,000

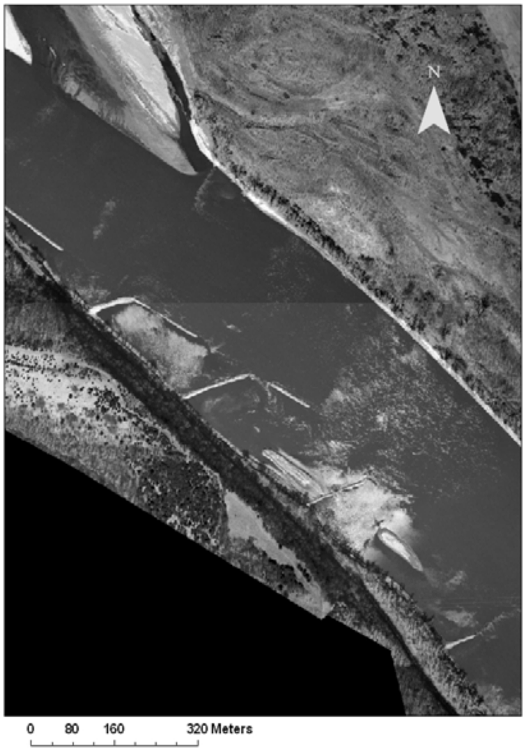
km 254 (mile 158 (PT) Scale 1:9,000

km 254 (PT) Scale 1:6,000

km 275 (mile 171(a, b) WD Scale 1:6,000

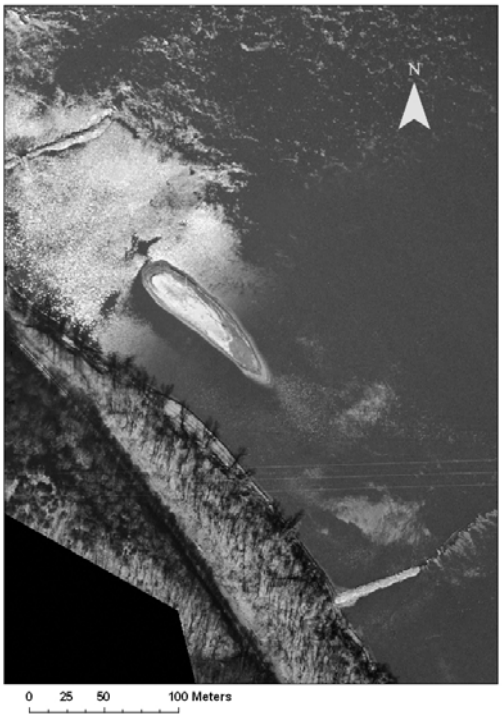
km 275a (mile 171) (WD) Scale 1:2,000

km 275b (WD) Scale 1: 2,500



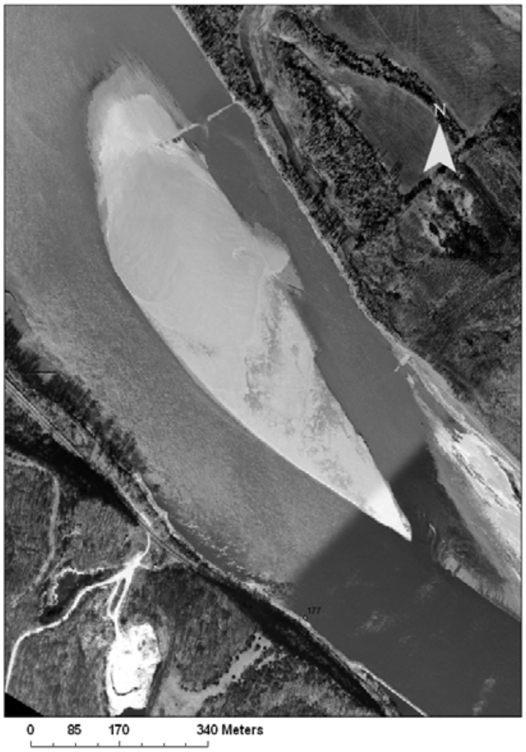
km 284 (mile 176.5 a, b) (WD) Scale 1:6,000

