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# Abstract

Sandbars and islands provide important nesting and foraging habitat for birds (including listed species) and shallow water habitat for many aquatic species in riverine ecosystems. In-stream habitat is especially important in incised channels lacking floodplain connectivity, with channel bars providing important riparian habitat. However, some river management practices significantly alter and sometime eventually eliminate these important habitats. Several US Army Corps of Engineers districts are planning or actively building instream bars and islands using flow management and/or instream structures. Sister agencies (e.g., US Bureau of Reclamation) have similar initiatives downstream of their reservoir structures. This report outlines considerations for establishing and managing sandbar and island features. It presents a compilation of proven techniques for promoting sandbar and island development and for reducing erosion of these features.

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# Preface

This study was conducted for the US Army Corps of Engineers (USACE) Albuquerque District under P2 project 151885, "Creation of Channel Bars for Instream Habitat" and Ecosystem Management Restoration Research Program (Funding Account Code U4378253; AMSCO Code 031342). The technical monitor was Dr. Michael D. Porter.

The work was a joint effort between the Environmental Engineering Branch (EPE) of the Environmental Processes and Engineering Division (EP) and the Ecological Resources Branch (EEE) of the Ecosystem Evaluation and Engineering Division (EE), US Army Engineer Research and Development Center, Environmental Laboratory (ERDC-EL). At the time of publication, Dr. Michael Rowland was chief of EPE, and Mr. Warren P. Lorentz, was chief of EP. Mr. Harley McAlexander was acting chief of EEE, and Mr. Mark Farr was chief of EE. Dr. Brook Herman was the program manager of the Ecosystem Management and Restoration Research Program, and Dr. Jennifer Seiter-Moser was the technical director for Civil Works. The deputy director of ERDC-EL was Dr. Brandon Lafferty, and the director was Dr. Edmond Russo.

COL Teresa A. Schlosser was the commander of ERDC, and the director was Dr. David W. Pittman.

# 1 Introduction

## 1.1 Background

Sediment retention by reservoirs and changes in river hydrology below dams can significantly alter or eliminate important floodplain and instream habitats. Sandbars and islands are often important habitat for many species in river ecosystems. While they are inundated, they are important shallow water habitat for many aquatic species and provide nesting and foraging habitat for birds (including listed species) as spring runoff recedes. Channel bars also provide an important riparian habitat component for incised river channels lacking floodplain connectivity. However, some river management practices can lead to significant alteration or elimination of these important habitats. Reduction in the availability and quality of sandbar habitat — habitat that is crucial for dependent species in systems lacking floodplain connectivity — has been noted for many managed rivers. Throughout the United States, endangered and threatened species may utilize emergent sandbars as nesting habitat (e.g., Interior Least Tern) or inundated vegetated sandbars as nursery habitat (Rio Grande Silvery Minnow). Coutant (2004) hypothesized that newly hatched white sturgeon embryos (eleutheroembryos) remain in shallow waters, hiding in crevices for protection from predation. Other species may also depend on associated habitats to complete essential components of their life cycles.

Several US Army Corps of Engineers (USACE) districts are planning or actively building instream bars and islands using flow management and/or instream structures, and sister agencies (e.g., US Bureau of Reclamation) have implemented similar initiatives downstream of their reservoir structures. However, a significant barrier to meeting the requirements of biological opinions or recovery plans is the ability to effectively implement habitat management techniques. Mechanical construction of sandbars and islands can be costly, and in many locations, associated logistical problems cannot be overcome. Measures that take advantage of natural sedimentation and hydrologic processes can provide a cost-effective alternative for creating and sustaining these essential instream habitats. Modeling is a key component of this approach; however, available models capable of predicting the initiation of sandbars, erosion, and quality of associated instream habitat are limited to high-fidelity, multi-dimensional sediment transport models. These models require considerable data, yet prediction errors are high due to natural variability. Planning-level models are needed to address the array of engineering and ecological questions within the available planning horizon and with available data.

Another challenge is that evaluating species utilization of sandbar habitat may require extensive data collection. The appropriate habitat for life-stage requirements of each species of concern vary significantly (e.g., available gravel for nesting, shallow water for foraging, or vegetated cover for protection), and quantifying the suitability of the habitat is beyond the scope of this report. A clear understanding of threatened and endangered species life histories and associated monitoring would provide examples for adaptive management that would streamline data collection, analysis, and interpretation.

## 1.2 Objective

The techniques, guidance, and models presented in this report will enable USACE districts to develop strategies to utilize flows, structural modifications, and available sediment supply to create bar/island habitats on regulated and/or incised channels. These tools can be used to avoid jeopardy decisions, recover endangered and threatened species, and improve outcomes of ecosystem management and restoration projects. Considerable cost savings for districts may be realized, particularly if flows can be manipulated to create habitat that would otherwise require costly construction actions. A better understanding of the applicability for various techniques will allow improved implementation of small, inexpensive instream structures to be utilized in conjunction with existing flow regimes.

This report is a compilation of effective techniques with supporting conceptual and analytical models needed to predict sandbar and island erosion and creation through aggradation as a function of sediment supply and river flows. The report provides guidance for designing structural techniques (chevrons, groins, etc.) to promote instream sandbar and island habitat formation. Case studies evaluating the application of the techniques and models for a variety of environmental and hydrologic settings across the nation provide useful information for practitioners. Models addressing conditions for initiating sandbar formation and the feedback mechanisms associated with vegetation provide the ability to assess alternatives for bar creation and associated habitat benefits/impacts.

Hydrological connectivity to terrestrial habitats can be accomplished by floodplain lowering, sandbar construction, or dynamic sandbar building. Constructed sandbars and islands may be a cost-effective approach for restoring hydrological connectivity to floodplain habitats. The cost effectiveness and reliability of constructed sandbars may be evaluated using a model or a field experiment. Performance can be evaluated as the area of suitable habitat in terms of availability (species life history), longevity (habitat persistence or useful life span), plant succession, and sustainable geomorphology. Comparing the costs (construction) and benefits (performance) for the different alternative construction methods would identify where each of the different approaches is cost effective for implementation. Floodplain lowering may be more effective in reaches with a low sediment supply while dynamic sandbar building depends on a higher availability of sediment. During the initial evaluations, various management techniques should be investigated for ability to achieve project goals, cost effectiveness, and sustainability.

## 1.3 Approach

Guidance for designing structural techniques for dynamic sandbar formation provides opportunities to stabilize in-stream infrastructure while conveying habitat benefits, informing appropriate habitat management, and increasing the resilience and functionality of the whole system for habitat management while addressing infrastructure issues. Simultaneously assessing the appropriate sandbar habitat technique and management techniques increases the resilience and functionality of the created habitat.

Adaptive management (AM) provides a framework for evaluating the interrelationships of these concepts to better inform habitat and water management strategies. As relationships become better understood, it becomes easier to efficiently and effectively determine the most appropriate techniques for a particular project. Historical data and imagery are often useful to quickly assess current conditions for rivers and create generalizations for implementing changes. Case studies are presented that document the efficacy of flow modification or structures in various riverine scenarios.

Generalizable models that describe critical conditions for initiating sandbar formation and the feedback mechanisms associated with vegetation to the extent practicable have been developed. The algorithms and conceptual models utilized on the Missouri River were applied and calibrated to test the model's efficacy to solving similar problems in different regions. The lessons learned on the Missouri River will allow more precise prediction models to be developed for districts facing sandbar habitat issues and enable districts to determine the best approach to increasing habitat in other river systems.

There are some limitations to this strategy. Residual uncertainties related to maintaining productivity after habitat is created and biological responses to management actions are likely. Availability at different flows, vegetation, water quality, dispersal, and other factors influence existing habitats. These factors could also affect the success of newly created habitats. Models can predict the initiation of sandbar formation, but erosion and deposition can influence the stability and longevity of created functional surfaces. Few case studies exist for some models, and some promising materials suggested for flow control structures have not been tested for these purposes. To implement this strategy in the face of these and other uncertainties, an approach was crafted to improve the success of management actions through the use of measurable objectives, targeted monitoring and research, and analysis of data in a manner that reduces uncertainty and leads to better informed decision making.

Interdisciplinary teams (e.g., biologists, hydrologists, planners, program managers, geomorphologists, and engineers) with a wide range of experience and knowledge are requisite to this strategy. A project delivery team (PDT), drawing from many districts and having unique experience and needs, will usually provide a more complete understanding of potential problems and potential solutions. In addition, local governments, property owners, commercial enterprises, and other shareholders may have unique insights based on years of observations.

Successful adaptive management requires integrating the best available data and information, model predictions, and judgement from available professionals into a cohesive response. The response must include a plan to collect additional information upon which to base future assessments and adaptive management decisions.

# 2 Considerations for Bar and Island Creation, Enhancement, or Preservation in Regulated Rivers

The environmental consequences of reservoir construction and operation often include an altered flow regime, lost connectivity (longitudinal and floodplain), and downstream channel degradation (Juracek 2015). A century of water management practice and infrastructure development on the Rio Grande River has significantly changed the hydrology and channel geomorphology. As a result, three endangered species (Southwestern Willow Flycatcher, Rio Grande Silvery Minnow, and New Mexico meadow jumping mouse) and one threatened species (Western Yellow-Billed Cuckoo) are listed under the Endangered Species Act along the Rio Grande within the state of New Mexico.

In general, rivers downstream of dams experience channel degradation (i.e., bed and bank erosion), eventually widening the channel to a new planform (Schumm et al. 1984). Understanding the complex physical relationships that drive sandbar and island development, maturation and senescence is essential for identifying where dynamic processes can be used to produce emergent sandbar habitat (ESH).

## 2.1 Effects of reservoirs on hydrology

Nearly every large river in America is directly or indirectly manipulated by dams and other flow control structures. Environmental consequences of reservoirs and their operations include altered flow and sediment regimes, downstream channel degradation (or aggradation in some cases), alteration of floodplain connectivity and a myriad of related ecological effects. Graf (2006) compared 36 pairs of regulated and unregulated river reaches and observed that regulated reaches have 32% larger low-flow channels, 50% smaller high-flow channels, 79% less active floodplain area, and 3.6 times more inactive floodplain area. Larger low-flow channels result in slower velocities and less reaeration, usually leading to lower water quality. Smaller high-flow channels and smaller floodplain areas increase velocities during flood events, resulting in greater habitat damage from erosion.

Sandbars and islands increase the effective habitat area within a channel beyond just bankside habitat. They also provide unique habitat not associated with river banks. Unfortunately, hydrologic changes induced by reservoir operations can be detrimental to sandbar and island formation and sustainability. The resulting habitat loss can be devastating to some species such as the endangered and listed species on the Rio Grande River.

The effect of altered river hydrology on in-river habitat tends to be site specific, although some generalizations can be made. All storage reservoirs alter, to some extent, the magnitude, timing (seasonal patterns), frequency, duration, and rate of change of downstream river flows. For example, western reservoirs are commonly operated to store water during periods of high runoff and release stored flows at times when flows would naturally be much lower, reducing peak flows and increasing base flow. Flood control dams limit peak flows that are usually responsible for the majority of sediment transport in many riverine systems. Sandbar formation usually occurs coincident with high flows. Thus, elimination of high flows tends to limit the development of new sandbars and islands.

The reduction or elimination of high flows that scour vegetation from bar and island surfaces allows vegetation to become better established and more deeply rooted. Natural annual cycles of vegetation colonization and subsequent scour that maintain sandbars and islands as active, sparsely vegetated, lower-elevation surfaces with high hydrologic connectivity are replaced by vegetation growth and succession to seral or climax states that promote sediment accretion and vertical evolution of island or floodplain surfaces, with a concurrent decrease in hydrologic connectivity. The magnitude of the effects described above are generally correlated with the extent to which previously unregulated flows and associated sediment (see Section 2.2) and vegetation processes have been altered.

Superimposed on large-scale hydrologic effects related to magnitude in seasonality, short-term daily or even hourly fluctuations in river levels associated with hydropower generation can significantly affect channel morphology and ecological condition of downstream reaches. Further, the rate of change in flows associated with hydropower generation, water supply storage, or flood management are usually different associated with unregulated hydrology. They are also likely different from the hydrographs most suitable for ecological needs such as vegetation cycling on bar surfaces.

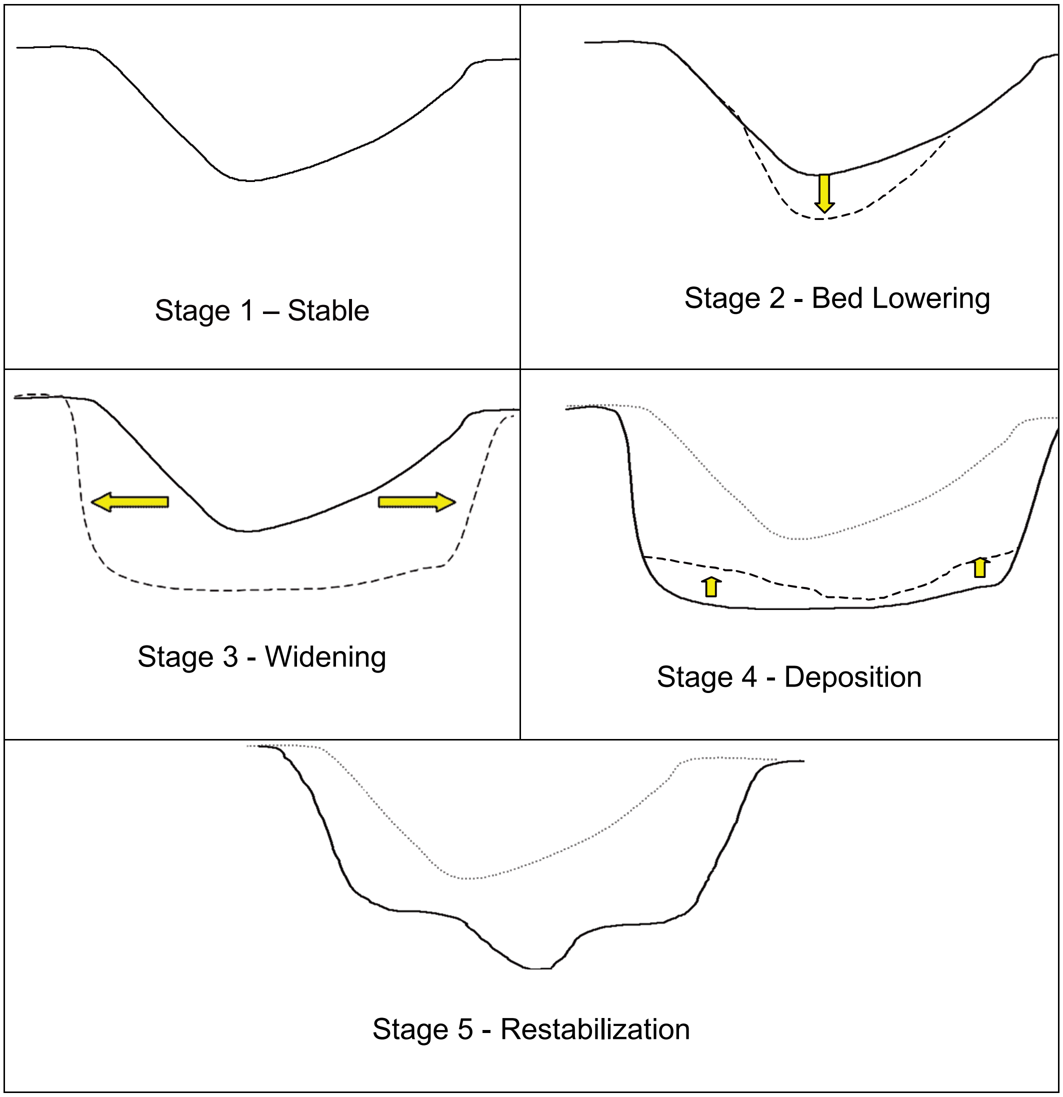
## 2.2 Effects of reservoirs on sediment processes

Dams impede downstream sediment transport. Upstream of the dam, decrease in energy slope caused by the reservoir pool leads to sediment deposition and aggradation at the head of the reservoir pool (i.e., the formation of a delta). Sediments that accumulate within the reservoir pool may be submerged or emergent depending upon the pool level. Consequently, dams can create sandbar and island habitat within the reservoir that is ephemeral, varying with reservoir water level and sediment supply. These features are often highly stratified, with coarse foundation substrates and fine surface substrates. Deposition of fine sediment on coarse substrata can increase egg and larvae mortality by smothering habitat required by many invertebrate and fish species (Waters 1995; Poff et al. 1997; Henley et al. 2000).