km 284a (mile 176.5) (WD) Scale 1:2,000



km 284b (WD) Scale 1:2,000

km 285 (mile 177) (PT) Scale 1:9,000



km 285 (PT) Scale 1:6,000

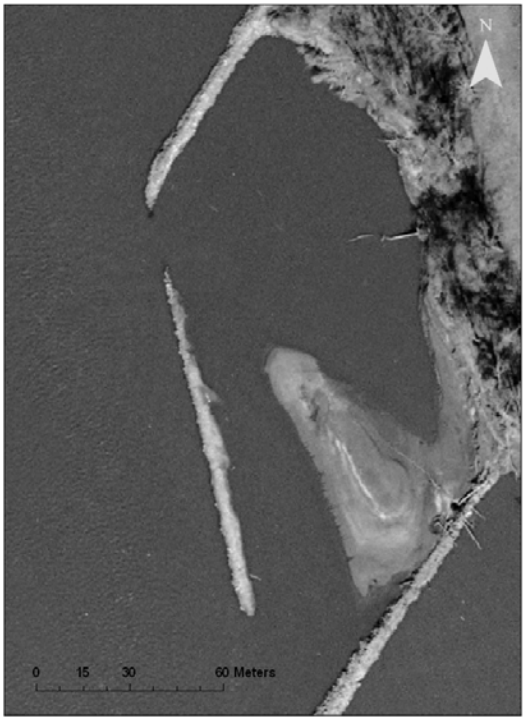
km 288 (mile 179) (PT) Scale 1:9,000

km 288 (PT) Scale 1:6,000

km 320 (mile 199) (WD) Scale 1:6,000

km 320 (WD) Scale 1:2,000

km 334 (mile 208) (WD) Scale 1: 3,500

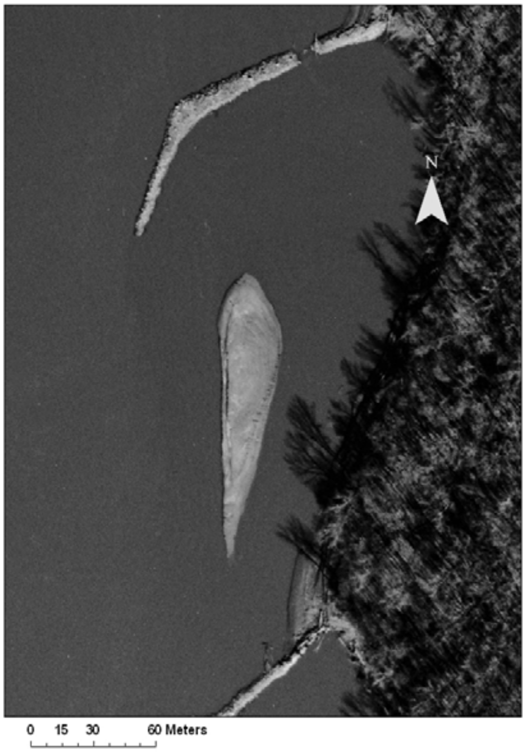


km 334 (WD) Scale 1:1,000

km 343 (mile 213) (PT) Scale 1:9,000

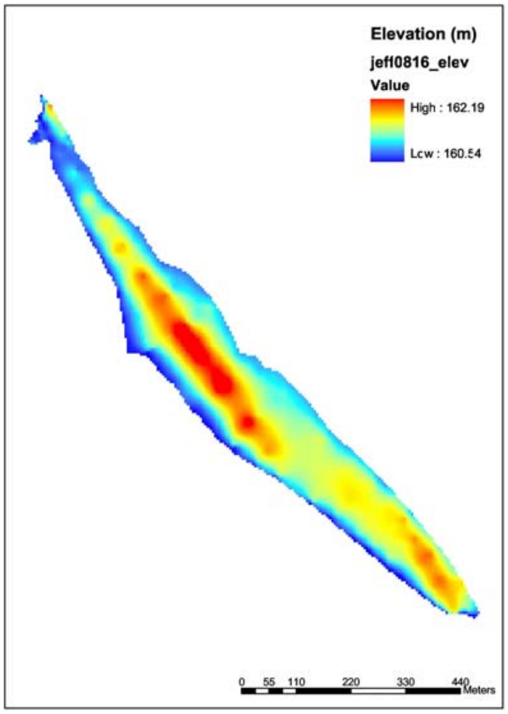
km 343 (PT) Scale 1:6,000

km 381 (mile 236.5) (WD) Scale 1:6,000

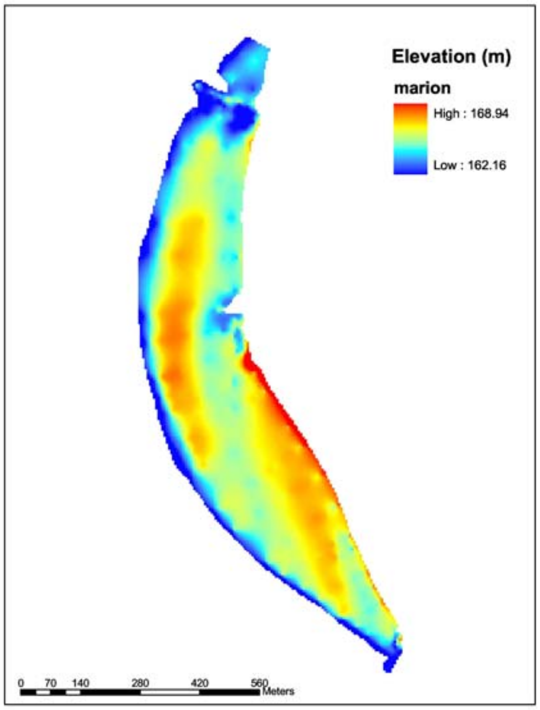


km 381 (WD) Scale 1:1,500

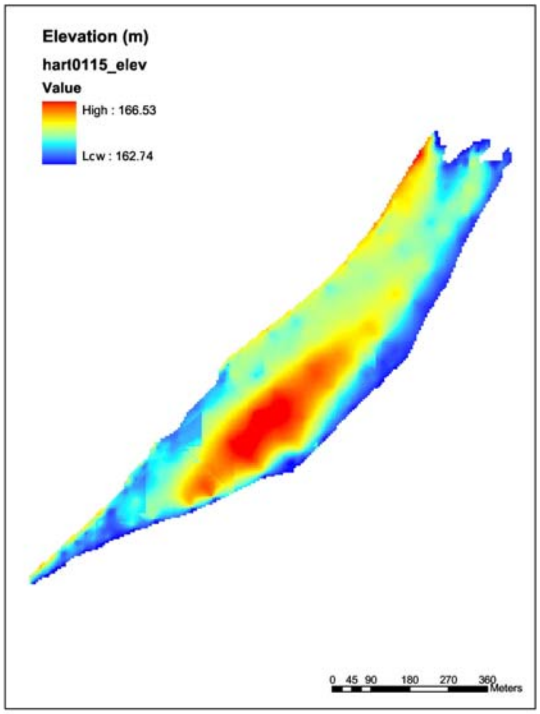
Figure B.2. Elevation grids for six point sandbars created from topographic survey's completed at lowest discharge. See Table 2.3 for discharge and area of each grid.



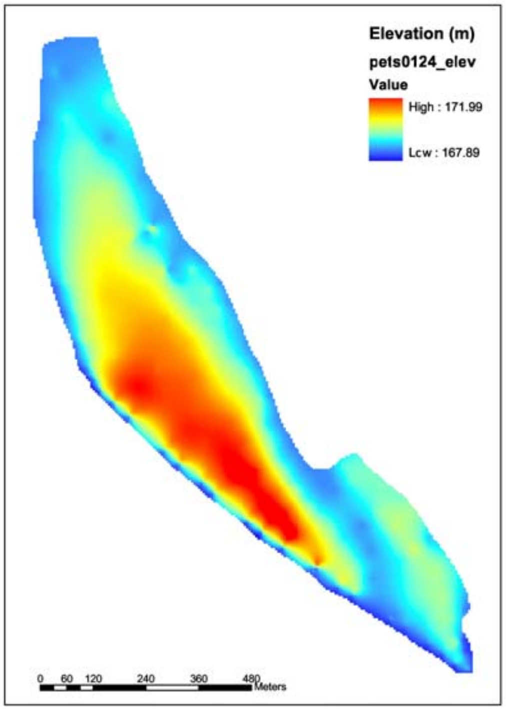
km 234 (mile 145.5)



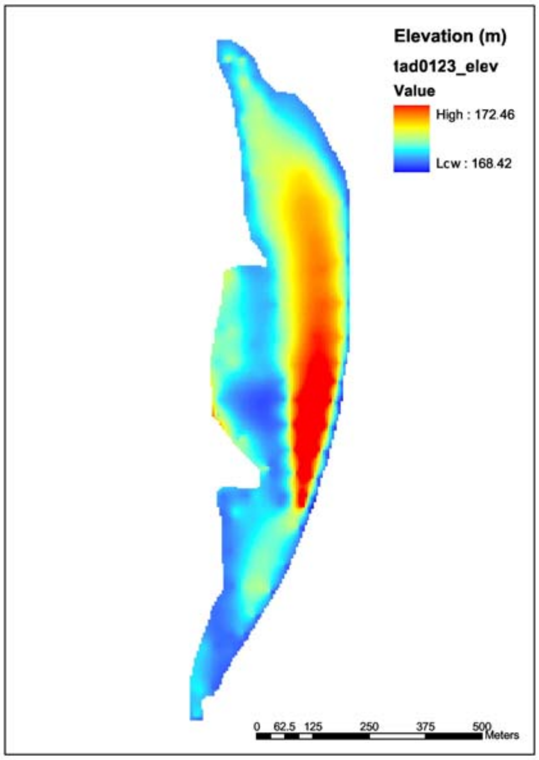
km 253 (mile 157)



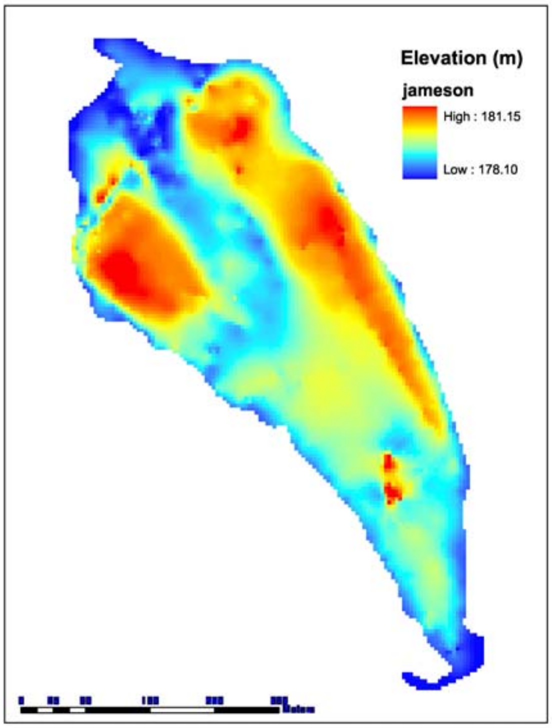
km 254 (mile 158)



km 285 (mile 177)

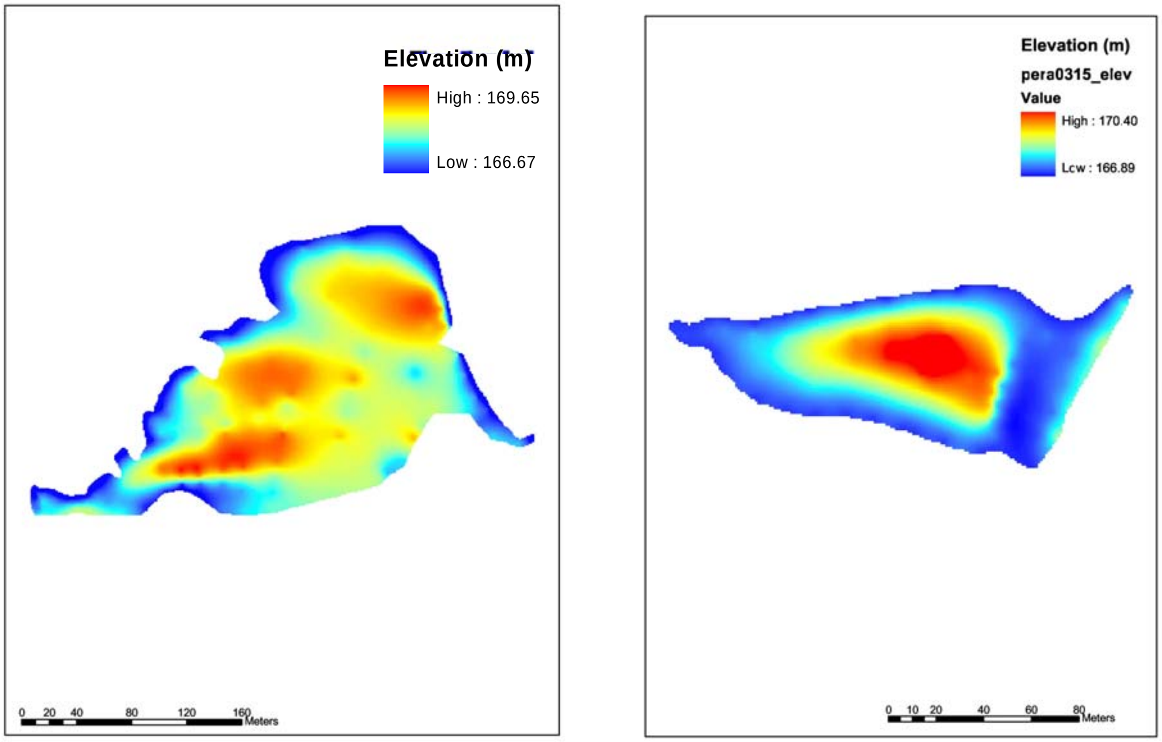


km 288 (mile 179)



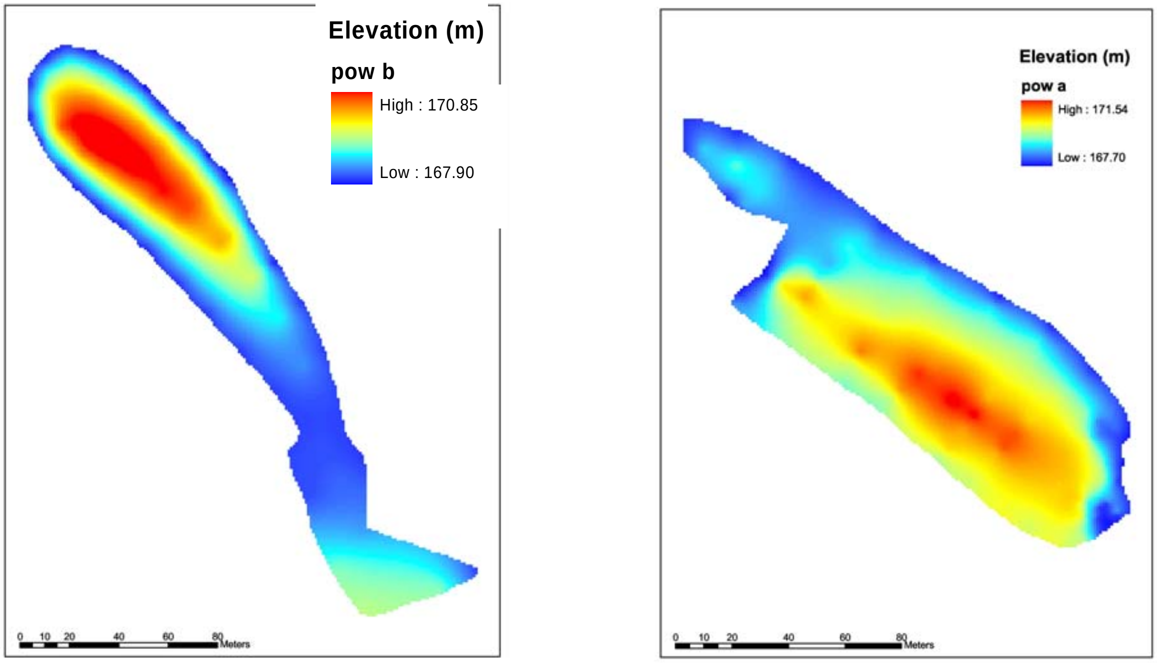
km 343 (mile 213)

Figure A.2. Elevation grids for seven wing-dike sandbars created from topographic surveys completed at lowest discharge. See Table 2.3 for discharge and area of each grid.



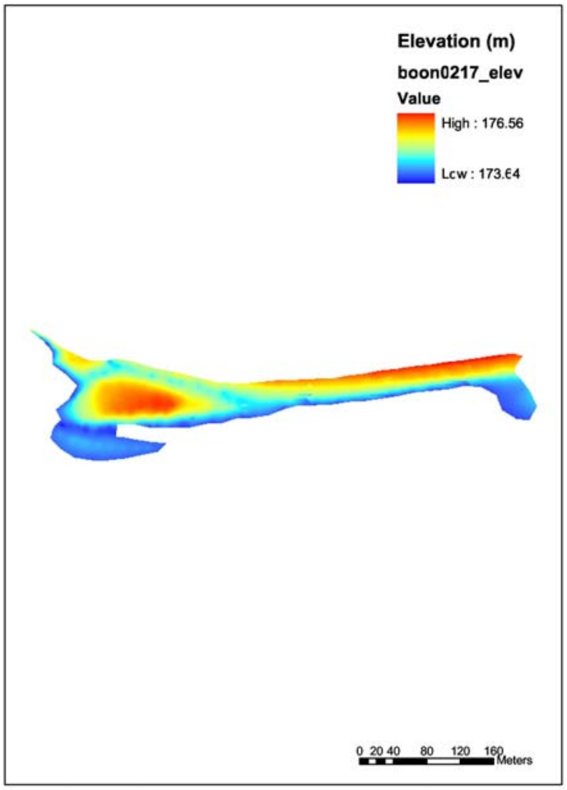
km 275 (mile 171b)

km 275 (mile 171a)

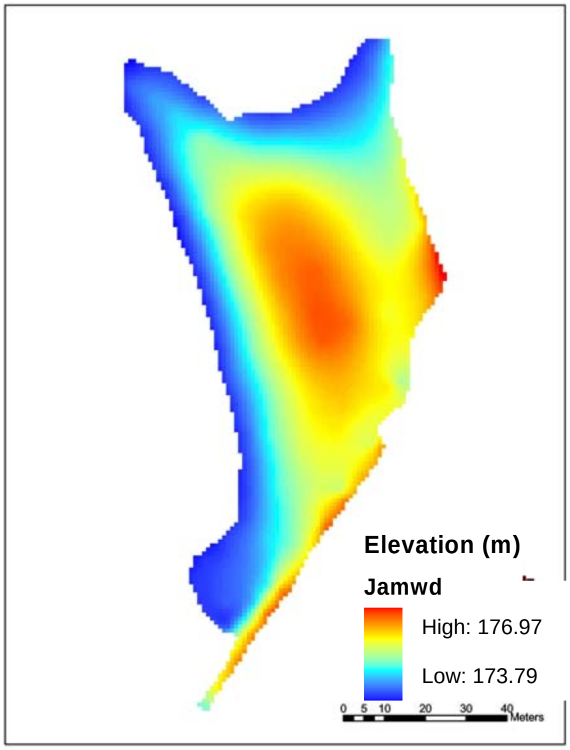


km 284 (mile 176.5b)

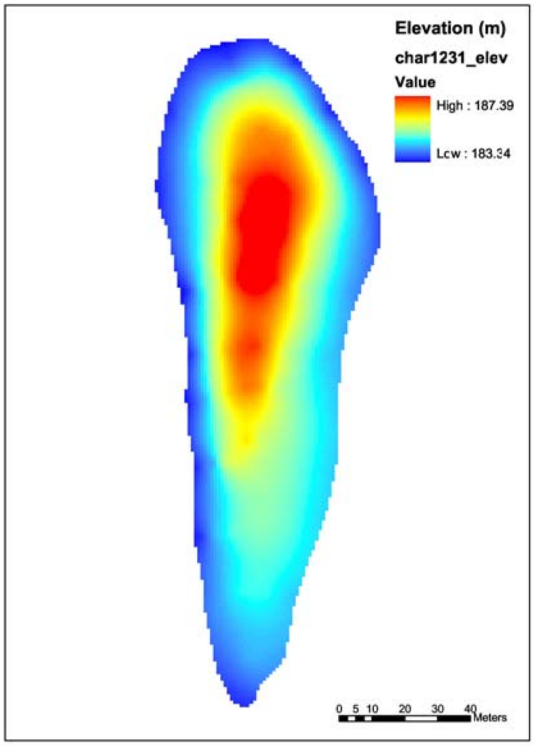
km 284 (mile 176.5a)



km 320 (mile 199)



km 334 (mile 208)



km 381 (mile 236.5)