Most large reservoirs are effective sediment traps. Thus, water discharged past the dam is practically devoid of bed-material-sized sediments. Scouring occurs at the discharge point, and the channel bed will erode and lower (degrade) as the high-energy, sediment-starved water attempts to replenish its sediment load (Leopold et al. 1992; Petts 1984; Juracek 2001). Depending upon the magnitude of the degradation, channel widening may also occur as banks become over steep and geotechnically unstable, consistent with the first two stages of the Channel Evolution Model (CEM) described by Schumm et al. (1984) (Figure 1).

The CEM describes five stages of channel response to increased flows or decreased sediment supply, characterizing the incision process observed in studies of Mississippi streams. The CEM has been extended to describe a number of situations involving hydrologic, sediment, or other impacts that lead to initiation of channel incision (degradation). In a typical equilibrium channel (Stage 1) subjected to a decrease in sediment load, the streambed degrades (Stage 2) until the critical bank height is exceeded and the bank fails (Stage 3), increasing channel width and sediment load. The original floodplain habitat may be destroyed by erosion or become hydrologically disconnected as stream level and water table drop. Eventually, deposition resumes within the lowered and widened channel bed (Stage 4), and the system establishes a new equilibrium (Stage 5).

Figure 1. **Stages of channel incision in the Channel Evolution Model (CEM).**




The downstream extent of degradation below a reservoir depends on several factors including bed material size, valley slope, and other geologic controls, hydrologic regime, etc. It may require several decades after reservoir construction to fully realize the changes induced by the new hydrology. The presence and character of downstream tributaries can greatly influence the channel's response. Large, sediment-rich tributaries sometimes deliver sufficient sediment to the mainstem to reduce downstream impacts. Even in cases where the mainstem flow dominates, short-duration, high-intensity storms in tributary watersheds can contribute appreciable quantities of flow and large quantities of sediment. Several of these tributaries exist along the Rio Grande River (Nordin and Beverage 1965).

Particle-size composition of the substrate close to the reservoir often undergoes coarsening as higher in-channel velocities entrain finer particles and transport them downstream. Changes in the particle-size composition of the bed are ecologically important because many aquatic organisms have specific substrate requirements (Petts 1980; Allan 1995; Gore and Shields 1995; Korte 2010). Bed material composition also affects important geomorphic processes, including the formation and condition of sandbars and islands in the reach. This is especially true for gravel-bed and sand-bed rivers where very coarse sands or gravels, even in small quantities, often lead to the development of an armor layer.

## 2.3 Effects of river regulation on downstream channel bars and islands

Sandbar and island dynamics are directly and indirectly affected by river flow regulation. The primary hydrologic effects described in Section 2.1 and the consequent channel degradation characterized in Section 2.2 tend to reduce or eliminate existing sandbars in the reach immediately below the dam. Generally, this condition will extend downstream to the point where sufficient sediment yield (from the bed, banks, and tributaries) has occurred to support bar development and/or maintenance. The location of this transitional zone is not static; it will change gradually over time with other geomorphic adjustments and can change abruptly due to significant flow events or sediment yield (e.g., a major landslide or tributary inflow).

When a riverbed becomes armored downstream of the dam, very little bed material movement occurs when flows are below the threshold for incipient motion of the coarser armoring material. As flows exceed that value, the predominant process is sediment transport and erosion, the rate of which will increase with discharge, until a second threshold is reached. When long-term erosion exceeds sedimentation, channel incision occurs (Fischenich and Morrow 2000). As flows increase above that second threshold, localized erosion continues but may be offset by bar growth or the formation of new bars in some areas, provided there is a sufficient load of bed-material sized sediments (coupled with appropriate depositional environments) to permit bar building. This phenomenon served as the basis for the development of models to predict sandbar growth and decay on the Missouri River, as described in the following section.

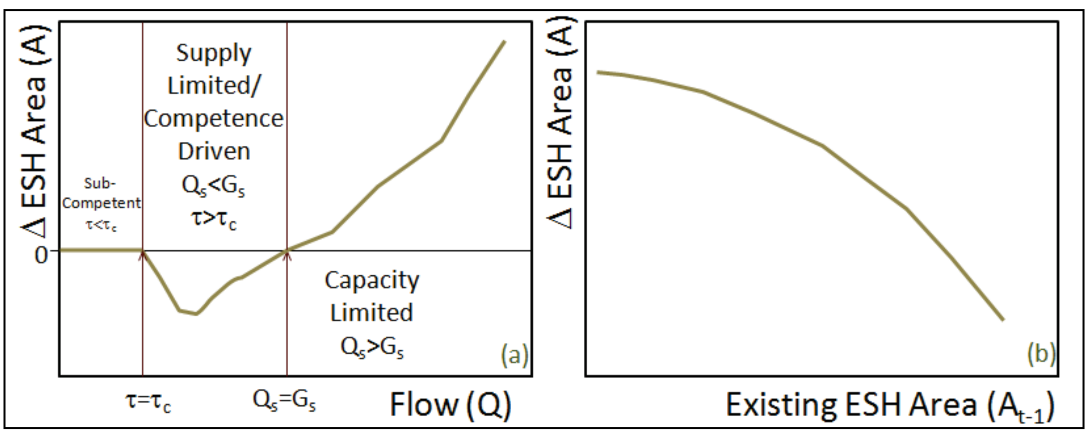
## 2.4 Conceptual model of sandbar growth and decay in regulated rivers

Understanding the processes that control the formation, growth, adjustment, and decay of bars and islands is essential to planning, design, and management of those features on regulated rivers. Fischenich* proposed a three-driver conceptual model described by an algorithm with the following form:

$$\Delta A_t \sim f\,(Q, d, A_{t-1}) \qquad (1)$$

where $\Delta A_t$ is the estimated change in ESH area above a reference plane in time period t, Q is a flow metric (mean, peak, or threshold), d is the days of flow above the threshold, and $A_{t-1}$ is the ambient ESH area (Figure 2). The conceptual model predicts that the change in ESH area (A) is inversely proportional to ambient area ($A_{t-1}$).

Figure 2. Theoretical relationships between (a) predicted emergent sandbar habitat (ESH) response and the driving independent variable and (b) predicted ESH response and the ambient (existing) bar area*.




The relationship with flow (and duration) is complex. Because of the non-linearity of sediment supply and transport capacity, there is a theoretical flow (i.e., shear stress) threshold where sediment supply ($Q_s$) meets transport capacity ($G_s$). Above that threshold ($Q_s > G_s$), bars build, and below that threshold ($Q_s < G_s$) bars erode and fail. However, in regulated systems, where supply is muted and base flow magnitudes or durations are

* Fischenich J., J. Tripe, D. Meier, D. Pridal, S. Givson, J. Hickey, and T. Econopouly. 2014. Unpublished. *Models, Data and Literature to Support Habitat Analyses for the Missouri River Effects Analysis*." Vicksburg, MS: US Army Corps of Engineers.

artificially elevated, the system is competence driven (maximum size of sediment transported) rather than capacity driven (amount of sediment transported). Elevated base flows are competent to erode bars, though watershed processes are not supplying new sediments to the reach, leading to accelerated long-term bar loss (Topping et al. 2003).

Mechanistically, however, the processes are more complicated than a simple $Q_s > G_s$ threshold. There are several physical processes that require process theory to modify the simple continuum mechanics* assumption, including the following:

- Supply Limitation — Downstream of dams, all bar building sediments are locally sourced, originating from the bed (including existing bars), tributaries, and banks. This has two implications. First, the theoretical threshold where Qs exceeds Gs is not a function of spatially averaged watershed processes but of localized stochastic sources, making it more erratic and not theoretically mandatory (i.e., bars may build locally even when Qs<Gs on a reach-wise and even cross-section averaged basis). Second, the sediment supply (Qs) is probably non-stationary and has a declining trend. Past flow events that built bars did so by mining non-renewable sources, and future events may find less sediment available.
- Water Level Control — The source-capacity threshold is likely secondary to a mechanistic system threshold. The river cannot build bars unless the existing bars are at least submerged. WEST Consultants† reported that Missouri dunes built to a level within a few feet of the water surface level of the 2011 flood. Submerged bars built at higher flows may be emergent at lower flows.
- Geotechnical Process — Toe scour and sloughing processes (geotechnical failures) drive bar loss somewhat independently of sediment capacity. These processes are exacerbated by positive pore water pressure within the bar and can be significant during rapid flow drawdowns. Budhu and Gobin (1994) and Webb et al. (2000) hypothesized that the loss of cohesive soils to storage in upstream reservoirs has increased the susceptibility of Colorado River bars to

* Mechanical behavior of materials modeled as a continuous mass rather than as discrete particles.

† WEST Consultants. 2014. Unpublished. *Geomorphic Change Evaluation in Support of ESH*. Prepared for the US Army Corp of Engineers, Omaha District.

these *flanking* processes. This hypothesis is likely generalizable to other locations as well, where the loss of cohesive soils to storage in large reservoirs having high (nearly 100%) trap efficiency will likely increase vulnerability of downstream river bars.

- Local Hydraulics — Bars can build through a variety of processes; most are dependent upon local hydraulic conditions conducive to both erosion and, especially, deposition. Bar development has been shown to be associated with lateral separation zones and eddies (Logan et al. 2010), dune stacking at expansions (Lancaster 1992), and even marginal changes in shear or depth in adjacent areas. WEST Consultants[*] provides numerous examples.
- Ice and Wind — Aeolian (wind-driven) bar erosion can be significant on many western sand-bed rivers, and ice may *scalp* significant quantities of material from bars, particularly during breakup. The driving flow parameter in the conceptual model (Q) does not include these processes explicitly, but they are indirectly accounted for (in part) by the inverse relationship of Q with ambient area ($A_{t-1}$).
- Vegetation — Vegetation adds temporal complexity to bar processes and habitat quality. The present bar algorithm does not incorporate these effects. However, there are acknowledged feedback mechanisms between sediment deposition and vegetation establishment that could lead to predictive error if not explicitly accounted for.
- Anthropogenic Sandbar Construction and Management — ESH construction and vegetation clearing have been used as management practices on the Missouri River and can confound both mechanistic predictions of sandbar response and statistical models of ESH availability. The addition of sandbars, in the case of constructed ESH, or through clearing of existing vegetated sandbars creates anomalies that can skew parameterization of any empirical or semi-empirical model, not to mention their actual effect on hydraulic and sediment transport conditions for that reach.

Changes in sediment load, flow regime, and boundary conditions can disrupt the existing balance, resulting in a stream that undergoes rapid morphologic changes until equilibrium is restored.

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[*] WEST Consultants. 2014. Unpublished. *Geomorphic Change Evaluation in Support of ESH*. Prepared for the US Army Corp of Engineers, Omaha District.

The conceptual model outlined above and shown in Figure 2 was parameterized for three reaches of the Missouri River by fitting observed data to the hypothesized response*. The resultant ESH models were used to predict changes in sandbar habitat as a function of reservoir operations and served as a basis for evaluating alternative management strategies. Coupled with demographic models for piping plovers and least terns (the species of interest in that system), population estimates are made based upon the amount of ESH available during nesting and fledging seasons (May–August). Figure 3 is an example of the parameterized model for the reach of river below Gavins Point Dam, based on the following relationships:

$$A_t^* = A_t^* + \begin{cases} 0 & Q \le 22\text{k cfs} \\ -0.0076Q + 168 + .015(1300 - A_{t-1}^*) & 22\text{k} \le Q \le 35\text{k cfs} \\ (-0.0000046A_{t-1}^* + 0.02)Q + 0.171A_{t-1}^* - 810 & Q > 35\text{k cfs} \end{cases} \quad (2)$$

where $A^*_t$ is the computed ESH area above a reference plane at time t, Q is the mean monthly flow, and $A^*_{t-1}$ is the existing ambient ESH area at the previous time-step.

Comparable predictive models can be developed for other rivers, provided they exhibit the behavior represented by the hypothesized relationship described above (i.e., they “fit the conceptual model”). Model parameterization relies upon continuous discharge measurement as well as sandbar area measurements from surveys, satellite imagery or aerial photographs to determine a starting acreage. Measured ESH must be transformed to an equivalent amount relative to some reference plane or a baseline flow using a flow-area relation because sandbar area varies with stage. For the reach below Gavins Point in the Missouri River in the above example, the baseline condition is a reference plane defined by the water surface at a flow of 31,600 cfs†‡ (Figure 3).

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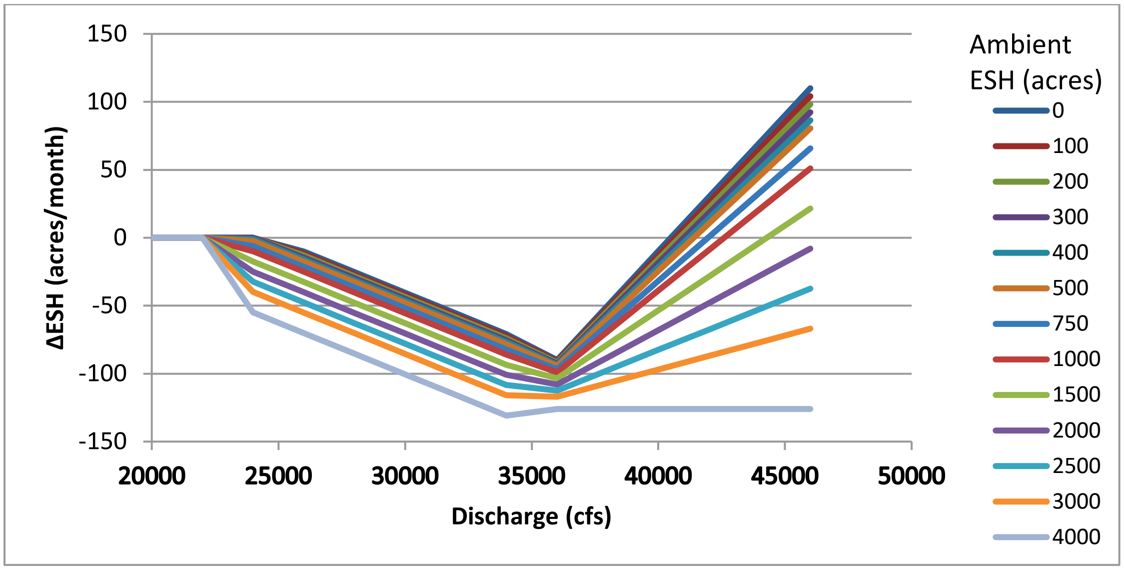
* Fischenich J., J. Tripe, D. Meier, D. Pridal, S. Givson, J. Hickey, and T. Econopouly. 2014. Unpublished. Models, Data and Literature to Support Habitat Analyses for the Missouri River Effects Analysis.” Vicksburg, MS: US Army Corps of Engineers.

† For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

‡ For a full list of the unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 345-7, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

Figure 3. Parameterized model of ESH for the reach of Missouri River downstream of Gavins Point Dam showing change in ESH (acres/month) as a function of discharge and ambient ESH acreage.



# 3 Planning for Bar/Island Creation

Rivers that once supported extensive sandbar, island, and floodplain habitat may no longer be capable of developing or maintaining that habitat because of changes in the hydrology, sediment yield, or channel condition. Historical conditions may be helpful in establishing impact or in making inferences about habitat needs but generally provides no basis for assessing a regulated channel's ability to support bars and islands under future conditions. Those assessments should be made based upon an understanding of sandbar dynamics under current and future processes.

Researchers have employed theoretical and empirical approaches to develop predictive algorithms for the occurrence and type of bar found in a particular river (Church 1992; Crosato and Mosselman 2009; Fujita 1989; Knighton and Nanson 1993; Tubino and Seminara 1990). These algorithms can be helpful in characterizing expected bar and island patterns given prevailing or predicted conditions. However, most of these approaches do not take into consideration the effects of vegetation, which can profoundly influence the development and fate of island and bar features.