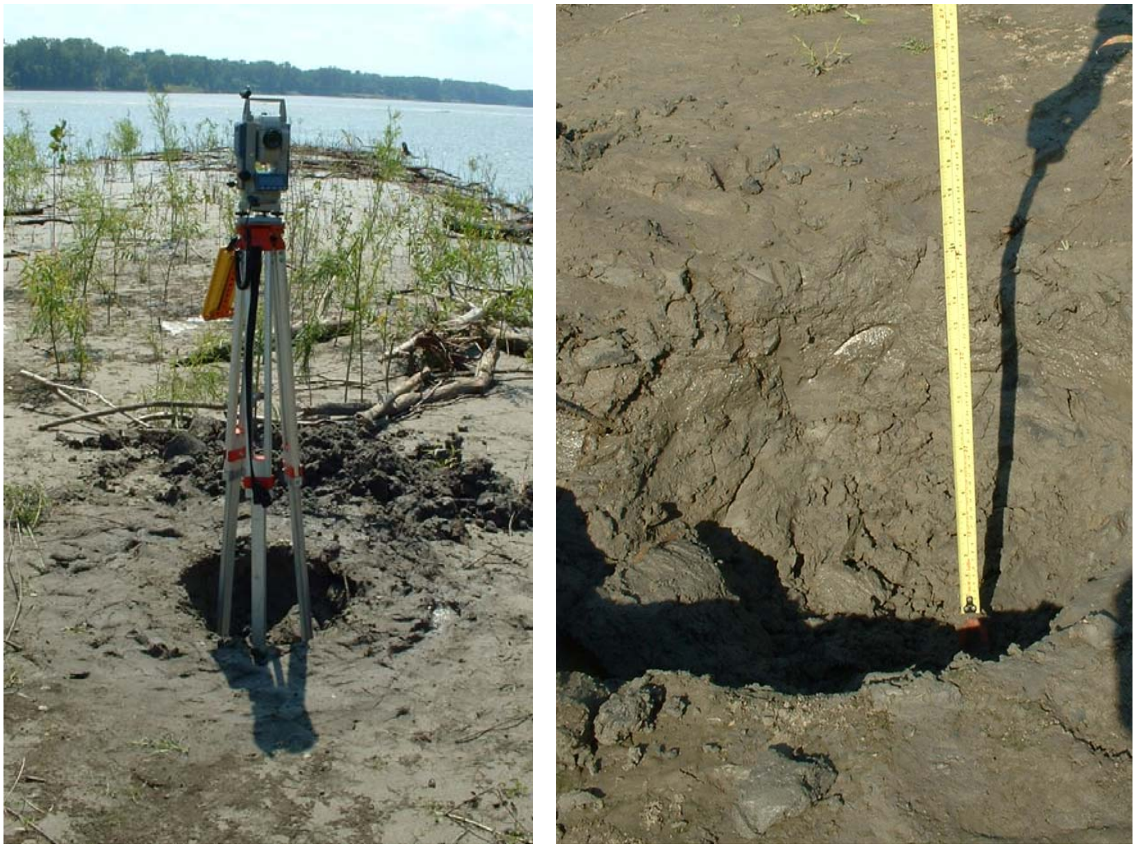


Figure B.3. Photographs documenting sediment deposition after a high flow event on sandbar Rkm 284 (mile 176.5b), surveyed on 07/28/2004.

Appendix C. Modeled mean area of morphometric depth (-) and elevation (+) classes and modeled perimeter and area calculations used to calculate shoreline development index.

Table C.1. Modeled mean area, in hectares, ± 1 SD at three morphometric elevation classes between six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment of the Lower Missouri River, MO km 402 to 209, calculated to evaluate effects of discharge on sandbar morphometry.

	Morphometric elevation class (m)					
Discharge (kcfs)	0.0 to 0.5		0.51 to 1.0		1.01 to 1.5	
	Wing-dike	Point	Wing-dike	Point	Wing-dike	Point
10	0.0 ± 0.0	0.1 ± 0.1	0.2 ± 0.2	2.2 ± 2.8	0.3 ± 0.2	4.9 ± 3.8
12	0.0 ± 0.0	0.2 ± 0.3	0.3 ± 0.2	3.0 ± 3.5	0.2 ± 0.2	5.1 ± 3.5
14	0.1 ± 0.1	0.5 ± 0.8	0.3 ± 0.3	3.7 ± 4.0	0.2 ± 0.2	5.2 ± 3.1
16	0.1 ± 0.1	0.9 ± 1.2	0.3 ± 0.2	4.3 ± 4.4	0.3 ± 0.2	5.2 ± 2.6
18	0.2 ± 0.2	1.7 ± 1.9	0.3 ± 0.2	4.6 ± 4.1	0.3 ± 0.2	5.5 ± 2.4
20	0.3 ± 0.3	2.4 ± 2.7	0.2 ± 0.1	4.7 ± 3.8	0.3 ± 0.2	5.8 ± 2.1
22	0.3 ± 0.3	3.1 ± 3.5	0.2 ± 0.2	5.0 ± 3.4	0.3 ± 0.3	6.3 ± 2.0
24	0.3 ± 0.2	3.7 ± 4.0	0.3 ± 0.2	5.2 ± 3.0	0.3 ± 0.3	6.6 ± 1.8
26	0.3 ± 0.1	4.2 ± 4.4	0.3 ± 0.2	5.2 ± 2.5	0.3 ± 0.4	6.7 ± 1.8
28	0.2 ± 0.1	4.5 ± 4.2	0.3 ± 0.2	5.5 ± 2.2	0.3 ± 0.4	6.8 ± 2.0
30	0.3 ± 0.2	4.7 ± 3.8	0.3 ± 0.2	6.1 ± 1.8	0.3 ± 0.4	6.5 ± 2.2
32	0.3 ± 0.2	4.9 ± 3.5	0.3 ± 0.3	6.5 ± 1.7	0.3 ± 0.4	5.9 ± 2.6
34	0.3 ± 0.2	5.2 ± 3.0	0.3 ± 0.3	6.9 ± 1.7	0.3 ± 0.4	5.3 ± 2.6
36	0.3 ± 0.2	5.4 ± 2.4	0.3 ± 0.4	7.2 ± 1.9	0.3 ± 0.4	4.6 ± 2.4
38	0.3 ± 0.2	5.9 ± 2.1	0.3 ± 0.4	6.9 ± 2.3	0.3 ± 0.3	4.1 ± 2.4
40	0.3 ± 0.2	6.3 ± 1.7	0.3 ± 0.4	6.6 ± 2.6	0.2 ± 0.3	4.0 ± 2.7
42	0.3 ± 0.3	6.7 ± 1.5	0.3 ± 0.4	5.9 ± 2.4	0.2 ± 0.2	3.6 ± 2.4
44	0.3 ± 0.3	7.1 ± 1.9	0.3 ± 0.4	5.2 ± 2.2	0.2 ± 0.2	3.1 ± 1.8
46	0.3 ± 0.4	7.0 ± 2.3	0.3 ± 0.4	4.7 ± 2.2	0.1 ± 0.2	2.6 ± 1.7
48	0.3 ± 0.4	6.7 ± 2.6	0.3 ± 0.3	4.3 ± 2.3	0.1 ± 0.1	2.2 ±

						1.8
50	0.3 ± 0.4	6.3 ± 2.5	0.2 ± 0.3	3.8 ± 1.9	0.1 ± 0.1	2.0 ± 1.8
52	0.3 ± 0.4	5.8 ± 2.5	0.2 ± 0.3	3.2 ± 1.5	0.1 ± 0.0	1.7 ± 1.6
54	0.3 ± 0.4	5.4 ± 2.3	0.2 ± 0.2	2.6 ± 1.5	0.0 ± 0.0	1.5 ± 1.5
56	0.3 ± 0.4	4.9 ± 2.1	0.1 ± 0.2	2.2 ± 1.8	0.0 ± 0.0	1.2 ± 1.4
58	0.2 ± 0.3	4.1 ± 1.4	0.1 ± 0.1	2.1 ± 1.9	0.0 ± 0.0	1.1 ± 1.6
60	0.2 ± 0.3	3.4 ± 1.1	0.1 ± 0.1	1.8 ± 1.8	0.0 ± 0.0	1.0 ± 1.8
62	0.2 ± 0.3	2.8 ± 1.5	0.1 ± 0.1	1.6 ± 1.6	0.0 ± 0.0	1.0 ± 1.8
64	0.2 ± 0.2	2.3 ± 1.7	0.0 ± 0.0	1.3 ± 1.5	0.0 ± 0.0	0.8 ± 1.7
66	0.1 ± 0.2	2.2 ± 1.9	0.0 ± 0.0	1.1 ± 1.5	0.0 ± 0.0	0.7 ± 1.5
68	0.1 ± 0.1	1.9 ± 1.9	0.0 ± 0.0	1.0 ± 1.6	0.0 ± 0.0	0.5 ± 1.1
70	0.1 ± 0.1	1.5 ± 1.6	0.0 ± 0.0	0.9 ± 1.7	0.0 ± 0.0	0.3 ± 0.7
72	0.1 ± 0.0	1.1 ± 1.4	0.0 ± 0.0	0.9 ± 1.8	0.0 ± 0.0	0.2 ± 0.4
74	0.0 ± 0.0	0.9 ± 1.4	0.0 ± 0.0	0.8 ± 1.7	0.0 ± 0.0	0.1 ± 0.2
76	0.0 ± 0.0	0.8 ± 1.5	0.0 ± 0.0	0.7 ± 1.6	0.0 ± 0.0	0.0 ± 0.0
78	0.0 ± 0.0	0.9 ± 1.6	0.0 ± 0.0	0.5 ± 1.2	0.0 ± 0.0	0.0 ± 0.0
80	0.0 ± 0.0	0.9 ± 1.7	0.0 ± 0.0	0.3 ± 0.8	0.0 ± 0.0	0.0 ± 0.0
82	0.0 ± 0.0	0.9 ± 1.8	0.0 ± 0.0	0.2 ± 0.4	0.0 ± 0.0	0.0 ± 0.0
84	0.0 ± 0.0	0.8 ± 1.7	0.0 ± 0.0	0.1 ± 0.2	0.0 ± 0.0	0.0 ± 0.0
86	0.0 ± 0.0	0.7 ± 1.6	0.0 ± 0.0	0.0 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
88	0.0 ± 0.0	0.6 ± 1.2	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
90	0.0 ± 0.0	0.4 ± 0.8	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
92	0.0 ± 0.0	0.2 ± 0.5	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
94	0.0 ± 0.0	0.1 ± 0.3	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ±

						0.0
96	0.0 ± 0.0	0.0 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
98	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
100	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0

Table C.2. Modeled mean area, in hectares, ± 1 SD at three morphometric depth classes between six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment of the Lower Missouri River, MO km 402 to 209, calculated to evaluate effects of discharge on sandbar morphometry.

	Morphometric depth class (m)					
	0.0 to 0.5		0.51 to 1.0		1.01 to 1.5	
Discharge (kcfs)	Wing-dike	Point	Wing-dike	Point	Wing-dike	Point
10	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
12	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
14	0.0 ± 0.0	0.0 + 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
16	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
18	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
20	0.0 ± 0.0	0.0 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
22	0.0 ± 0.0	0.3 ± 0.4	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
24	0.1 ± 0.1	0.7 ± 0.8	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
26	0.2 ± 0.2	1.2 ± 1.2	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
28	0.3 ± 0.3	1.9 ± 1.9	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
30	0.3 ± 0.3	2.6 ± 2.6	0.0 ± 0.1	0.2 ± 0.3	0.0 ± 0.0	0.0 ± 0.0
32	0.3 ± 0.2	3.2 ± 3.5	0.1 + 0.2	0.4 ± 0.6	0.0 ± 0.0	0.0 ± 0.0
34	0.3 ± 0.1	3.7 ± 4.0	0.2 + 0.2	0.9 ± 1.0	0.0 ± 0.0	0.0 ± 0.0
36	0.3 ± 0.1	4.2 ± 4.5	0.2 + 0.3	1.4 ± 1.3	0.0 ± 0.0	0.1 ± 0.2

38	0.3 ± 0.2	4.4 ± 4.3	0.3 ± 0.2	2.0 ± 1.8	0.0 ± 0.1	0.2 ± 0.4
40	0.3 ± 0.2	4.7 ± 3.9	0.3 ± 0.2	2.6 ± 2.6	0.1 ± 0.2	0.4 ± 0.7
42	0.3 ± 0.2	4.9 ± 3.5	0.3 ± 0.1	3.3 ± 3.4	0.2 ± 0.3	0.7 ± 0.9
44	0.3 ± 0.2	5.3 ± 3.0	0.3 ± 0.1	3.9 ± 4.1	0.2 ± 0.3	1.0 ± 1.0
46	0.3 ± 0.2	5.7 ± 2.5	0.3 ± 0.2	4.2 ± 4.4	0.2 ± 0.2	1.5 ± 1.3
48	0.3 ± 0.2	6.1 ± 2.1	0.3 ± 0.2	4.5 ± 4.4	0.2 ± 0.1	2.1 ± 1.9
50	0.3 ± 0.2	6.6 ± 1.9	0.3 ± 0.2	4.8 ± 4.0	0.3 ± 0.1	2.8 ± 2.6
52	0.3 ± 0.3	6.7 ± 1.9	0.3 ± 0.2	5.2 ± 3.7	0.3 ± 0.2	3.5 ± 3.4
54	0.3 ± 0.3	6.7 ± 2.2	0.3 ± 0.2	5.6 ± 3.2	0.3 ± 0.2	4.1 ± 4.1
56	0.3 ± 0.4	6.6 ± 2.5	0.3 ± 0.2	5.9 ± 2.7	0.3 ± 0.2	4.4 ± 4.3
58	0.3 ± 0.4	6.3 ± 2.6	0.2 ± 0.2	6.3 ± 2.5	0.3 ± 0.2	4.7 ± 4.3
60	0.3 ± 0.4	6.1 ± 2.7	0.2 ± 0.2	6.4 ± 2.3	0.3 ± 0.2	5.2 ± 4.2
62	0.3 ± 0.4	5.9 ± 2.7	0.3 + 0.2	6.4 ± 2.3	0.2 ± 0.2	5.5 ± 3.9
64	0.3 ± 0.4	5.4 ± 2.3	0.3 ± 0.3	6.3 ± 2.3	0.2 ± 0.2	5.9 ± 3.4
66	0.2 ± 0.4	4.6 ± 1.6	0.3 ± 0.4	6.1 ± 2.4	0.2 ± 0.2	6.1 ± 3.1
68	0.2 ± 0.3	3.9 ± 1.3	0.3 ± 0.4	6.1 ± 2.6	0.2 ± 0.2	6.1 ± 2.8
70	0.2 ± 0.3	3.1 ± 1.5	0.3 ± 0.4	6.0 ± 2.8	0.2 ± 0.2	6.1 ± 2.5
72	0.2 ± 0.3	2.7 ± 1.6	0.3 ± 0.4	5.6 ± 2.5	0.2 ± 0.2	6.0 ± 2.2
74	0.2 ± 0.2	2.2 ± 1.6	0.3 ± 0.4	4.9 ± 2.2	0.3 ± 0.3	6.0 ± 2.4
76	0.1 ± 0.2	1.6 ± 1.3	0.2 + 0.4	4.2 ± 2.1	0.3 ± 0.3	5.9 ± 2.5
78	0.1 ± 0.1	1.1 ± 1.3	0.2 ± 0.3	3.4 ± 1.9	0.3 ± 0.4	5.9 ± 2.6
80	0.1 ± 0.1	0.8 ± 1.4	0.2 ± 0.3	2.5 ± 1.8	0.3 ± 0.4	5.2 ± 2.1
82	0.1 ± 0.1	0.8 ± 1.4	0.2 ± 0.3	1.9 ± 1.6	0.3 ± 0.5	4.2 ± 2.6