Dean and Schmidt (2011) describe feedbacks across multiple scales leading to progressive channel narrowing in the Big Bend region of the lower Rio Grande. They show that frequent floods imposed negative feedback on extensive riparian vegetation growth prior to dam construction in the 1940s and helped to maintain a wide, sandy, multi-threaded river. Subsequent reductions in the peak and mean flows due to water extractions and regulation in the upper basin have led to channel narrowing via sediment transport and supply conditions described above. Coincident introduction of invasive exotics such as salt cedar (*Tamarix chinensis*) has created positive feedback on channel narrowing by promoting rapid vertical accretion of the floodplain.

Loheide and Booth (2011) describe the effects of incised and over-widened channel morphologies on riparian and floodplain vegetation with a feed-forward model that links geomorphic, hydrologic, and ecological responses. They show how the distribution of floodplain and riparian vegetation is highly contingent on the morphological channel state, which in turn controls groundwater and soil moisture patterns and species response. Their model can help anticipate feedbacks between the vegetative and geomorphic responses for a given set of conditions.

Most of the planning considerations for a bar/island creation project are the same as for any other water resources or ecosystem restoration project on a river. Some of the unique factors depend upon the approach chosen for the project. Chapters 3 and 4 of this report are organized around six basic strategies for bar and island creation:

- high flows from reservoir releases
- sediment bypasses or sluicing
- direct construction by placement of on-site or off-site aggregate material using dredges or other heavy equipment
- placing structures that promote sediment deposition
- manipulating the channel and floodplain
- managing vegetation on existing bar and island features.

Other approaches are possible, though less commonly applied, typically for logistical or cost reasons or due to highly localized conditions. Readers are encouraged to infer guidance based upon the aforementioned categories when applying these concepts to other strategies. Chapter 4 includes additional details on the last four methods in particular.

## 3.1 Ecological importance of floodplain connectivity

Active floodplains serve as nutrient and sediment sinks resulting in improved water quality in the stream. Healthy floodplains also attenuate flows and lessen the peak magnitude of floods, and water receding from floodplains often contains a substantial amount of food utilized by stream fishes. The availability of vegetated, low-velocity, inundated habitat can have important implications for fish reproduction, recruitment, and population viability. Many fish species require floodplain habitats for successful reproduction, and some utilize floodplains during all phases of their life cycles. Inundated floodplains provide spawning and nursery habitat for many fish species, including Rio Grande Silvery Minnow (*Hybognathus amarus*; silvery minnow) (Gonzalez et al. 2012, 2014; Pease et al. 2006; Medley and Shirley 2013). Water management (reservoir regulation) and drought have reduced the magnitude of the spring snowmelt hydrograph in some regions, decreasing inundation frequency and the associated connectivity between the river and the floodplain.

Establishing or enhancing floodplain function should be a priority objective when inundated areas provide important habitat for migrating or nesting waterfowl, endangered species, or culturally or economically important fish species that require floodplain wetlands to complete their life cycles. Floodplain habitat are also important for growth, production, or harvest of sport or commercial fishes. Hydrologically connected floodplains with functioning wetlands contribute to channel stability, potentially decreasing the rate of future channel incision.

In incised channels with reduced floodplain connectivity, instream shallow or periodically emergent habitats become even more important, with sandbars and islands providing important ecological functions for river ecosystems. They provide nesting and foraging habitat for birds (including listed species) and important shallow-water habitat for numerous species (e.g., Interior Least Tern in the Missouri River, silvery minnow in the Rio Grande, described in the following).

### 3.1.1 Species of concern

A variety of threatened or endangered species are affected by habitat loss due to reduced floodplain connectivity. Two examples are the silvery minnow and the Interior Least Tern. The silvery minnow was a formerly widespread endemic fish species, now restricted to 170 mi of the Rio Grande in New Mexico (USFWS 2010, 2017). Studies over the past 20 yr have focused on different perspectives of silvery minnow life history, with differing conclusions on preferred spawning habitat and mechanisms for transport of early life stages. The Southwestern Willow Flycatcher (*Empidonax traillii extimus),* listed as an endangered species in 1995, is an insectivore and feeds in the riparian zone. The Interior Least Tern (*Sterna antillarum athalasso)*, listed as an endangered species in 1985, is primarily a fish eater, feeding in shallow waters of rivers, streams, and lakes (Texas Parks and Wildlife Foundation 2017).

#### 3.1.2 Habitats of concern

Section 7(a)(2) of the Endangered Species Act (ESA) requires federal agencies, in consultation with the relevant Service, to "insure that any action authorized, funded, or carried out by such agency . . . is not likely to jeopardize the continued existence of any endangered species or threatened species or result in the destruction or adverse modification of [critical] habitat of such species." Section 7(a)(1) of the act directs all federal agencies "in consultation with and with the assistance of the Secretary, [to] utilize their authorities in furtherance of the purposes of [the ESA] by carrying out programs for the conservation of [species listed as endangered or threatened]."

Silvery Minnow, for example, prefers large streams with slow to moderate current flowing over a mud, gravel, or shifting sand-silt substrate. They typically occupy stream habitats where water depths are moderate, 0.2 to 0.8 m and with low velocity, 0 to 30 cm/s. During the winter, these fish are most commonly found in nearly still water with debris cover. During low flows, they are found in isolated pools and in reaches immediately down stream of diversion structures. Rio Grande Silvery Minnow has also been found in irrigation ditches and canals (USFWS 2017 and Cowley et al. 2007). Silvery Minnow spawning typically coincides with spring runoff peaks when water temperatures exceed 18°C to 24°C (Dudley and Platania 1997). The USFWS (2003b) notes “spring runoff peak flows that overbank the floodplain and create seasonally important larval habitat in May and June are strongly correlated with higher silvery minnow density as measured in the fall.” Thus, high spring flows and floodplain connectivity are important for primary needs for population recruitment.

Interior Least Terns use a variety of floodplain features during the nesting season (May – August). Nesting habitat includes bare or sparsely vegetated sand, shell, and gravel beaches, sandbars, islands, and salt flats associated with rivers and reservoirs. These birds prefer large areas of open habitat and tend to avoid thick vegetation and narrow beaches. Sand and gravel bars within a wide unobstructed river reach, or open flats along shorelines of lakes and reservoirs, provide favorable nesting habitat. Nesting locations are often at the higher elevations away from the water's edge since nesting season usually starts when river levels are high and relatively small amounts of sand are exposed (Texas Parks and Wildlife Foundation 2017).

## 3.2 Identifying objectives and constraints

USACE projects are objective driven and must comply with a number of different policies, including the National Environmental Protection Act. Clear articulation of goals and objectives allows iterative comparison of management outcomes against these objectives and adjustment of management actions or the objectives themselves based on learning over time. An effective strategy requires specific success metrics and a time horizon to guide and improve decision making that facilitates progress toward the goal. Modifications to objectives, actions, and decisions may be made at any time during the decision-making step based on information gained from implementation and monitoring (Williams et al. 2009).

Increasing the occurrence, distribution, or quality of river-based habitat in the form of emergent sandbars or islands may be an effective way of meeting some goals and could be a reasonable part of an objective set for project. A variety of alternatives exists for developing or altering these features/habitats, and specific approaches for evaluating the costs, benefits, and trade-offs tend to be project specific.

When setting objectives and considering alternatives, consideration should be given to the following (not inclusive) factors relating to sandbar and island habitat for species of concern.

- What type(s) of habitat is needed?
- What types of bars would provide that habitat?
- How much bar habitat is needed?
- Where should bars be located?
- Should bar features be static or dynamic, vegetated or unvegetated?
- What is the necessary hydrologic regime to build, maintain, or preserve bars?
- How can bar or island habitat be developed or constructed?
- What is the design life of each bar/island?
- How will ecological and geomorphic function be monitored and evaluated?
- Can the approach be adaptively managed?

## 3.3 Siting and design of sandbar and island features

Sandbars and islands occur in predictable locations on river systems. As depositional features, they are found at locations — reachwide or highly localized — where bed material is routinely in motion (providing a potential supply), bed material sediment load exceeds transport capacity at some set of flows (providing material that will deposit), and locations where sudden increase in sediment supply or sudden decrease in transport capacity or both creates the conditions for deposition (resulting in bar formation). Alternatively, sandbars and islands are typically absent from areas with consistently high sediment transport capacity, or with low sediment supply regardless of transport capacity (i.e., without adequate sediment loads in transport, bars will not be able to form).

### 3.3.1 Increased bed material sediment supply or load

Sandbars and islands are commonly found at or downstream from the confluence of tributaries that deliver large sediment loads or sediment of a larger caliber than that found in the bed material of the receiving river. They can also occur downstream of other sediment sources such as actively eroding banks or depositional features on the bed that scour during high flows. Alternating bars are located on the insides of bends (meander bends), across from actively eroding outer banks.

On rivers with high sediment loads, bars are likely to form immediately downstream from any obstruction (e.g., a snag or large woody debris [LWD] complex) that interrupts the flow field and induces deposition of sediment. Though islands and bars are more likely to be found in reaches prone to aggradation (i.e., with sediment supply that exceeds capacity), they can occur in degrading reaches as well. Bars may have more limited life in those circumstances or may scour out at high flow and redeposit during falling stage if sufficient sediment load is in transport.

### 3.3.2 Decreased sediment transport capacity

On river reaches with a uniform slope, a minimum channel width and or cross-sectional area can often be identified and used to define a threshold for bar formation. Below this threshold, sediment transport capacity (based on flow conditions and sediment size) is too high for bar or island formation. Conversely, bars often develop at flow expansions (increases in width or cross-sectional area) because transport capacity drops suddenly in those locales. Mid-channel bars typically form on exposed riffles or in crossings of large rivers. Bars or islands can also form where floodplains widen (e.g., where levee setbacks occur), even when the main channel is uniform. Reaches where channel avulsions or secondary channel formations occur are also candidates for bar development because of the corresponding decrease in transport capacity. Bar and island development may also occur due to changes in floodplain vegetation, which increases local or reach-wise roughness (see Section 4.3).

Another condition associated with sudden decrease in sediment transport capacity is a decrease in bed or water surface slope, most typically seen at the confluence of a steeper tributary with a gently sloped mainstem or at the bottom of a riffle where it enters a flatter pool. The decrease in energy slope at these locations decreases sediment transport capacity, and sediment deposition results. In the case of tributaries, this decrease in capacity is not sufficient to carry the mainstem sediment load or the additional sediment delivered by the tributary itself. Extensive bar complexes can develop downstream from confluences as a result.

#### 3.3.3 Siting considerations

Understanding where bars and islands are likely to form is a good starting point for project planning. It will help in predicting where bars are likely to form if high flows are to be used, where bars are likely to be sustained if vegetation management practices are used, and where to locate projects involving bar/island construction or deliberate promotion of bar formation. Several other factors also need to be considered, including biological needs, site access, constructability, material availability, etc. (see Section 3.4). Another important factor for planning is the recognition that bars and islands are typically dynamic features; they are seldom permanent, even over engineering timescales, and the dynamic processes that accompany and characterize them are often of ecological significance.

Configuration and placement of flow obstruction structures will influence project success. Higher (taller) structures indicate higher and longer associated sandbars but also require higher flows to accomplish this aim, as deposition typically ceases within approximately 12–18 in. of the water surface. Position and orientation in the flow affects the efficiency of the flow obstruction structure. In a Missouri River study*, angling dikes helped reduce potential for scour but also reduced potential sandbar area. Spacing multiple structures can promote sediment deposition, but spacing will also depend on the particular location of existing features. A series of dikes can be placed to capture flow and promote sediment deposition in the area between the dikes. WEST Consultants* recommended a minimum spacing of four times the effective length of the upstream structure to maximize sandbar area, but spacing will also be affected by the channel planform (i.e., greater spacing is possible on convex vs. concave banks and on bends with greater radius of curvature).

Existing features will be influenced by flow obstruction structures and should be considered during the planning process. Existing features can be

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eroded, enhanced, or otherwise altered depending on the position and makeup of the management structure. For example, Remus and Davinroy (2001) reported that a shallow water habitat associated with a shoal was moved by altering the placement of chevrons in a channel.

Locations to avoid attempting bar or island construction include places without sufficient sediment supply, such as immediately downstream from impoundments, heavily revetted banks, or channelized sections with heavy grade control. Reaches with consistently high transport capacity such as steep riffles, areas upstream from mobile headcuts, or heavily channelized sections even without grade control, should also be avoided when possible.

## 3.4 Materials, equipment, constructability, and other factors

The approach taken may depend upon a variety of factors as previously discussed. If flows can be used, assuming sufficient sediment supply, development of sandbars and islands may occur without further intervention, but there is greater uncertainty in the outcome. Flows can also be combined with other techniques to ensure that bars and islands that develop are consistent with objectives. For example, flows can be manipulated in conjunction with the placement of LWD in key locations and configurations to ensure that bars develop where intended and have the desired characteristics.

In a study of the Missouri River for the Omaha District of USACE, WEST Consultants[*] considered the suitability of 14 materials that can be used to create various best management practices (BMPs) or management measures for use in structures intended to promote sediment deposition and sandbar creation:

- riprap
- LWD
- wood piles
- timber cribs
- geotextile tubes
- biodegradable coir palisades
- sediment curtains
- hay or straw bales

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- sunken barges
- porcupines and jetty jacks
- concrete jacks and dolosse
- flexible armor with LWD
- screens and nets
- recycled tires.

WEST Consultants* screened the materials based on flow obstruction effectiveness, removal success, public safety, constructability, and a damage/risk assessment. Criteria included considerations such as the following:

- Was the material suitable for sandbar deposition?
- Has the material been used for a similar purpose?
- Was the material biodegradable or would structure removal be necessary?
- Were there public safety issues during construction or while the structure was deployed?
- Ease of construction.
- Durability and design life.
- Was the structure susceptible to damage by high flow, ice, or erosion damage due to scour or overtopping?

Eight materials were deemed unsuitable using these criteria: wood piles, timber cribs, riprap, porcupines, concrete jacks, flexible armor, screens/ nets, and recycled tires. Three more materials, geotextiles tubes, biodegradable coir palisades, and submerged barges, were rated average or below average and were also eliminated. Three materials, hay bales, LWD, and sediment curtains, were selected for feasibility and cost analysis. Hay bales were selected by the Omaha District for further analyses as part of a modeling exercise primarily because of the wide availability and low cost of rolled hay bales in the region and because the material was unlikely to cause long-term deleterious effects even if the structure failed. Details of the evaluation and results using two

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configurations (weirs and chevrons) and several spacing options can be found in the WEST Consultants* report.

Although initially screened out in the WEST Consultants* report, a number of the materials and techniques have been demonstrated to be effective in promoting sediment deposition and bar formation and might be considered viable alternatives in locations other than the Missouri River, depending on project objectives and constraints. Even on the Missouri River, for example, wood piles, timber cribs, and riprap are significantly the most commonly employed materials and techniques for river training and floodplain development. Wood piling and timber cribbing were utilized extensively in the initial rectification of the channel, while riprap groins of various configurations are utilized exclusively for current operations.

### 3.4.1 Riprap

Although it is often negatively viewed because of perceived environmental impacts, riprap remains one of the most versatile and cost-effective materials for use in riverine structures and can be effectively employed for sandbar and island creation and stabilization. Fischenich (2003) presented an assessment of riprap that demonstrates the perceived impacts are often unwarranted and provides an objective framework for evaluating its appropriateness and effects in any case-specific application. Drawbacks to the use of riprap (aside from cost and availability in some locations) tend to relate to its stability when used in sand-bed rivers, although the use of sound designs can overcome this concern.

### 3.4.2 Large woody debris (LWD)

When considering effectiveness, cost, and environmental factors, LWD may well be the best material for creating structures that promote bar and island formation. The National Large Wood Manual (USBR ERDC 2016) provides detailed guidance on assessment, planning, design, and maintenance of large wood in fluvial ecosystems, in addition to summarizing historical loading rates, ecological benefits, long-term considerations, and detailed engineering considerations. LWD provides a

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number of important ecological functions but has been substantially reduced in most large rivers by anthropogenic factors, often through a combination of reducing width or extent of riparian forests, which reduces source area, controlling morphology, or flooding, which reduces recruitment and active removal of accumulations of existing instream wood for safety, navigation, or other concerns.

Wood can influence channel morphology, fluvial processes, the storage of sediment and organic matter, and the evolution of depositional features like bars and islands. Many regulatory agencies advocate the reintroduction of large wood, and when employed as part of an engineered logjam (ELJ) or even small snag complexes, LWD can be used to create multi-objective sandbar and island features. Primary drawbacks of LWD include lack of available material in some locations, and concerns regarding potential infrastructure and safety considerations, and flooding or erosion impacts, all of which are addressed by USBR ERDC (2016) with specific reference to calculating risks and ensuring regulatory compliance.