84	0.0 ± 0.0	0.8 ± 1.5	0.2 ± 0.2	1.5 ± 1.5	0.3 ± 0.4	3.4 ± 3.0
86	0.0 ± 0.0	0.8 ± 1.5	0.1 ± 0.2	1.2 ± 1.4	0.2 ± 0.4	3.0 ± 3.0
88	0.0 ± 0.0	0.8 ± 1.6	0.1 ± 0.1	1.0 ± 1.4	0.2 ± 0.3	2.8 ± 2.8
90	0.0 ± 0.0	0.9 ± 1.7	0.1 ± 0.1	0.9 ± 1.4	0.2 ± 0.3	2.4 ± 2.5
92	0.0 ± 0.0	0.9 ± 1.8	0.1 ± 0.1	0.8 ± 1.4	0.2 ± 0.3	2.0 ± 2.1
94	0.0 ± 0.0	0.8 ± 1.7	0.0 ± 0.0	0.8 ± 1.4	0.2 ± 0.2	1.6 ± 1.8
96	0.0 ± 0.0	0.7 ± 1.6	0.0 ± 0.0	0.8 ± 1.5	0.1 ± 0.2	1.3 ± 1.6
98	0.0 ± 0.0	0.6 ± 1.3	0.0 ± 0.0	0.8 ± 1.6	0.1 ± 0.1	1.1 ± 1.5
100	0.0 ± 0.0	0.4 ± 0.9	0.0 ± 0.0	0.9 ± 1.7	0.1 ± 0.1	0.9 ± 1.4

Table C.3. Mean perimeter and total exposed area + 1 SD for six point and seven wing-dike sandbars within the Grand River to Osage River segment of the Lower Missouri River, MO (km 402 to 209). Sandbar perimeter was predicted from modeled data of emergent sandbar area over a range of discharges (10 kcfs to 100 kcfs).

	Point Sandbars		Wing-dike Sandbars	
Discharge (kcfs)	Mean Perimeter (m)	Mean of total exposed area (m^2)	Mean Perimeter (m)	Mean of total exposed area (m^2)
10	3250 ± 448	281166 ± 93532	742 ± 444	15754 ± 12579
12	3250 ± 448	281166 ± 93532	742 ± 444	15754 ± 12579
14	3252 ± 452	281147 ± 93493	742 ± 444	15754 ± 12579
16	3257 ± 458	281096 ± 93423	744 ± 443	15743 ± 12586
18	3269 ± 472	280941 ± 93202	746 ± 442	15719 + 12599
20	3301 ± 505	280397 ± 92632	749 ± 442	15642 + 12594
22	3333 ± 512	278596 ± 91159	788 ± 500	15415 + 12367
24	3375 ± 533	274227 ± 87063	809 ± 508	14572 + 11805
26	3461 ± 610	269286 ± 83463	773 ± 446	13751 + 11296
28	3510 ± 683	261496 ± 78654	743 ± 387	13067 + 11042
30	3574 ± 729	253454 ± 73229	707 ± 372	12535 + 10905
32	3670 ± 842	244386 ± 68324	676 ± 374	11996 + 10707
34	3656 ± 825	234861 ± 63249	674 ± 410	11438 + 10480
36	3557 ± 739	225010 ± 59255	670 ± 455	10794 + 10138
38	3462 ± 582	215611 ± 55969	652 ± 457	10165 + 9762

40	4139 ± 1641	215591 ± 55627	624 ± 432	9523 + 9347
42	4101 ± 1674	205830 ± 56519	575 ± 378	8954 + 9107
44	3984 ± 1754	194118 ± 55369	533 ± 337	8344 + 8743
46	3356 ± 655	165976 ± 55931	500 ± 328	7759 + 8427
48	3317 ± 761	151311 ± 55086	474 ± 308	7177 + 8093
50	3279 ± 880	134821 ± 51707	457 ± 293	6566 + 7595
52	3044 ± 828	119216 ± 48455	437 ± 281	5944 + 6941
54	2790 ± 825	104169 ± 45628	417 ± 263	5157 + 6003
56	2562 ± 866	90587 ± 44856	403 ± 263	4430 + 5095
58	2293 ± 895	77325 ± 45347	366 ± 227	3708 + 4230
60	2001 ± 791	65592 ± 44865	307 ± 253	3085 + 3586
62	1703 ± 728	53925 ± 46114	280 ± 244	2583 + 2809
64	1422 ± 759	45462 ± 44806	251 ± 205	2072 + 2185
66	1231 ± 748	39384 ± 42821	222 ± 167	1707 + 1582
68	1103 ± 836	33579 ± 40155	195 ± 148	1389 + 1265
70	950 ± 809	27877 ± 36814	171 ± 129	1059 + 852
72	751 ± 676	21952 ± 34691	139 ± 99	757 + 563
74	535 ± 614	18408 ± 34131	105 ± 69	522 + 492
76	436 ± 615	15537 ± 30580	65 ± 67	338 + 425
78	398 ± 587	13915 ± 27894	53 ± 66	265 + 354
80	366 ± 566	12427 ± 25151	47 ± 60	191 + 261
82	343 ± 549	10940 ± 22342	32 ± 43	126 + 189
84	323 ± 523	9256 ± 19369	29 ± 39	106 + 163
86	293 ± 494	7495 ± 16329	18 ± 31	53 + 94
88	259 ± 469	5567 ± 12328	11 ± 29	14 + 38
90	207 ± 391	3672 ± 8416	0 ± 0	0 + 0
92	128 ± 242	1965 ± 4542	0 ± 0	0 + 0
94	99 ± 197	1063 ± 2527	0 ± 0	0 + 0
96	51 ± 104	290 ± 663	0 ± 0	0 + 0
98	8 ± 20	16 ± 40	0 ± 0	0 + 0
100	8 ± 20	16 ± 40	0 ± 0	0 + 0

Appendix D. Modeled mean area and percent area of total hectares of submergent ATTZ (-0.0 to 0.3, -0.0 to 0.5, -0.0 to 1.0, and -0.0 to 1.5 m) and emergent-ATTZ (+0.0 to 0.3 and +≥1.0 m) classes.

Table D.1. Modeled mean area, in hectares, ± 1 SD at two submergent-ATTZ (depth) classes for six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment of the Lower Missouri River, MO (km 402 to 209). Classification of Lower Missouri River sandbars into submergent ATTZ and emergent ATTZ elevation and depth classes are relative to the water's moving edge (0.0 m) and biota life history information. (See text for details)

Discharge (kcfs)	Depth class (m)			
	0.0 to 0.3		0.0 to 0.5	
	Wing-dike	Point	Wing-dike	Point
10	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
12	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
14	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
16	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
18	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
20	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.1
22	0.0 ± 0.0	0.3 ± 0.4	0.0 ± 0.0	0.3 ± 0.4
24	0.1 ± 0.1	0.7 ± 0.8	0.1 ± 0.1	0.7 ± 0.8
26	0.2 ± 0.2	1.1 ± 1.1	0.2 ± 0.2	1.2 ± 1.2
28	0.2 ± 0.2	1.6 ± 1.6	0.3 ± 0.3	2.0 ± 1.9
30	0.2 ± 0.1	2.0 ± 2.1	0.3 ± 0.3	2.6 ± 2.6
32	0.1 ± 0.1	2.3 ± 2.6	0.3 ± 0.2	3.2 ± 3.5
34	0.1 ± 0.1	2.5 ± 2.8	0.3 ± 0.1	3.7 ± 4.0
36	0.2 ± 0.1	2.7 ± 2.8	0.3 ± 0.1	4.2 ± 4.5
38	0.2 ± 0.1	2.8 ± 2.5	0.3 ± 0.2	4.4 ± 4.3
40	0.2 ± 0.1	2.9 ± 2.0	0.3 ± 0.2	4.7 ± 3.9
42	0.2 ± 0.1	3.1 ± 1.7	0.3 ± 0.2	4.9 ± 3.5
44	0.2 ± 0.1	3.4 ± 1.5	0.3 ± 0.2	5.3 ± 3.0
46	0.2 ± 0.1	3.7 ± 1.4	0.3 ± 0.2	5.8 ± 2.5
48	0.2 ± 0.1	3.9 ± 1.3	0.3 ± 0.2	6.1 ± 2.1
50	0.2 ± 0.1	4.0 ± 1.2	0.3 ± 0.2	6.6 ± 1.9
52	0.2 ± 0.2	4.2 ± 1.6	0.3 ± 0.3	6.7 ± 1.9
54	0.2 ± 0.2	4.1 ± 1.6	0.3 ± 0.3	6.7 ± 2.2
56	0.2 ± 0.3	3.8 ± 1.6	0.3 ± 0.4	6.6 ± 2.5
58	0.2 ± 0.3	3.7 ± 1.7	0.3 ± 0.4	6.3 ± 2.6
60	0.2 ± 0.3	3.6 ± 1.8	0.3 ± 0.4	6.1 ± 2.7
62	0.2 ± 0.2	3.4 ± 1.6	0.3 ± 0.4	5.9 ± 2.7

64	0.2 ± 0.2	3.0 ± 1.1	0.3 ± 0.4	5.4 ± 2.3
66	0.1 + 0.2	2.2 ± 0.7	0.2 ± 0.4	4.6 ± 1.6
68	0.1 + 0.2	1.8 ± 0.8	0.2 ± 0.3	3.9 ± 1.3
70	0.1 ± 0.1	1.5 ± 1.0	0.2 ± 0.3	3.1 ± 1.5
72	0.1 ± 0.1	1.5 ± 1.1	0.2 ± 0.3	2.7 ± 1.6
74	0.1 ± 0.1	1.1 ± 1.0	0.2 ± 0.2	2.2 ± 1.6
76	0.1 ± 0.1	0.7 ± 0.8	0.2 ± 0.1	1.6 ± 1.3
78	0.1 ± 0.0	0.5 ± 0.8	0.1 ± 0.1	1.1 ± 1.3
80	0.0 ± 0.0	0.5 ± 0.8	0.1 ± 0.1	0.8 ± 1.4
82	0.0 ± 0.0	0.5 ± 0.9	0.1 ± 0.1	0.8 ± 1.4
84	0.0 ± 0.0	0.5 ± 0.9	0.0 ± 0.0	0.8 ± 1.5
86	0.0 ± 0.0	0.5 ± 0.9	0.0 ± 0.0	0.8 ± 1.5
88	0.0 ± 0.0	0.5 ± 1.0	0.0 ± 0.0	0.8 ± 1.6
90	0.0 ± 0.0	0.6 ± 1.1	0.0 ± 0.0	0.9 ± 1.7
92	0.0 ± 0.0	0.6 ± 1.2	0.0 ± 0.0	0.9 ± 1.8
94	0.0 ± 0.0	0.5 ± 1.0	0.0 ± 0.0	0.8 ± 1.7
96	0.0 ± 0.0	0.4 ± 0.8	0.0 ± 0.0	0.7 ± 1.6
98	0.0 ± 0.0	0.2 ± 0.5	0.0 ± 0.0	0.6 ± 1.3
100	0.0 ± 0.0	0.1 ± 0.3	0.0 ± 0.0	0.4 ± 0.9

Table D.2. Modeled mean area, in hectares, ± 1 SD at two submergent-ATTZ (depth) classes for six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment of the Lower Missouri River, MO (km 402 to 209). Classification of Lower Missouri River sandbars into submergent ATTZ and emergent ATTZ elevation and depth classes are relative to the water's moving edge (0.0 m) and biota life history information. (See text for details).

Discharge (kcfs)	Depth class (m)			
	0.0 to 1.0		0.0 to 1.5	
	Wing-dike	Point	Wing-dike	Point
10	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
12	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
14	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
16	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
18	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
20	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.1

22	0.0 ± 0.0	0.3 ± 0.4	0.0 ± 0.0	0.3 ± 0.4
24	0.1 ± 0.1	0.7 ± 0.8	0.1 ± 0.1	0.7 ± 0.8
26	0.2 ± 0.2	1.2 ± 1.2	0.2 ± 0.2	1.2 ± 1.2
28	0.3 ± 0.3	2.0 ± 1.9	0.3 ± 0.3	2.0 ± 1.9
30	0.3 ± 0.3	2.8 ± 2.7	0.3 ± 0.3	2.8 ± 2.7
32	0.4 ± 0.3	3.7 ± 3.7	0.4 ± 0.3	3.7 ± 3.7
34	0.4 ± 0.4	4.6 ± 4.6	0.4 ± 0.4	4.6 ± 4.6
36	0.5 ± 0.4	5.6 ± 5.5	0.5 ± 0.4	5.6 ± 5.5
38	0.5 ± 0.4	6.4 ± 6.0	0.6 ± 0.5	6.7 ± 6.1
40	0.5 ± 0.4	7.3 ± 6.5	0.6 ± 0.5	7.8 ± 6.6
42	0.5 ± 0.3	8.3 ± 6.9	0.7 ± 0.6	8.9 ± 7.1
44	0.5 ± 0.4	9.1 ± 7.0	0.7 ± 0.6	10.2 ± 7.5
46	0.5 ± 0.4	10.0 ± 6.6	0.8 ± 0.6	11.5 ± 7.7
48	0.5 ± 0.4	10.6 ± 6.1	0.8 ± 0.5	12.7 ± 7.9
50	0.5 ± 0.4	11.3 ± 5.2	0.8 ± 0.5	14.1 ± 7.7
52	0.5 ± 0.4	11.9 ± 4.4	0.8 ± 0.6	15.4 ± 7.4
54	0.5 ± 0.5	12.3 ± 3.7	0.8 ± 0.6	16.4 ± 6.9
56	0.6 ± 0.5	12.5 ± 3.1	0.8 ± 0.7	16.9 ± 6.1
58	0.6 ± 0.6	12.7 ± 3.1	0.8 ± 0.7	17.4 ± 5.4
60	0.6 ± 0.6	12.5 ± 3.7	0.8 ± 0.8	17.7 ± 4.8
62	0.6 ± 0.7	12.3 ± 4.5	0.8 ± 0.8	17.8 ± 4.7
64	0.6 ± 0.7	11.7 ± 4.3	0.8 ± 0.8	17.5 ± 4.5
66	0.5 ± 0.7	10.8 ± 3.8	0.8 ± 0.9	16.9 ± 4.2
68	0.5 ± 0.7	9.9 ± 3.6	0.8 ± 0.9	16.0 ± 4.2
70	0.5 ± 0.7	9.1 ± 3.4	0.7 ± 0.9	15.3 ± 4.4
72	0.5 ± 0.7	8.3 ± 3.1	0.7 ± 0.9	14.4 ± 4.5
74	0.4 ± 0.6	7.2 ± 2.9	0.7 ± 0.9	13.1 ± 4.5
76	0.4 ± 0.6	5.9 ± 2.7	0.6 ± 0.9	11.8 ± 4.3
78	0.3 ± 0.5	4.5 ± 2.6	0.6 ± 0.9	10.4 ± 3.9
80	0.3 ± 0.4	3.4 ± 2.7	0.6 ± 0.8	8.5 ± 4.0
82	0.2 ± 0.3	2.7 ± 2.8	0.5 ± 0.8	6.9 ± 4.7
84	0.2 ± 0.2	2.3 ± 2.8	0.5 ± 0.7	5.7 ± 5.0
86	0.2 ± 0.2	2.0 ± 2.9	0.4 ± 0.6	5.0 ± 4.9
88	0.1 ± 0.1	1.8 ± 3.0	0.3 ± 0.5	4.6 ± 4.8

90	0.1 ± 0.1	1.8 ± 3.1	0.3 ± 0.4	4.2 ± 4.7
92	0.1 ± 0.1	1.7 ± 3.2	0.2 ± 0.3	3.7 ± 4.7
94	0.0 ± 0.0	1.6 ± 3.2	0.2 ± 0.2	3.2 ± 4.6
96	0.0 ± 0.0	1.5 ± 3.1	0.2 ± 0.2	2.8 ± 4.4
98	0.0 ± 0.0	1.4 ± 2.9	0.1 ± 0.1	2.5 ± 4.2
100	0.0 ± 0.0	1.3 ± 2.6	0.1 ± 0.1	2.2 ± 4.0

Table D.3. Modeled mean area, in hectares, ± 1 SD at two emergent-ATTZ (elevation) classes for six point sandbars and seven wing-dike sandbars within the Grand River to Osage River segment of the Lower Missouri River, MO (km 402 to 209). Classification of Lower Missouri River sandbars into submergent ATTZ and emergent ATTZ elevation and depth classes are relative to the water's moving edge (0.0 m) and biota life history information. (See text for details).