Once larger issues of appropriateness of specific types of large wood assemblages in a system are addressed, legal and regulatory concerns are settled, and the ecological benefits weighed against other materials or approaches, engineering considerations including materials, access, constructability and required equipment become the driving factors in constructability of effective ELJs. Project objectives targeting species and habitats of concern, refined by asking questions such as those laid out in Section 3.2, can help the practitioner determine which type of configuration, the size and type of wood to use, and specific methods for anchoring in place, including the longevity of materials and the structure itself.

Some type of anchoring is typically required for an ELJ, as wood materials are generally mobile at some flow. With a focus on wildlife ecology and mimicking a natural setting to improve endangered species status, wood structures designed for bar and island building, enhancement, or preservation should naturally include the minimum of manufactured materials such as steel pile, cable, chain, or concrete, for a variety of reasons. Bar or island building requires the structure to be stable when bed material is moving, so adequate and appropriate levels of anchoring must be provided. If flow is heavily regulated (predictable or with low variability) and sediment supply is high and readily mobilized, less anchoring may be required for a reasonably stable structure to persist. Key logs, wood pilings, and rock materials can be effectively used to provide passive anchoring (weight, ballast or placement keeps the structure in place) for an ELJ, particularly if the structure is designed to be commonly emergent or withstand infrequent flow events and is in a relatively low-risk environment with little infrastructure downstream (USBR and ERDC 2016).

If the system or reach is sediment starved (e.g., downstream from a dam, below heavily channelized or revetted banks), flows are highly variable, or the bar or island feature must be more persistent (i.e., the feature is not designed to scour and fill repeatedly but to fill and generally grow or maintain its configuration and constituent sediment), then additional anchoring is required. To actively anchor an ELJ, additional materials are used to tie structures into bed or banks, and additional ballast can be used to weight structures down. Still, avoiding synthetic or manufactured materials is most desirable, though in some cases may be unavoidable. Careful consideration of the goals and objectives, specific setting, and desired outcomes will determine materials and methods.

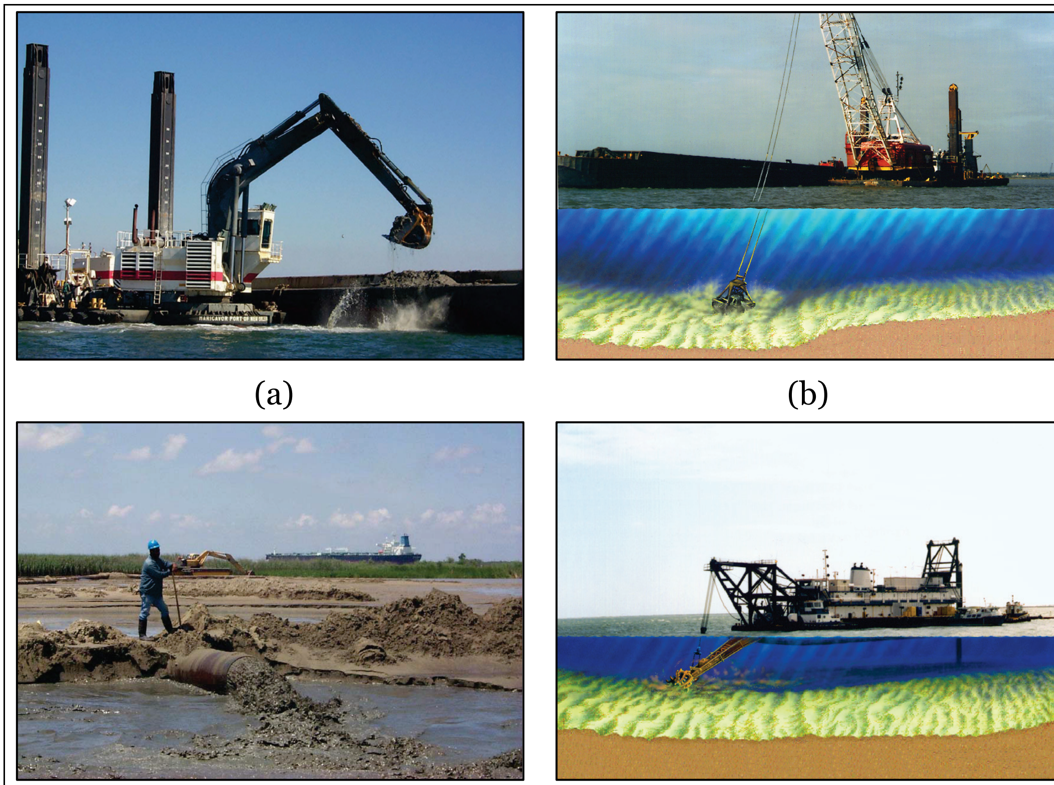
As for all construction approaches, good access and constructability can make or break a large wood-based construction project. Constructing ELJs requires collecting and stockpiling sections of large wood of the correct size, the right species for the setting (live, dead, highly degradable, persistent, etc.), and handled with specialized equipment capable of picking up, manipulating, and carefully placing individual pieces, such as an excavator with a thumb attachment (see Section 4.2.3 for additional detail on construction techniques). Site access is important as well, and with the need for excavators so equipped and the length and size of wood material required, particularly in large rivers, attached structures on the same working bank are much more straightforward to construct. Otherwise, equipment can be barged into the channel, and materials loaded or dragged with chains into place — wood materials are buoyant, so getting them into place is easier than for rock, but making them stay in place is more difficult.

### 3.4.3 Mechanical construction

The mechanical construction of sandbars and islands can be an appropriate technique in situations where material availability and constructability permit. In cases where bars and islands need to be constructed in very specific locations or to a specific dimension, mechanical construction offers the greatest degree of control. Principal types of equipment include hydraulic pipeline dredges (cutterhead, dustpan, plain suction, and sidecaster), hopper dredges, clamshell dredges, excavators (land and water based), and drag lines (Figure 4). Factors in the selection of mechanical construction (or dredging) equipment include the following:

- physical characteristics of sediments
- quantities to be dredged
- dredging depth
- distance to placement area
- physical environment of and between areas
- contamination level of sediments
- method of placement
- production required
- availability of dredges or other construction equipment.

Figure 4. Examples of equipment and operations for mechanical sandbar and island construction (a) barge-mounted excavator, (b) clamshell, (c) hydraulically dredged discharge point, and (d) hydraulic (cutteread) dredge.



(a) (b) (c) (d)

The size of the project (or more appropriately, required production rate) and the availability and accessibility of the equipment are usually the deciding factors, although other considerations can determine the outcome. The cutterhead dredge is the most widely used dredge in the United States and is capable of excavating most types of material and pumping it through pipelines to the desired disposal or placement site. Cutterhead dredges can operate on an almost continuous dredging cycle, resulting in maximum economy and efficiency. In situations when the head is not required, it can be removed and the dredge operated as a plain suction dredge. Production rates depend upon the size and horsepower of the pumps, but 150 to 500 $m^3$/hr are typical for medium-sized dredges (16–18 in., 520 hp). Portable cutterhead dredges are available; these require less draft and may be more applicable to smaller rivers. Larger cutterhead dredges are also available, capable of producing in excess of 1500 $m^3$/hr.

Cutterhead dredges are typically not self-propelled. They require mobilization with tow boats. Cutterhead and suction dredges can present operational challenges in rivers with medium and coarse sands that also have rapid currents. Holding the dredge in position while working upstream is difficult; the spuds often slip because of scouring of the surrounding sediments. Operating in a downstream direction is similarly challenging because the river currents tend to move the sediments away from the suction head.

The dustpan dredge is a hydraulic suction dredge that uses a widely flared dredging head that includes water jets to loosen and agitate sediments. These dredges were developed specifically for operation in rivers with beds consisting primarily of sand and gravel. They operate by making parallel passes from downstream to upstream, usually with the aid of winch cables attached to anchors or the banks. The cut depth is typically less than 1 m, and a dustpan dredge usually advances 150 to 300 m/hr. Production rates as high as 2300 $m^3$/hr are possible.

Dustpan dredges are self-propelled and can be moved rapidly over long distances to worksites. However, they are not particularly well suited for transporting dredge material long distances; pumping distances are limited to approximately a thousand feet without the use of a booster pump. Because it has no cutterhead, it cannot loosen hard, compacted materials.

Excavators, clamshells, and drag lines can be operated from the dredge to excavate material from one location and place it at another. All three can be operated from shore as well, but unless the excavation and placement sites are very close together, this is impractical for most bar and island construction projects. Compared to the dredges described above, even barge-operated heavy equipment can be impractical for bar and island creation because the material must be placed on the barge and moved to the placement site, requiring extra handling, fuel, and time. One advantage is that this equipment can remove rugged bottom materials such as clay, hardpacked sand, glacial till, stone, or riprap and can be used to pick up and reposition LWD found in the channel. They can also operate on relatively small rivers and in tight areas. However, it is difficult to retain soft, semi-suspended, fine-grained, and non-cohesive materials in the buckets of the equipment. Production rates are relatively low (15 – 75 $yd^3$/hr) when compared to hydraulic dredges.

Regardless of the technique used, mechanical construction requires consideration of the placement and stabilization of the material. Specifically, it must be determined whether the material can be placed within open water or requires confinement. Confined placement, typically achieved by constructing a dike that partially or fully encloses the desired bar or island, minimizes material loss, turbidity, and required fill material quantity per surface acre. When constructed of riprap or other hardened material, a confinement dike can also reduce subsequent erosion of the placed material. However, biological objectives may preclude the use of confinement dikes because they do not afford desired habitat characteristics.

### 3.4.4 Vegetation management

Whether sandbars are created by fluvial processes or mechanical means, all sandbars present opportunities for colonization by pioneering vegetation. Primary succession on sandbars in the Midwest and western United States by native vegetation is dominated by two trees in the willow family (*Salicaceae*) that rapidly colonize sandbars: various species of cottonwood and willow. These are often the pioneer species on a sandbar due to their similarity of seed propagation and their staggering fecundity (Karrenberg et al. 2002). Both species will root adventitiously and can withstand long periods of anaerobic respiration. In some locations, however, non-native species (e.g., *Tamarix* spp) may outcompete cottonwood and willow. All of the woody colonizers are effective at inducing local sediment deposition when flows inundate the plant canopy, leading to the vertical growth of bars and islands.

In the case of the Silvery Minnow, vegetated islands provide benefits for various life stages. If a vegetated island is preferential to the species of interest, then measures can be taken to promote vegetation, such as managing flows to promote seedling vitality, placing plantings, and controlling invasive vegetation to allow native vegetated stands. Conversely, some species require barren sandbars for nesting and foraging, which will require vegetation removal. When vegetation removal is employed to create barren sandbar or island habitat, the type and age of vegetation are primary considerations as to whether the removal can be achieved by herbicides or if mechanical removal will be necessary. Treatment strategies using herbicides tend to be more effective and less costly than mechanical removal but require that vegetation management occurs quickly after colonization. Wiley and Lott (2012) advocate for a tiered management strategy using (1) managed flows to limit seedling germination or cause young seedling mortality; (2) relatively simple and cost-effective methods for physically removing first-year recruits before the end of their first growing season; and (3) more costly methods for vegetation removal (that also require new sand deposition) to restore sandbar deposition zones once succession has advanced far enough for the simple physical removal methods in tier 2 to become infeasible.

Herbicidal treatments have been shown to be effective for herbaceous vegetation and for woody vegetation in its first year (or perhaps 2 yr) of growth (Barz et al. 2009). Grazing and/or burning may be an effective means of removing vegetation in some cases. Regardless of the technique employed, a subsequent flow capable of mobilizing the surface sediments may be required.

Plant control strategies should be compatible with project objectives, existing non-target flora and fauna, and regulatory requirements. There are 14 generic herbicide active ingredients registered for use in aquatic sites (i.e., for application directly to water) by the US Environmental Protection Agency, though state agencies may further limit application of some herbicides. Proximity to potable water sources or high recreational use areas may preclude the use of some chemical treatment methods. The timing and frequency of application need to be considered both from the standpoint of effectiveness and the avoidance of impacts. Most herbicides must be applied to actively growing plants to be effective, so control strategies are seasonal. Application periods may be further constrained by other environmental considerations ranging from lifecycle requirements of threatened or endangered species to daily weather patterns (heavy rain or high winds may preclude application).

Mowing followed by herbicide application or burning may be effective in managing vegetation beyond the first year of establishment or before vegetation becomes too high or too deeply rooted. In those circumstances, heavy equipment is likely required, and successful removal becomes less likely. At that point, goals may shift from removal to control to ensure that vegetation does not advance into new areas. When heavy vegetation is targeted for removal, two additional steps may be required to keep the site free from vegetation in the future (Wiley and Lott 2012). First, the removal should include the additional step of clearing all brush piles from the site. Second, a dredge should be used to completely cap the site with new sand, to regain sandbar elevation that may have been lost in the removal process so that any remaining propagules are buried too deeply to re-sprout.

# 4 Techniques for Bar and Island Development and Protection

## 4.1 Alternatives for developing and protecting bars and islands

As described in Chapter 3, there are six basic strategies for bar and island creation (restated below). Other techniques may also be effective, and combinations of techniques are often particularly effective. This report deals primarily with the following six strategies, placing a particular emphasis on 3 through 6, as they are more commonly applicable and practicable than the first two.

1. Use of high flows from reservoir releases
2. Use of sediment bypasses or sluicing
3. Direct construction by dredging or with other heavy equipment
4. Placement of structures that promote sediment deposition
5. Manipulation of the channel and floodplain
6. Management of vegetation on existing bar and island features.

To better organize and streamline this report, some management measures have been grouped into classes of activities that have similar considerations and effects. The various methods for bypassing sediments at reservoirs, for example, are grouped together and given only passing attention because they are typically impractical or too expensive to implement and are not likely to receive favorable consideration. Mechanical construction of sandbars can be accomplished with a variety of equipment and strategies (see also Section 3.4.3) but are treated herein in terms of either hydraulic or mechanical dredging and placement techniques.

The category of practices for which classification is most useful is in the myriad of structural techniques intended to promote sediment deposition by interrupting or obstructing flow. WEST Consultants* identified several structural measures with potential for promoting sediment deposition and creating bars or islands and divided them into four categories:

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- Spur Dikes, Groins, Wing Dams, Jetties
- Bendway Weirs, Stream Barbs, Bank Barbs
- Rock Vanes, Submerged Vanes
- Chevrons.

West Consultants* provides useful information when evaluating specific measures (and the materials that can be used to create them; see Section 3.4), but the authors feel their categorical organization is inappropriate because (1) it ignores several useful practices and (2) techniques with similar performance characteristics are not functionally grouped. Instead, the following taxonomy is used:

- Emergent structures connected to the bank
- Submerged structures connected to the bank
- Structures not connected to the banks
- ELJs and other LWD structures.

The distinction between emergent and submerged structures presents a challenge because emergent structures can become submerged under flood flow conditions and submerged structures can be exposed under low flow conditions. However, because their function is radically different under these conditions, and they are typically designed to perform *primarily* under one condition or the other, they are treated as such in this report.

## 4.2 Design and effectiveness of alternative management measures

In this section, the state of the practice and current understanding of the effectiveness of different management techniques, based on the six strategies described in the previous section, are discussed using the experience of the authors, case studies, and literature review results.

### 4.2.1 Flow and sediment management for the creation and maintenance of bars and islands

Section 2.4 of this report provides a conceptual approach for utilizing flows to create sandbar habitat downstream of reservoirs. The approach

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involves discharge flows exceeding an erosional and transport threshold for sufficient duration to (1) entrain sediments downstream in erosive areas and (2) deposit them in depositional areas, thus creating new sandbar habitat. A general model construct is presented that has been applied to the Missouri River and could, theoretically, be extended to other rivers provided there were data to parameterize the model. Section 2.4 notes model parameterization requires continuous discharge data and detailed starting sandbar area measurements. The purpose of the model is to help with planning and evaluating potential flow management alternatives so that the benefits, impacts, and various trade-offs can be considered in light of other alternatives for sandbar and island creation.