	Elevation class (m)			
	0.0 to 0.3		>1.0	
Discharge (kcfs)	Wing-dike	Point	Wing-dike	Point
10	0.0 ± 0.0	0.0 ± 0.0	1.3 ± 1.1	25.9 ± 7.2
12	0.0 ± 0.0	0.0 ± 0.0	1.3 ± 1.1	24.9 ± 6.6
14	0.0 ± 0.0	0.1 ± 0.1	1.2 ± 1.1	23.9 ± 6.3
16	0.0 ± 0.0	0.2 ± 0.3	1.2 ± 1.0	22.9 ± 6.2
18	0.1 ± 0.1	0.6 ± 0.8	1.1 ± 1.0	21.8 ± 6.1
20	0.2 ± 0.1	1.0 ± 1.1	1.0 ± 1.0	20.9 ± 6.1
22	0.2 ± 0.2	1.6 ± 1.7	1.0 ± 0.9	19.8 ± 6.2
24	0.2 ± 0.2	1.9 ± 2.1	0.9 ± 0.9	18.6 ± 6.3
26	0.2 ± 0.1	2.3 ± 2.7	0.9 ± 0.8	17.5 ± 6.4
28	0.1 ± 0.1	2.5 ± 2.8	0.8 ± 0.8	16.2 ± 6.4
30	0.1 ± 0.1	2.7 ± 2.8	0.7 ± 0.7	14.6 ± 6.3
32	0.2 ± 0.1	2.8 ± 2.4	0.7 ± 0.7	13.0 ± 6.1
34	0.2 ± 0.1	2.9 ± 2.0	0.6 ± 0.6	11.4 ± 5.8
36	0.2 ± 0.1	3.1 ± 1.7	0.5 ± 0.5	9.9 ± 5.2
38	0.2 ± 0.1	3.3 ± 1.5	0.4 ± 0.4	8.6 ± 4.8
40	0.2 ± 0.1	3.5 ± 1.3	0.4 ± 0.3	7.6 ± 4.5
42	0.2 ± 0.1	3.9 ± 1.2	0.3 ± 0.3	6.6 ± 4.2
44	0.2 ± 0.1	4.0 ± 1.0	0.2 ± 0.2	5.6 ± 3.9
46	0.2 ± 0.2	4.2 ± 1.3	0.2 ± 0.2	4.7 ± 3.8

48	0.2 ± 0.2	4.4 ± 1.7	0.2 ± 0.1	3.9 ± 3.8
50	0.2 ± 0.3	4.1 ± 1.6	0.1 ± 0.1	3.3 ± 3.6
52	0.2 ± 0.3	3.8 ± 1.6	0.1 ± 0.1	2.8 ± 3.3
54	0.2 ± 0.3	3.5 ± 1.6	0.1 ± 0.1	2.4 ± 3.0
56	0.2 ± 0.2	3.3 ± 1.5	0.0 ± 0.1	2.0 ± 2.8
58	0.2 ± 0.2	3.0 ± 1.4	0.0 + 0.0	1.6 ± 2.6
60	0.1 ± 0.2	2.5 ± 0.9	0.0 ± 0.0	1.3 ± 2.4
62	0.1 ± 0.2	1.9 ± 0.7	0.0 ± 0.0	1.1 ± 2.1
64	0.1 ± 0.1	1.5 ± 0.9	0.0 ± 0.0	0.9 ± 1.8
66	0.1 ± 0.1	1.4 ± 1.1	0.0 ± 0.0	0.7 ± 1.5
68	0.1 ± 0.1	1.3 ± 1.2	0.0 ± 0.0	0.5 ± 1.1
70	0.1 ± 0.1	1.1 ± 1.1	0.0 ± 0.0	0.3 ± 0.7
72	0.1 ± 0.0	0.8 ± 0.9	0.0 ± 0.0	0.2 ± 0.4
74	0.0 ± 0.0	0.6 ± 0.8	0.0 ± 0.0	0.1 ± 0.2
76	0.0 ± 0.0	0.5 ± 0.9	0.0 ± 0.0	0.0 ± 0.0
78	0.0 ± 0.0	0.5 ± 0.9	0.0 ± 0.0	0.0 ± 0.0
80	0.0 ± 0.0	0.5 ± 0.9	0.0 ± 0.0	0.0 ± 0.0
82	0.0 ± 0.0	0.5 ± 1.0	0.0 ± 0.0	0.0 ± 0.0
84	0.0 ± 0.0	0.6 ± 1.1	0.0 ± 0.0	0.0 ± 0.0
86	0.0 ± 0.0	0.6 ± 1.2	0.0 ± 0.0	0.0 ± 0.0
88	0.0 ± 0.0	0.5 ± 1.0	0.0 ± 0.0	0.0 ± 0.0
90	0.0 ± 0.0	0.3 ± 0.8	0.0 ± 0.0	0.0 ± 0.0
92	0.0 ± 0.0	0.2 ± 0.5	0.0 ± 0.0	0.0 ± 0.0
94	0.0 ± 0.0	0.1 ± 0.3	0.0 ± 0.0	0.0 ± 0.0
96	0.0 ± 0.0	0.0 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
98	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
100	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0

Table D.4. Percent area of total hectares of submergent ATTZ (-0.0 to 0.3, -0.0 to 0.5, -0.0 to 1.0, and -0.0 to 1.5) and emergent-ATTZ (+0.0 to 0.3 and +≥1.0) classes for six point (PT) sandbars and seven wing-dike (WD) sandbars within the Grand River to Osage River segment of the Lower Missouri River, MO (km 402 to 209). Percent area is based on total hectares for all six point sandbars (≈169 ha) and seven wing-dike sandbars (≈11 ha) available for the entire sandbar-ATTZ across all discharges. Q = Discharge

	Elevation class (m)				Depth class (m)							
	0.0 to 0.3		> 1.0		0.0 to 0.3		0.0 to 0.5		0.0 to 1.0		0.0 to 1.5	
Q (kcfs)	WD	PT	WD	PT	WD	PT	WD	PT	WD	PT	WD	PT
10	0	0	85	92	0	0	0	0	0	0	0	0
12	0	0	80	89	0	0	0	0	0	0	0	0
14	1	0	76	85	0	0	0	0	0	0	0	0
16	2	1	73	81	0	0	0	0	0	0	0	0
18	5	2	70	78	0	0	0	0	0	0	0	0
20	10	3	66	74	1	0	1	0	1	0	1	0
22	13	6	62	70	2	1	2	1	2	1	2	1
24	12	7	58	66	7	2	8	2	8	2	8	2
26	10	8	54	62	12	4	13	4	13	4	13	4
28	9	9	50	57	13	6	17	7	17	7	17	7
30	9	10	46	52	11	7	18	9	21	10	21	10
32	10	10	41	46	9	8	18	12	24	13	24	13
34	11	10	37	41	9	9	16	13	27	16	27	16
36	10	11	32	35	10	10	16	15	31	20	32	20
38	10	12	27	31	10	10	16	16	33	23	35	24
40	10	13	23	27	10	10	17	17	34	26	39	28
42	10	14	18	23	10	11	17	18	33	29	43	32
44	10	14	15	20	10	12	17	19	33	32	47	36
46	10	15	11	17	10	13	16	20	33	35	48	41
48	11	16	10	14	10	14	17	22	33	38	49	45
50	13	14	7	12	10	14	16	23	33	40	49	50
52	13	13	5	10	10	15	17	24	33	42	50	55
54	12	12	4	9	11	15	18	24	34	44	51	58
56	11	12	3	7	13	14	19	24	35	45	52	60
58	10	11	2	6	13	13	20	23	36	45	52	62
60	8	9	2	5	12	13	20	22	36	44	52	63
62	7	7	1	4	11	12	19	21	36	44	51	63
64	6	5	1	3	9	11	18	19	35	41	51	62
66	6	5	1	3	8	8	16	16	34	38	50	60
68	5	5	0	2	7	6	14	14	32	35	48	57
70	5	4	0	1	6	5	12	11	31	33	46	54

72	3	3	0	1	6	5	11	10	29	30	45	51
74	2	2	0	0	5	4	10	8	27	25	43	47
76	1	2	0	0	5	2	9	6	24	21	40	42
78	1	2	0	0	3	2	7	4	21	16	38	37
80	1	2	0	0	2	2	5	3	18	12	35	30
82	1	2	0	0	1	2	4	3	15	10	32	24
84	1	2	0	0	1	2	2	3	12	8	29	20
86	0	2	0	0	1	2	2	3	10	7	25	18
88	0	2	0	0	1	2	1	3	8	6	22	16
90	0	1	0	0	1	2	1	3	6	6	19	15
92	0	1	0	0	0	2	1	3	4	6	16	13
94	0	0	0	0	0	2	1	3	3	6	13	11
96	0	0	0	0	0	1	0	3	2	5	10	10
98	0	0	0	0	0	1	0	2	1	5	8	9
100	0	0	0	0	0	0	0	1	1	4	6	8

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