Managing annual flows for sandbar creation is challenging in most cases for the Middle Rio Grande; water is an important and highly regulated commodity, and high discharges necessary to create sandbars can reduce opportunities to use that water for other purposes with existing claims, including irrigation, power generation, and water supply. If not otherwise constrained, the greatest opportunity may involve *reshaping* flows, with releases designed in such a way as to lower reservoir pools to their normal multipurpose levels in anticipation of significant runoff. If the same volume of water can be evacuated from the reservoir at a higher discharge but for a lower duration, it may be possible to exceed the threshold for sandbar creation.

There are proven techniques to pass sediment through or around reservoirs, which can lead to the creation of bars and islands from the sediment supply side, but these are not practical in many situations because of the high cost. Kondolf et al. (2014) summarize approaches and experiences in managing reservoir sediments. Where geometry is favorable, it is often possible to bypass sediment around the reservoir, which reduces reservoir sedimentation and supplies sediment to downstream reaches with rates and timing similar to pre-dam conditions. Sluicing (or drawdown routing) permits sediment to be transported through the reservoir rapidly; however, it requires relatively large capacity outlets. Drawdown flushing involves scouring and re-suspending sediment deposited in the reservoir and transporting it downstream through low-level gates in the dam; it works best in narrow reservoirs with steep longitudinal gradients and with flow velocities maintained above the threshold to transport sediment. Turbidity currents can sometimes be vented through the dam, with the advantage that the reservoir need not be drawn down to pass sediment. Note that many of these sediment management techniques also require flow management to achieve sediment transport below the dam, incurring issues inherent to flow management alterations. However, combining sediment and flow management techniques can provide a bigger return on a costly investment by delivering the sediment supply that has been cut off at the reservoir with the flows capable of transporting it.

### 4.2.2 Techniques for constructing bar/island features

#### *4.2.2.1 General guidance*

Open-water placement techniques for riverine sediments are similar from one type of hydraulic dredge to another. Continuous pipeline placement with some type of baffle plate to diffuse discharge is standard practice. Mechanically dredged material may also be placed via barge. With either placement technique, efficient management of open-water placement sites requires the ability to predict and track the movement, or fate, of dredged material upon release. This ability is essential to (1) achieve the intended outcome in terms of bar size, composition, etc., (2) meet the environmental requirements for site selection and use (i.e., water quality standards and site size and capacity), and (3) determine operational constraints related to placement methods.

The short-term fate of dredged material refers to its effects as it descends through the water column and settles on the bottom in the near field (the vicinity of the placement area) within the minutes and hours following its release. Factors influencing dredged material behavior at open-water placement sites include the following:

- The physical characteristics of the dredged material, such as its particle size distribution and mineralogical composition.
- The nature of the placement operation, including the type of discharge vessel, discharge rate, and solids concentration of the slurry.
- The hydraulic environment in the vicinity of the placement site, including currents, waves, tide, and storms.
- Bottom sediment characteristics and topography (Johanson, Bowen, and Henry 1976; Barnard 1978).
- Water depth.

The great variability of these factors from site to site, as well as potential seasonal fluctuations, increases the difficulty of predicting open-water dredged material behavior.

Barge and pipeline are the typical placement methods of dredged material in open water when constructing sandbar and island features. Release to the receiving water is the only aspect of dredged material placement over which direct control can be exercised by conventional dredge operations. Once the material is released from the dredge, the mechanics of the transport phase is beyond manipulation by operators. The use of confinement structures and/or heavy equipment to reshape the placed sediments is common when it is necessary to ensure that the resultant bar or island meets design characteristics for habitat.

Pipeline dredges produce a slurry mixture of water and solids (sediment), with solids concentration ranging from a few grams to several hundred grams per liter. This slurry is transported by pipeline and discharged at the placement site in a relatively continuous stream. Placement from a cutterhead or other hydraulic pipeline dredge is continuous in that the placement site receives a constant flow of material until the pipeline discharge port is repositioned to another site, operations are interrupted (e.g., the swing anchors are repositioned or there is passing traffic), or dredging ceases. The behavior of pipeline-discharged material can vary because of its initial trajectory (horizontal vs. vertical) and whether it exits in the air or water. In addition, pipeline discharge ports may include a variety of baffle or deflector plates and cylindrical or conical diffusers, which can also affect the plume behavior (Teeter 2000).

Several predictive models listed in Table 1 were developed through the Dredged Material Research Program (DMRP) and the Dredging Research Program (DRP) (now combined into Dredging Operations and Environmental Research Program [DOER]) to address short-term fate factors of dredged material disposed in open water. These models are modules in the Automated Dredging and Disposal Alternatives Modeling System (ADDAMS) (Schroeder et al. 2004). ADDAMS is an interactive personal computer-based design and analysis system containing models to assist engineers, planners, and dredging operations managers in predicting the fate and behavior of dredged material. The general goal of ADDAMS is to provide state-of-the-art computer-based tools that will increase the accuracy, reliability, and cost effectiveness of dredged material management activities in a timely manner.

Depending upon project objectives and the desired characteristics of the sandbar or island, it may be desirable to utilize “confined placement” (i.e., placement of dredged material within diked areas). A confined disposal facility (CDF) is an engineered structure for containment of dredged material. These structures may be constructed at upland sites or nearshore sites with one or more sides in water (sometimes called *island containment areas*). If a confinement structure is desired or necessary, readers are encouraged to consult EM 1110–2–5025 *Dredging and Dredged Material Management* (USACE 2015) for additional guidance, as planning, design, and operation of CDFs require more detail than is appropriate for this report.

Table 1. Automated Dredging and Disposal Alternatives Modeling System (ADDAMS) modules related to dredged material placement.

| Model | Description | Application | Reference |
|---|---|---|---|
| CDFATE | Computation of mixing zone size or dilution for continuous discharges | Pipeline discharge | Chase* |
| STFATE | Short-term fate of dredged material disposed in open water for predicting deposition and water quality effects | Discrete discharge from barge or hopper | Johnson (1990) |
| MPFATE | Fate of dredged material from multiple placements in open water | Multiple discharges from barge or hopper | Hayter et al. (2012) |
| LTFATE | Estimates the movement of dredged material placement mounds over long periods of time | Any dredged material mound | Scheffner et al. (1995); Sheffner (1996) |

#### *4.2.2.2 Case study experience on the Missouri River*

The Omaha District of USACE has been constructing emergent sandbar habitat on the Missouri River since 2005. Projects are constructed under a programmatic environmental impact statement with a site-specific environmental assessment developed for each project. Sandbar construction sites are chosen by a multi-agency team utilizing a number of

* Chase, D. 1994. Unpublished. *CDFATE User’s Manual*. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

site-selection criteria. One of the main selection criteria is a site where a shallowly submerged sandbar already exists. There are wider areas in the river and/or areas out of the main river flow (thalweg) where sandbars naturally form (in the Gavins Point River Segment, for example, minimum width for sandbar formation is 2,300 ft). The ESH program capitalizes on these areas of natural accumulation of sand by raising these shallowly submerged sandbars to exposed elevations.

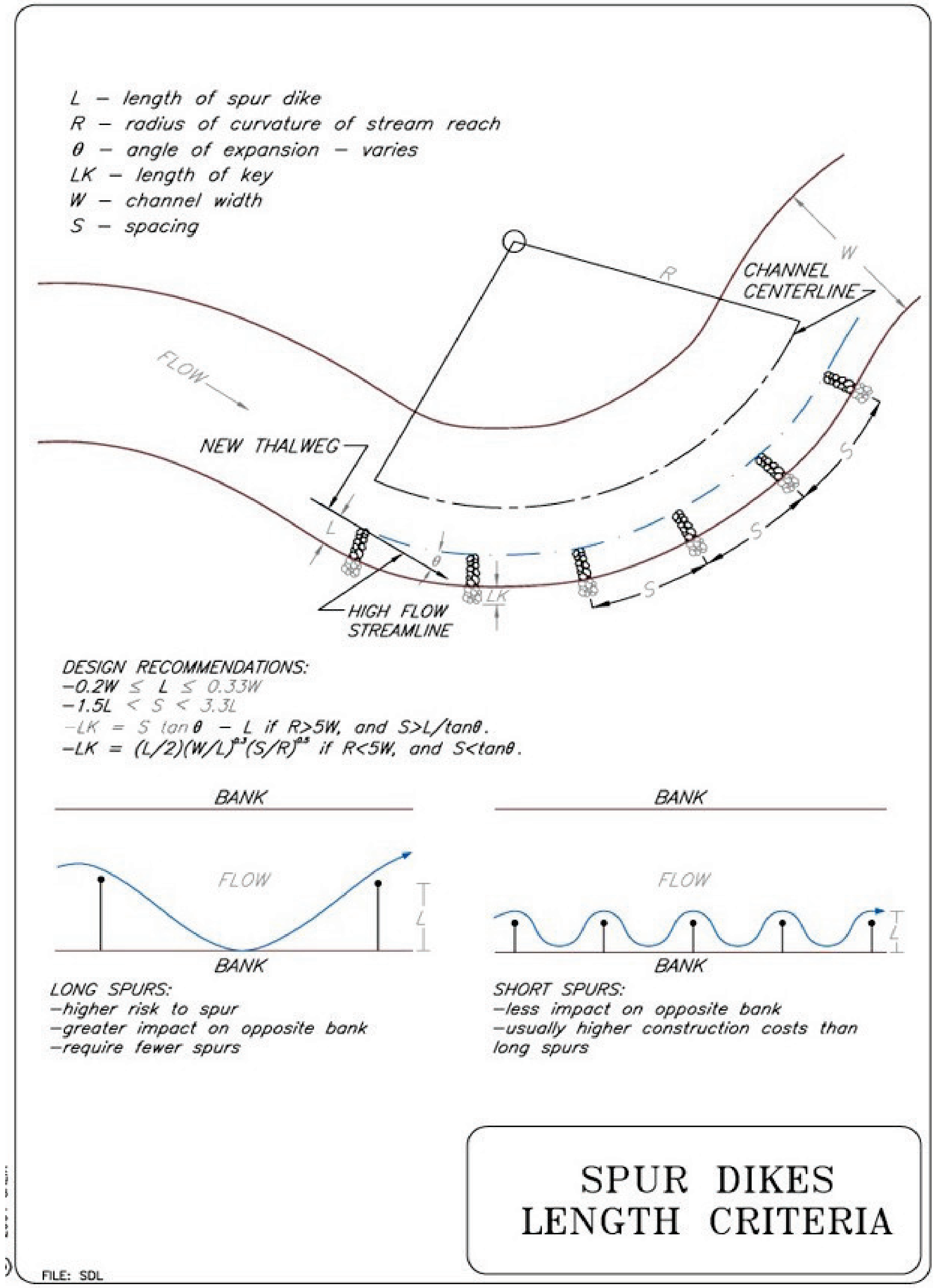
Complexes of multiple small sandbars with small channels between them are preferred over large, single sandbars in this setting because experience has shown that multiple small bars increase foraging (edge) habitat area and provide additional barriers to predators. USACE places restrictions on the depth of dredge cuts made during construction (4 ft or the elevation of the thalweg, whichever is less; this area is assumed to be part of the active bed). If kept within these criteria (working within the active bed), it is presumed that material would only be shifted within the same cross section and designed to remain below flood stages, helping to ensure that no localized change (no net impact) in hydraulic conveyance would occur from the proposed projects.

Methodologies used for construction of sandbars on the Missouri River vary by each project site location. The contractor is allowed some freedom to choose their preferred construction methodology. Various combinations of dredging and/or heavy equipment such as backhoes, draglines, bulldozers, and scrapers are utilized to construct the sandbar to specified contours and elevations. The construction season for ESH projects is short, as it is limited to the times of year when the least terns and piping plovers are not in the area and weather conditions are favorable.

In a system of this size, a 100 ft dredging/excavation buffer adjacent to existing bank lines is established to decrease erosion potential. In addition, a 75 ft buffer is established around the footprints of the constructed sandbars from which no borrow material is taken. This is intended to retain the designed slope of the constructed sandbar at the water's edge. Contractors are also provided the leeway to make all edges irregular, with variations of up to 50 ft landward and riverward of the edges shown in Figure 5 to produce the same effect.

Due to the dynamic nature of the river in this reach, it is sometimes necessary to field adjust sandbar design based on hydrology changes that have occurred between planning and construction of a project. To allow for this, USACE establishes a Maximum Placement Area zone for each project. Changes in the project footprint or layout are contained within this boundary.

Figure 5. Typical plan views of stone spur dikes (McCullah and Gray [2005]).



Temporary haul roads may be constructed to access fill material. Construction guidelines mandate that the roads be removed prior to completion of the project, returning the area(s) to preconstruction conditions. USACE also identifies areas for equipment staging and access and obtains real estate interests on those areas after having analyzed them for cultural resources, wetlands, and other sensitive resources. BMPs are required to avoid negative impacts, and all staging and access areas must be returned to their original state upon completion of construction activities.

### 4.2.3 Structural techniques promoting bar/island formation

One of the most effective approaches for creating sandbar habitat on medium- to large-sized rivers is to employ structure intended to interrupt the flow and create areas where bed material will deposit in the channel. Almost any type of flow obstruction can induce sediment deposition; however, structures need to be designed and placed deliberately to achieve specific outcomes, such as the formation of a bar or island of the desired composition, size, or elevation.

This section presents guidance and experiences relative to the use of structures to create depositional features that function as sandbars or islands. Structure types are organized categorically into functional groups as noted above, each of which has similar purpose and outcome relative to the functional need.

#### *4.2.3.1 Emergent structures that connect to the bank*

Emergent structures that connect to the bank include an array of structures often times referred to categorically as “flow deflection structures” and include spur dikes, groins, wing dams, and jetties, though there are a variety of other similar structures that go by different names (spur dike example shown in Figure 5). They are commonly constructed using graded stone (i.e., riprap), but they can be constructed using any material that will remain stable and in place under the range of anticipated flows.

Attached structures are usually constructed as a system of multiple structures that act together to increase bank and bed roughness, decreasing velocity and shear stress along the bank, and typically decreasing the active channel width, as the structures tend to extend above the water surface elevation (emergent) at all times but flood flows. Because the structures reduce flow velocities and increase roughness, they encourage sediment deposition in the area between the structures. Because these structures also reduce active channel width by occupying part of the cross section, they also tend to increase scour, especially near their streamward tips, and scour holes are likely to form in those locations. Additional scour and relocation of the thalweg to this area is typically not detrimental, as long as structures are sized, spaced, and footed into the bed properly (Figure 5).

The depositional patterns that occur between the structures depend upon a number of factors including structure height, porosity (depends on size distribution of constituent materials), angle relative to the bank, angle relative to the flow (see high flow stream line in Figure 5), top slope from bank to bed, strength of the secondary currents, etc. Depositional patterns can be further modified by notching the structures or by placing *reefs* of stone between the structures. Structures may be constructed to be effectively impermeable (e.g., rock groins), or permeable (e.g., wood pile dikes), and the resulting sediment deposition patterns will differ depending upon the degree of permeability.

In general, impermeable structures that extend above the water surface (i.e., emergent structures) will create velocity fields conducive to larger and higher depositional features. In all cases, however, impermeable groins will generate deeper scour holes at the toe of the structure (Kang et al. 2011; Teraguchi et al. 2008). The length of the zone of separation from the bank will be a function of permeability. An impermeable groin will have a separation zone approximately 8–12 times the structure length on a straight reach; at 40% permeability, the separation zone length will decrease to approximately 4–5 times the structure length (Kang et al. 2011). The strength of the circulation patterns will also be stronger downstream from structures with lower permeability.

Emergent structures are typically oriented perpendicular to the bank as a practical matter; this minimizes the amount of material required for construction to achieve the intended purpose. They can be angled up or downstream as well, but angling of the structures does not have the same effect as for submerged structures of similar design (i.e., they do not affect velocity vectors for overtopping flows). There are some subtle differences in that structures angled upstream may be slightly more effective in disrupting secondary currents while structures angled downstream are better at generating scour holes and have stronger recirculation.

The length of emergent flow deflection structures is usually defined as the projected length perpendicular to the flow direction, or how far into the channel cross section the structure extends, regardless of where it started on the bank. The optimal length of the structure depends on the objectives, channel geometry, and spacing between structures (Figure 5). Allowing for some scour at the tip of the structures, and to prevent adverse effects on water surface profiles, structure length should be limited to no more than 10% to 15% of the channel width and should not block more than 10% of the channel cross-sectional area (Fischenich and Allen 2000; WSAHP 2003).

Structure spacing depends upon objectives, structure length and shape, degree of permeability, and the channel radius of curvature. As described above, the distance downstream to the point where the separation zone fully reengages the bank is approximately 8 – 12 times projected length of the structure (often notated as 8-12L) on a straight reach with an impermeable groin and has been shown to range from 4L (inside bend) to 22L (outside bend) on meandering rivers (Sharma and Mohapatra 2012). For most river training works, spacing in the range of 3-5L is common — partly as a factor of safety and partly because the structures are never fully emergent. Overbank flows will overtop the structures, and vertical separation zones are much shorter.

If the intent is to promote sediment deposition and bar building, longer spacing — on the order of 4-6L in straight reaches and inside bends — is probably best as this sets up favorable circulatory patterns. With the wider spacing, both primary and secondary circulatory cells will typically be established. Sediment is transported from the main channel toward the groin field following the primary circulation cell, entering at the lower end of the cell and depositing from downstream to upstream (Yossef and de Vriend 2010). Spacing should generally be tighter on rivers with a relatively low ratio of radius of curvature ($R_c$) to top channel width (W), generally defined as $R_c/W < \sim 6$. Flow deflection structures should be avoided altogether on the outside of bends when $R_c/W < 3$ because flow separation will occur on the structure itself and favorable patterns for sediment deposition will not occur.

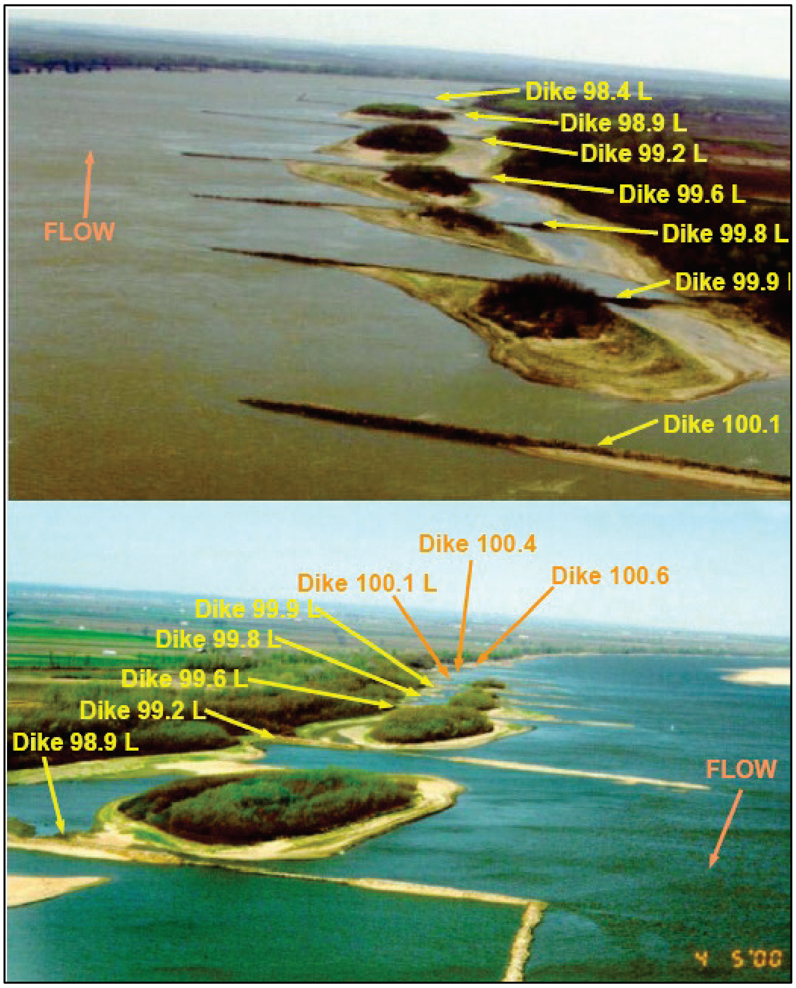
Dike field case examples

Sedimentation rates vary depending on age of the structure and location in the stream. Shields (1995) presented a report that detailed sedimentation associated with 26 dike fields on the Lower Mississippi River. Results indicated that dike fields experience a period of rapid sedimentation during the first few years after construction and eventually approach a state of dynamic equilibrium. When determining dyke field location, it is critical to determine the main purpose of the intended structure. Findings indicated that dike fields located on the inside of bends showed the most rapid rates of sedimentation while dike fields built for thalweg management actually showed signs of erosion. Rajaratnam and Nwachukwu (1983) reported that sediment deposition behind dikes is likely due to reduced velocities in this area. USACE* reported a positive correlation between dike construction and an increase in height or size of associated sandbars on the Lower and Middle Mississippi River. USACE* reported the greatest increase in sandbar habitat was near dike systems located on point bars or the outside of bends, but the habitat increase was not as significant in straight reaches.

The configurations of the dike fields affect the performance of the structures. Smith et al. (2001) modeled 15 design alternatives for a dike field consisting of five dikes to examine sediment transport (Figure 6). Three of the alternatives were able to provide a self-maintaining side channel, create a high elevation island area, and increase the depth of the navigation channel. The modeling results were then successfully applied to a dike field in the Middle Mississippi River. Yossef and Vriend (2010) studied emerged and submerged dikes and focused on sediment exchange and sediment transport patterns. For emergent dikes, the majority of sediment deposition took place at the downstream part of the area between structures. Sediment deposition took place across the entire area between structures if the dikes were submerged. Yossef and Vriend (2010) indicated that a net import of sediments into the dike fields was realized under all flow conditions.

* USACE (US Army Corps of Engineers). 1999. Unpublished. *Biological Assessment of Interior Population of the Least Tern, Regulating Works Project, Upper Mississippi River and Mississippi River and Tributaries Project, Channel Improvement Feature, Lower Mississippi River*. Vicksburg, MS: US Army Corps of Engineers, Mississippi Valley Division/Mississippi River Commission.

Figure 6. Dike field and islands on Middle Mississippi River (Smith 2001).




## Other measures

Other management measures may be preferable to spur dike construction, depending on the overall goal of the project. Teal and Remus (2001) analyzed sedimentation patterns at the confluence of the Bad and Missouri Rivers. They reported that lowering the reservoir pool water surface elevation is more effective for reducing sediment deposition in the reservoir compared to installing spur dikes in the headwaters. USACE* reported significant sedimentation in some areas, but the system-wide net effect on bare sandbar habitat due to dike construction was minimal. The

* USACE (US Army Corps of Engineers). 1999. *Biological Assessment of Interior Population of the Least Tern, Regulating Works Project, Upper Mississippi River and Mississippi River and Tributaries Project, Channel Improvement Feature, Lower Mississippi River*. Vicksburg, MS: US Army Corps of Engineers, Mississippi Valley Division/Mississippi River Commission.

entire project area and overall project goals should be considered before deciding on a management plan.

*4.2.3.2 Submerged structures that connect to the bank*

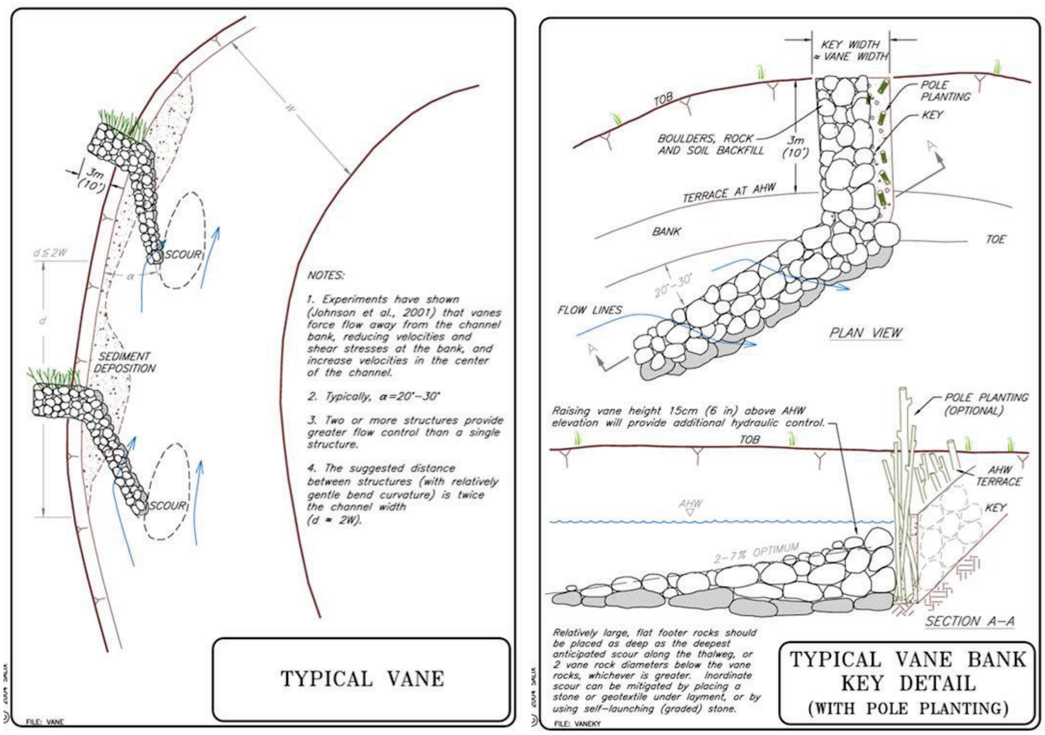
A variety of different structures are commonly used in bank stabilization, river restoration, and river rectification projects that perform a similar function to groins but that are deliberately designed to be overtopped frequently (Makar and AuBuchon 2012). The structures include vanes, bendway weirs, stream barbs, and bank barbs as well as a variety of other structures that have slightly different features or simply different names (e.g., J-hook vanes or rock vanes). Like groins, these structures increase roughness, dissipate energy, reduce velocity and shear stress near the bank, and alter velocity fields, scour, and deposition patterns in a channel reach.

Unlike groins and other emergent deflection structures, vanes and barbs are often constructed singularly and are intended to have a lesser effect on the cross-sectional shape (and hence, stage, velocity, and sedimentation) of the channel. Additionally, structure height, crest slope, spacing and angle relative to the bank and flow direction become more important design parameters because these are adjusted to manipulate the structure's effects on the flow field (Fischenich and Allen 2000; McCullah and Gray 2005). Because flows overtopping vane structures tend to be reoriented normal to the structure itself, submerged deflection structures are frequently designed to orient the velocity vectors either into or away from areas of interest (e.g., to relocate the thalweg or create a controlled scour hole or to reduce bank erosion). The strength of this effect depends on the depth of flow relative to the structure height. On a sloping structure, only a segment of the submerged portion of the structure has this effect, but the effect occurs on different parts of the structure across a wide range flows (i.e., river stages).

<u>Partially submerged vanes</u>

Rock vanes are gradually sloped from the bank downward into the bed, and the stream-ward ends are submerged at all flow levels (typically keyed into the bed at the anticipated thalweg location). Rock vanes are frequently angled upstream to redirect high-velocity flow away from the bank and toward the center of the channel (Figure 7). These structures can promote sediment deposition near the bank upstream and downstream of the structure, but upstream deposition is usually limited and seldom emergent. While the structures are most commonly oriented upstream, they can be effective perpendicular to the bank as well as angled downstream. The appropriate angle for the structure depends upon the site conditions and the objectives. Note that the porous rock vane structures commonly employed in restoration and stabilization projects on small to medium-sized gravel or cobble bed streams are not suited to sandbar and island formation. Those structures are deliberately designed to minimize bank erosion, limit bed material deposition, and enhance or control bed scour.

Figure 7. Illustrations of typical rock vanes (McCullah and Gray [2005]).




Sediment deposition usually occurs in former scour holes adjacent to the toe of the bank in a meandering stream, unlike spur dikes that induce deposition behind each structure (Bhuiyan et al. 2009). For multiple vanes, the amount of sediment deposition is greater in the former scour holes at the toe of the bank and extends further downstream due to scouring off the stream-ward ends of the rock vanes. Johnson et al. (2001) reported that rock vanes were very effective in preventing scour at a single span bridge. The vanes created low-velocity conditions at the bank face (even during flood flows), which promoted sediment deposition at the base of the bank while the faster, overtopping flow was directed into mid-channel. More than one vane is required to generate an outer bank secondary flow cell around an eroding meander bend.

Bank connected submerged vanes

Submerged vanes are similar to rock vanes and also redirect flow patterns away from the bank to reduce bank erosion, but they are commonly used for sediment control near diversions or water intakes. A submerged vane will typically enhance sediment deposition at the immediate frontal zone of the vane and bed scouring around the vane (Tan et al. 2005). They generate local roughness that alters the secondary circulation in the flow, changing the distribution of velocity, depth, and sediment transport in the region surrounding the vanes. They are not likely to generate sufficient sediment deposition to create emergent sandbars on their own, but when used in combination with other techniques, they can enhance bar formation.

Several factors should be considered when planning and designing vanes, including material availability, access, placement, geometry, constructability, etc. Submerged vanes can be constructed from a variety of materials including concrete, wood, rock, or sheet piles and are commonly placed in vane fields similar to spur dikes[*]. Vane alignment to the approach flow and dimensions of the vane will affect the effectiveness of the structure for energy dissipation, deposition, and scour. Results from Tan et al. (2005) indicated that the optimum skew angle to the approach flow for sediment diversion was 30°, and the optimum maximum vane height is two to three times the bedform height. Typical vane design factors are outlined by the Iowa Department of Natural Resources (IDNR 2006). Vanes, like groins, should generally be keyed into the bank to avoid flanking. The length of the key should be a minimum of 10 ft or 1.5 times the bank height, whichever is greater, and may be further increased if the radius of meander curvature is small, for highly erosive banks, and if it is the farthest upstream structure of the project site.

Bendway weirs

Bendway weirs are low-level, flat-crested, submerged sills that are placed in a bend on a river to redirect surface flow away from the outside bank. Bendway weirs intercept and displace secondary cells near the bed and

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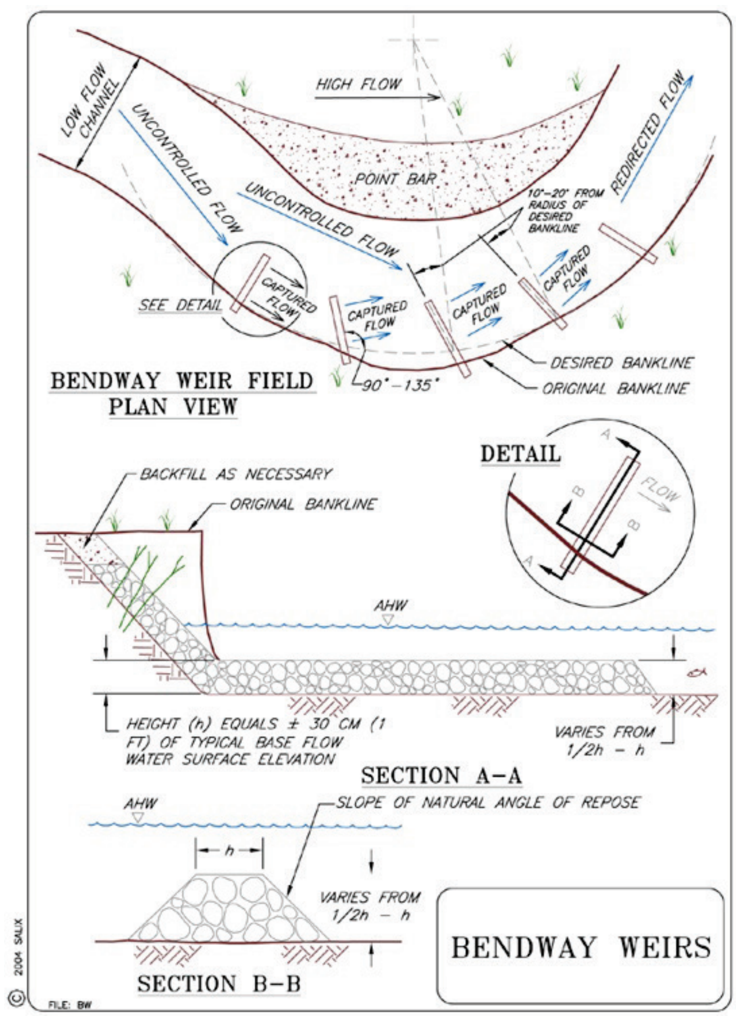
[*] WEST Consultants. 2012. Unpublished. *Missouri River from Gavins Point Dam to Ponca (RM 811 to 752) Evaluation of Flow Obstructions to Create Sandbar Habitat, Final Report*. Prepared for US Army Corps of Engineers, Omaha District.

redirect overtopping flows perpendicular to the weir (Figure 8) (Makar and AuBuchon 2012). They do not deflect flows in the same way as emergent structures or sloping vanes.

Bendway weirs were initially designed to normalize the velocity distribution and improve navigation sailing lines on bends in the Middle Mississippi River. The first system was installed in 1990 on the Middle Mississippi River upstream of the confluence with the Ohio River. They have subsequently been utilized in in a wide variety of settings for bank stabilization purposes, and variants have been employed on some aquatic ecosystem restoration projects. Although a systematic design procedure was offered in the second edition of HEC-23 (USDOT 2009), which appeared in 2001, the merits of the bendway weir for bank protection remain controversial (Lyn and Cunningham 2010).

Figure 8. Typical plan view and section of a bendway weir (McCullah and Gray [2005]).



The configuration identified to solve the problems within the Middle Mississippi River study reach was a series of level-crested bendway weirs spaced 700 ft apart, angled 30° upstream, with a crest elevation 15 ft below the low water reference plane. Table 2 summarizes relevant design guidance for general applications.

**Table 2. Design guidelines for bendway weirs from selected literature.**

| Source | Weir Length, L | | Weir Height, H | | Weir Top Width, $T_w$ | | Weir Spacing, S | | Angle from Upstream Bank, θ | | Transverse Slope | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Min | Max | Min | Max | Min | Max | Min | Max | Min | Max | Crest | Transition |
| McCullah and Gray (2005[a]) | W/3 | W/2 | W/2 | W | $2D_{100}$ | $3D_{100}$ | 1.5L | 1.5L | 80 | 70 | Flat | Flat |
| USDOT (2009[b]) | W/10[c] | W/3[c] | 0.3D[d] | 0.5D[d] | $2D_{100}$ | $3D_{100}$ | 4L | 5L | 60 | 85 | Flat | 1V:5H |
| Julien and Duncan (2003) | Longer is better | | Max permitting navigation | | None | None | 2L | 3L | 60 | 60 | None | None |
| NOTE: W = top channel width; D = mean annual high water depth; $D_{100}$ = diameter of the largest stone used in the structure | | | | | | | | | | | | |

[a]NCHRP Report 544.
[b]Hydraulic Engineering Circular (HEC) No. 23.
[c]HEC-23 further recommends structure length to cross the stream thalweg.
[d]HEC-23 further recommends structure height fall between annual mean flow and annual low flow water surface elevations.

Flow accelerates over the top of the weirs and decelerates between the weirs, often causing sedimentation between weirs (Julien and Duncan 2003; Papanicolaou and Elhakeen 2007) and behind the most upstream weir (Waterway Simulation Technology, Inc. 2002). Bendway weirs can promote sediment deposition in the area between the weirs because they reduce the magnitude of secondary flows in channel bends, reduce local velocities, and create general roughness (and energy loss) at most flows. Bendway weirs are most effective at reducing flow velocities during low flow* (Abad et al. 2008; Julien and Duncan 2003). During medium-flow stage conditions, the velocity between weirs is higher, and the channel may shift back towards the outer bank during high flows (Abad et al. 2008; Julien and Duncan 2003). Since bendway weirs are submerged during typical flows and deposition occurring below the normal water surface

* WEST Consultants. 2012. Unpublished. *Missouri River from Gavins Point Dam to Ponca (RM 811 to 752) Evaluation of Flow Obstructions to Create Sandbar Habitat, Final Report*. Prepared for US Army Corps of Engineers, Omaha District.

may only be exposed at the lowest stages, they are not particularly effective for emergent sandbar development because deposition is usually subaerial.

Bendway weirs case study

Papanicolaou and Elhakeem (2007) studied the performance of bendway weirs on the Raccoon River near Adel, IA. Nine bendway weirs, ranging from 45 to 90 ft in length, were spaced an average of two times the length and oriented perpendicular to the bank. The weirs were sloped from the streambed at the nose up to the bank height at the bank. Model and field results indicated that the weirs significantly reduced the flow velocities along the bank and between the weirs, allowing sediment deposition.

#### *4.2.3.3 Structures not connected to the banks*

Theoretically, any structure that creates an obstruction can be effective at initiating the development of a mid-channel sandbar. Three structure classes are particularly suited to this use: Chevrons and submerged vanes and ELJs and other woody debris structures, which are discussed in Section 4.2.3.4.

Submerged vanes

In their most well-known variation, the Iowa vanes, these structures are short, vertical, flat-topped, plate-like structures, anchored directly into the streambed rather than being keyed to the protected bank. Iowa vanes are a patented technique marketed by River Engineering International, Inc., Iowa City, IA. The structures are a foil-like device that function by dissipating or moving the secondary currents in a bendway (meander bend). They were first used in 1985 on the East Nishnabotna River near Red Oak, IA (Figure 9). Similar structures, known as palisades, were developed for application on the Sacramento River in California. These structures also function by disrupting secondary currents but use a geotextile suspended between two posts and a set of floats so the structure always remains just below the water surface.

Figure 9. Installation of concrete Iowa vanes at low flow.

Typically deployed in a regular multi-vane array in the vicinity of the protected bank, each vane induces its own secondary circulation, which together act to disrupt the larger-scale secondary current or helical flow associated with the bend. Their action can be rather subtle, and successful application may require more expertise in design and implementation than other countermeasures. Greater uncertainty and variability in field conditions may also limit their range of applicability. Odgaard (2008) reviewed the theoretical basis behind submerged vanes and discussed results of laboratory and field studies.

These structures have been used to achieve multiple objectives. Because they decrease secondary circulation flow in the cross section, secondary sediment transport is disrupted, which redistributes flow and sediment transport within a cross section. As a result, river bed aggradation may occur in portions of the cross section. However, the magnitude of deposition is usually minor, and it is unlikely these structures would be effective when used alone for creating sandbars. Depending on the circumstances, they may be useful when employed as part of a set of management measures constructed off the banks in the main channel and aimed at sandbar formation with bank protection.

Chevrons

These structures have been used to promote sediment deposition and to improve navigation. Chevrons are flat-topped rock structures placed in the middle of a river to improve the navigation channel. A chevron can be either sharp nosed (two angled rock dikes in a V shape) or blunt nosed (one U-shaped dike), installed nose-end upstream, and is designed to divert flow around the structure to deepen the channel (Figure 10). A scour hole is typically formed immediately downstream of the structure apex with the low velocity zone farther downstream where significant sediment deposition can occur. One advantage of the blunt-nosed chevron is that scour at the nose is greatly reduced compared to the sharp-nosed design. The primary purpose for chevron structures is to redirect flow for the improvement of navigation channels and help maintain sandbars and islands.

Chevron case examples

The majority of chevrons constructed on the Missouri River were designed to capture sediment to build sandbars (Remus and Davinroy 2001). Remus and Davinroy (2001) presented the results of a project designed to move a shoal from the direct sailing line to the opposite side of the river while maintaining the navigation channel. Three sharp-nose stone chevrons were placed between four existing dikes on the descending right bank of the river. The crown elevation of the upstream-most dike was set at the construction reference plane, and the second and third dikes were set 1 and 2 ft below, respectively. The wing angles of the chevrons were set at 60° from the primary flow direction, and the wing length was 75 ft.

Deposition increased considerably downstream of each structure. Survey data indicated that the sandbars created by each chevron stretched 30% to 50% of the length between the dikes and that higher elevation chevrons resulted in higher and longer associated sandbars. The overall results also show that the shallow water habitat associated with the shoal was successfully moved to the right side of the channel by the use of chevrons[*].

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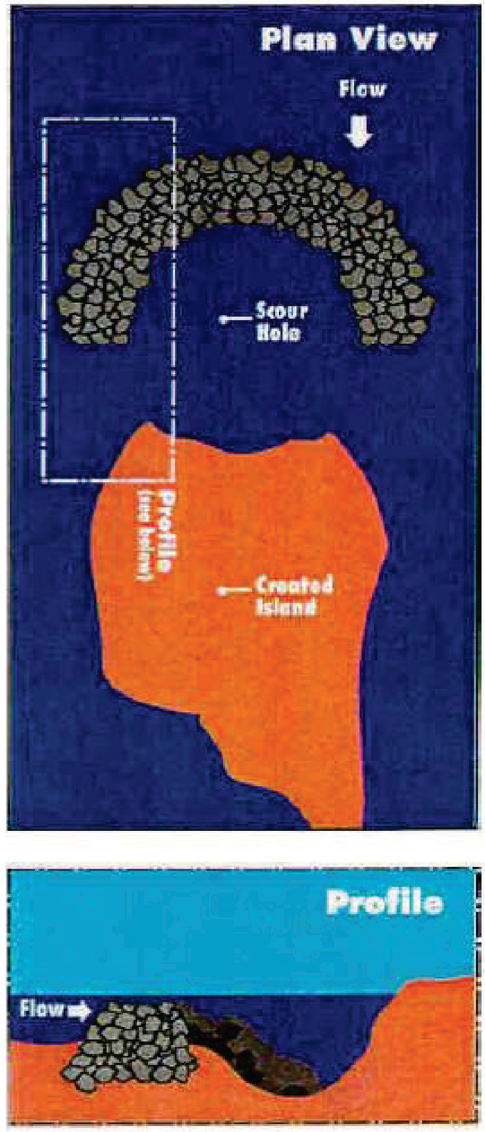
[*] WEST Consultants. 2012. Unpublished. *Missouri River from Gavins Point Dam to Ponca (RM 811 to 752) Evaluation of Flow Obstructions to Create Sandbar Habitat, Final Report*. Prepared for US Army Corps of Engineers, Omaha District.

Figure 10. Typical blunt-nose chevron installation (USACE 2008).



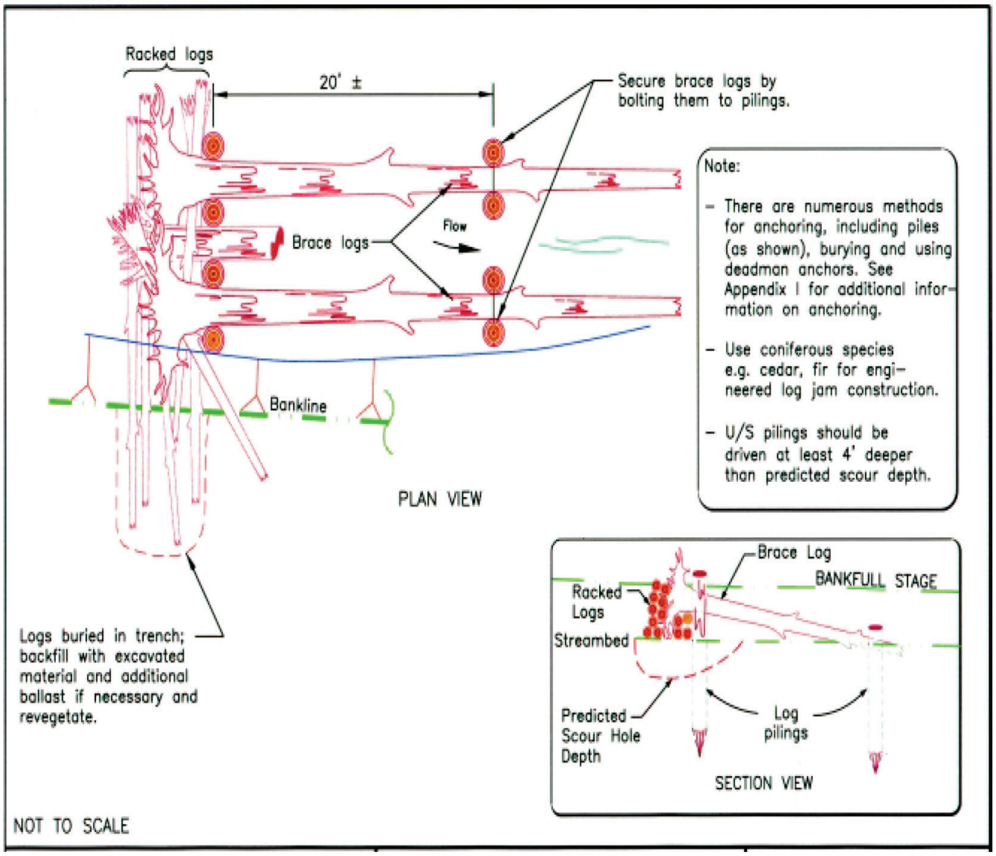

Davinroy et al. (1996) presented a design that placed chevrons upstream to reduce side channel flow and increase the conveyance in the main navigation channel. Blunt-nose chevrons were used to reduce the scour on the upstream head of the structure and increase downstream sediment deposition. The optimum design parameters included a height of 2 ft, crown width of 6 ft, side slopes of 1.5H:1V, a linear centerline length of 1,000 ft, and oriented directly into the flow. Davinroy et al. (1996) indicated that the sedimentation was a lasting benefit to the Mississippi River, as dredged material pumped into the area 3 yr earlier was still in the shadow boundary.

Low velocities created in the wake of a chevron can promote significant sediment deposition and the formation of small islands. Crawford et al. (2003) developed a design to create island nesting habitat for the Interior Least Tern in the Arkansas River. The design that provided proper scour conditions and deposition areas included a straight riprap structure upstream and a V-shaped chevron downstream (Crawford et al. 2003). The chevrons redirected the flow to promote sediment deposition that created an island within the center of the channel. Pridal (2010) reported on chevron construction on the Missouri River designed to create shallow water habitat. The design used two angled (sharp-nosed) dikes in the middle of the channel to direct flow around the structure and promote sediment deposition downstream. Scour occurred immediately downstream of the structure followed by a depositional zone farther downstream in the shadow.

#### *4.2.3.4 Engineered logjams (ELJs) and other LWD structures*

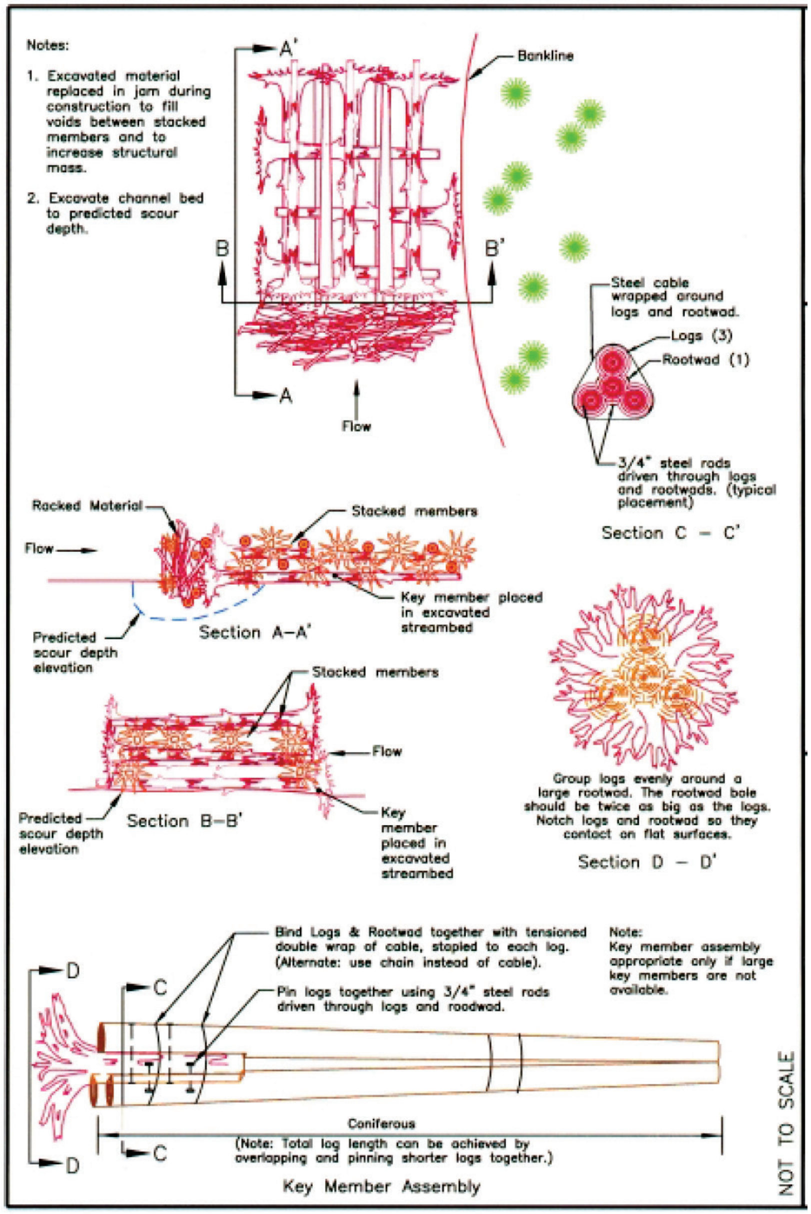
ELJs are collections of LWD placed to realign a channel or redirect flow away from a streambank needing protection from erosional forces. Because ELJs increase channel roughness and reduce flow velocities in the wake zone, they can be effective at promoting sediment deposition. They are typically patterned after stable, natural logjams and can be either unanchored or anchored in place using pilings, stone, fill, or manmade materials and most often have an emergent element to reduce boating safety concerns (Figure 11). They usually consist of one or several key members, typically large trees with root wads attached, that stabilize and anchor other woody debris that is *racked* against the key members. Other woody debris structures utilizing clusters of trees or woody debris, and even single trees, can be used effectively to induce sediment deposition and initiate bar formation. ELJs and LWD structures often have the added benefits of providing stabilization while affording beneficial aquatic habitat and substrate for aquatic organisms.

Figure 11. Schematic of an anchored engineered log jam (WSAHP 2003).




ELJs and LWD structures are particularly effective in aggrading channel reaches and on rivers that carry significant bed material loads (see discussion below). They can also recruit floating, large (or small) woody debris, which serves to replenish the structure and allow it to evolve. Depending upon the size of the structure relative to the channel, ELJs can induce localized scour, so when the aim is sandbar development, relatively minimalistic structures are required. When placed mid-river, the resulting split flow can cause some localized bank erosion, which tends to promote bar growth downstream. Depending upon how the structures are designed, keyed into the bed, anchored (or unanchored), and racked, they may be relatively deformable and able to adjust to the channel as it evolves, creating sustainable structures consistent with project goals and objectives (Figure 12).

Figure 12. Schematic of an unanchored engineered log jam (WSAHP 2003).




<u>Design, siting, and installation considerations</u>

Candidate sites for woody debris structures include those areas already exhibiting a propensity for sediment deposition (see Section 3.3). For example, placement of an ELJ or even a single large tree with a root wad at the head end of a shallow bar can lead to rapid aggradation and building of that bar. Candidate sites should also display low large wood loading relative to reference conditions, but large wood should be a natural component of the geomorphic landscape (USBR and ERDC 2016). Because most tree species produce wood that decays within a few years unless it is continuously submerged, large wood structures are generally not suited for long-term stabilization unless the wood is of a species exhibiting high durability under wetting and drying conditions (e.g., cedar, black locust, cypress, juniper, and mesquite). Alternatively, structures can be designed to be *sacrificial* insofar as they are required to persist only long enough so that the desired sedimentation sequence is initiated, if the depositional feature is expected to be self-sustaining, otherwise maintained, or if a temporary feature is consistent with project goals and objectives. Decaying material can also be periodically replaced as part of operation and maintenance activities.

When utilized for sandbar formation, large wood structures should be designed for those conditions when significant sediment transport is occurring and bar formation is expected. This typically means higher flows, on the order of bankful flow (~1.5–2 yr return interval). Hydraulic analyses will indicate the types of forces that can be expected (both drag and buoyant) that in turn will help with assessment of needed anchoring. The recently produced National Manual on Large Wood provides guidance on the calculations necessary to determine the forces on a structure and to determine the corresponding anchoring requirements (USBR and USACE 2016). When considering anchoring strategies, the use of burial or ballast (gravel or cobble fill) is generally preferred over cables and anchors (Fischenich and Morrow 2000). Driven piles should be the preferred approach if significant anchorage beyond ballast anchoring is necessary and feasible.

Natural buoyancy of wood materials can be a problem if the log needs to be completely submerged below the water surface. For this reason, construction during low water periods is preferable, and dewatering of the site during construction may be necessary. The use of walking excavators, winches, and even hand labor may be required for installation. A pile driver may be required if large members must be driven into the substrate. An excavator equipped with a bucket and hydraulic thumb is typically used to move logs but has limited capabilities to rotate and position logs. An excavator with a rotating grapple or log shovel may be preferred for larger projects. Contractors can equip an excavator with a detachable heel rack or rotating grapple or simply attach a set of log tongs, via heavy chain, to the back of the excavator bucket. If constructing a mid-channel structure, installation is much easier if it is possible to work from a floating barge (see Section 3.4.3).

### 4.2.4 Techniques that reduce erosion of bars and islands

Several of the management structures previously described reduce erosion and as long as they persist, will likely reduce erosion on the bars and islands they form. Spur dikes and similar structures are most noted for the reduction of bank erosion because of their proximity to the channel bank, and effectively stabilize the depositional features between the structures due to their relatively long design life. Parr et al. (2008) presented a study that used spur dikes to control erosion to protect highway infrastructure. Results indicated that the area between the spur dikes had filled in with sediment, and vegetation had been established, stabilizing the area at three of the four sites studied. Studies of chevrons and ELJs have demonstrated that they provide effective protection to the upper and sandbar and island features formed or maintained by the structures themselves but do not prevent lateral erosion where channel thalwegs migrate into sandbars and islands (Archer 2010). Vegetation, whether planted or established naturally, can effectively stabilize bars and islands, discussed in the following.

### 4.2.5 Role of vegetation in bar/island habitat formation and decay

Bar and island dynamics are tightly coupled with the recruitment and succession of riparian vegetation on many rivers (Bywater-Reyes et al. 2017). Emergent and submerged vegetation change the local velocity and shear stress (Fischenich 1996; Nepf 2012) and thus sediment processes and the associated feedbacks between bar building and vegetation recruitment and growth. Plant traits such as height, density, and stem flexibility vary with flow/stage and plant community composition and influence the susceptibility of plants to uprooting during floods and their morphodynamic effects (Bywater-Reyes et al. 2017). Vegetation impact on velocity, momentum loss at vegetation interfaces, and resultant flow stage remain poorly understood despite advances from assessing interactions between riparian vegetation and river processes (Osterkamp and Hupp 2010).

Vegetation can promote, sustain, and degrade sandbar, island, and shallow water habitats. Shoreline stabilization against further erosion is one positive effect of vegetation establishment, with the added benefit of shoreline fringe vegetation as a characteristic of long-term successful avian habitats (Wiley and Lott 2012). Vegetation can improve water quality, absorbing nutrients from agricultural and urban runoff, thus mitigating some negative impacts to nutrient-rich habitats (Morrow and Fischenich

2000). Dense vegetation that is periodically inundated may be desired, such that vegetation can stabilize and improve habitat quality. Vegetation affects sediment erosion, deposition, and particle size distribution on sandbars/islands by influencing velocity and current distributions. Plants generally trap finer particles and organic detritus, improve water retention and recharge, increase nutrient availability, and provide erosion resistance (Wiley and Lott 2012). Rio Grande Silvery Minnow have been shown to utilize vegetated floodplains during spawning (Fluder et al. 2007; Gonzalez et al. 2012, 2014; Medley and Shirley 2013).

The appropriate vegetation (species, density, etc.) should be determined based on project objectives, vegetation needed for targeted species habitat, and the need for stabilization given the erosional/depositional conditions. The needs of the target species should be considered when determining the amount of vegetated islands necessary (Wiley and Lott 2012). For example, sandbar nesting habitats for Interior Least Terns can be degraded due to advanced vegetation succession because these birds prefer open sandbar habitat and tend to avoid thick vegetation and narrow beaches (Johnson 2000). Vegetated sandbars may also be more heavily used by some predators than bare sandbars, particularly in attached sandbars, so suppression of vegetation may become a concern for maintaining nesting habitats.

There are some management or naturally occurring alternatives to maintain an appropriate vegetative state on sandbar habitats. Deposition of sand at hydraulically active elevated locations can deter vegetation establishment by maintaining a coarser substrate that drains easily and discourages germination, provided the vegetation is above the water table and does not have a taproot. Mechanical sandbar restoration may be necessary to recreate a desired habitat by disrupting and removing vegetation but can be extremely costly and may have undesirable ecological consequences[*] (USDOI 2006) (see Section 3.4.4). Project costs can be reduced if restoration is performed before large trees and dense vegetation are established (Wiley and Lott 2012) (see Section 3.4.4).

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[*] USACE. 2011. Unpublished. *Construct ESH Complexes Utilizing Geotextile Fabric at River Miles 757 and 789 and Pay for Performance at River Mile 759*. Missouri River Recovery Program, After Action Report, USACE-NWO, March 2011.

## 4.3 Island enhancement, maintenance, and management

Erosion is an intermittent but consistent process, and management of erosive processes impacting islands and sandbars in incising channels is especially important to maintain habitat acreage. Erosion can affect constructed features more than those that are naturally occurring under certain circumstances. For example, higher rates of overall erosion occur in constructed habitats when they are placed in areas with less than ideal physical characteristics (siting issue) in streams with otherwise adequate width, based on observations from 1998 to 2005*. The decay rate of sandbars also increases closer to the thalweg, near areas with high shear stress, and during moderately high flow rates (design and siting issues)*. The percentage loss of total ESH is assumed to be directly proportional to the quantity of ESH within a given segment because of the constriction of channel cross section area*.

High flow events can create new habitats but can also damage existing habitats. Storms can erode banks, lower island crest elevations, transport existing deposited sand and soil back into the main flow, and even cause existing islands to migrate (Donnelly et al. 2004). In contrast, significant flood events are capable of creating acreage by depositing large amounts of sediment on the falling limb of the hydrograph†. For example, USACE surveyed ESH acreage after the 2010 flood release from a dam and the 2011 flood on the Missouri River. The survey indicated 55.8 acres/mi in the winter of 2010 compared to 223.5 acre/mi in summer 2011, a 300% increase in acreage per mile. Average acreage per bar increased after the 2011 flood from 2.2 to 31.9 (2010) to 14.6 to 78.6 in summer 2011, the average elevation was raised from 1.1 ft (2010) to 3.3 ft (2011), and the slope increased from 1.4% to 2.0%. The total number of sandbars decreased after the 2011 flood (25 vs. 17) in that reach, however, suggesting large sandbars were created from a series of smaller ones, potentially reducing complexity of shallow water habitats and disconnection from banks that may increase access by land-dwelling predators.

* USACE. 2011. *Construct ESH Complexes Utilizing Geotextile Fabric at River Miles 757 and 789 and Pay for Performance at River Mile 759*. Missouri River Recovery Program, After Action Report, USACE-NWO, March 2011.

† WEST Consultants. 2014. Unpublished. *Geomorphic Change Evaluation in Support of ESH*. Prepared for the US Army Corp of Engineers, Omaha District.

The sandbars created during the 2011 flood event were highly transient, however, showcasing riverine dynamism in systems characterized by and dependent on in-stream depositional habitats for key species. The acres of sandbar per mile of river decreased from 223.5 acres/mi in summer 2011 back to 51.8 acre/mi by autumn 2013, with the highest rate of decay occurring between summer and fall 2011. The largest sandbars degraded more quickly, and the overall acreage of sandbars decreased rapidly after the flood (102.3 acres in summer 2011 to 32.2 acres in fall 2013). Shifting conditions and materials, including constantly moving bed material, deposition, and erosion, were listed as causes for the decreased habitat after the 2011 flood.

These findings emphasize the need to monitor and manage existing sandbars and find opportunities to create and maintain constructed sandbars to meet acreage and population targets. Collecting data concerning emergent habitats and endangered species populations are essential to provide accurate information to make informed decisions and update management methods and goals. Updated information may indicate one or more of the following scenarios depending on location and specific objectives: (1) only further monitoring is required because current targets have been met, (2) additional habitat should be created, (3) existing habitat should be preserved by clearing vegetation or other means.

# 5 Monitoring, Maintaining, and Adaptively Managing Bars and Islands

## 5.1 Conceptual basis for assessing impacts and benefits

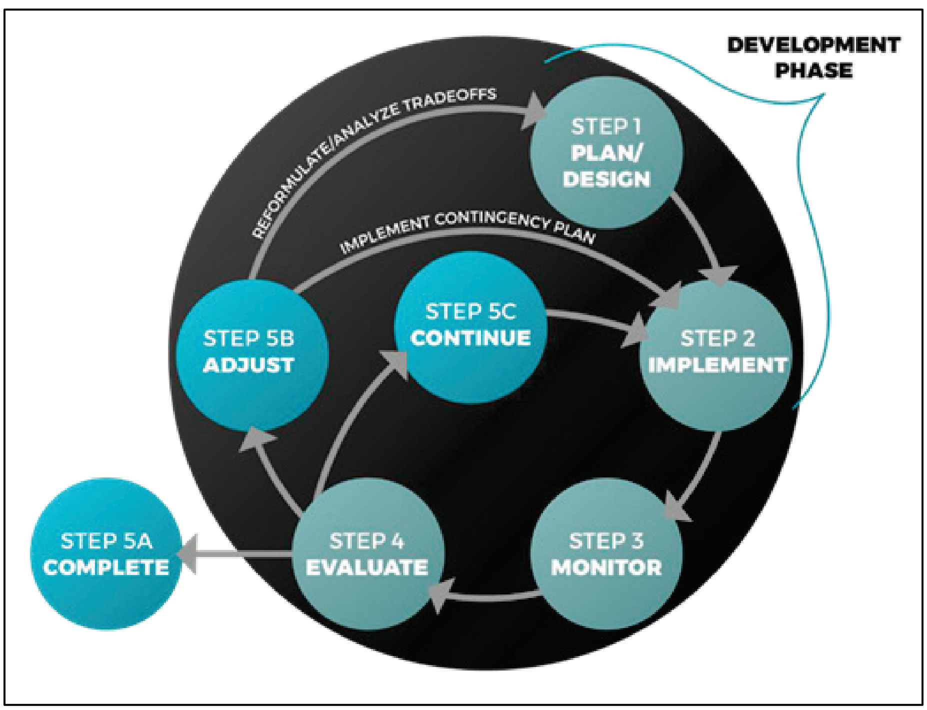
In discussions of objectives, constraints, siting, and design of sandbar and island features, Chapter 3 reminds the practitioner that riverine flow, sediment, and vegetative processes that remove, control, build, and sustain sandbar and island features are dynamic, resulting in a shifting mosaic of habitats even under conditions of relative system equilibrium. While total amounts or proportions of habitat types may be recreated, enhanced, optimized, or preserved (e.g., emergent, shallow water, bare sandbar or island, individual features, or complexes), individual features are seldom permanent, even over management timescales, and in many cases riverine ecologic function is dependent on the dynamic processes responsible for these features and their shifting location, constituent sediment, or vegetation. Basically, uncertainty is a characteristic typical of habitat types created or preserved by engineering approaches and structures summarized in Chapter 4. Similarly, the performance of various management actions in successfully creating and sustaining sandbar or island features will vary by system and even by reach, necessitating flexibility in their use over time. Addressing uncertainty is important for planning bar and island restoration and critical for managing these resources following implementation.

For those reasons, it is important that large-scale bar or island restoration projects and programs proceed utilizing an experimental design under an adaptive management framework. An active adaptive management approach provides (a) time and latitude to implement, monitor and assess actions in a structured fashion to promote learning, (b) opportunities for studies that should yield answers to critical questions more quickly than would occur through implementation alone, and (c) the flexibility to reject, modify or introduce actions and/or adjust objectives based on knowledge gained through the process. This approach recognizes the trade-offs between the need to take action to benefit the ecosystem or target species, the time required to reduce uncertainties, and the need to minimize life-cycle costs and impacts. A structured approach wherein hypotheses are developed and rigorously tested through implementation, monitoring, assessment, and (if necessary) adjustment provides the best approach to determine, for example, which actions are most effective on a system.

### 5.1.1 Adaptive management (AM) framework

For each type, amount, location, or value of enhanced habitat created, PDTs need the capability to predict, monitor, assess, maintain, and adaptively manage these features to ensure project goals and objectives are met. These capabilities should be explicitly aimed at reducing the inherent uncertainty in project outcomes, given the dynamic riverine environment. AM provides a proactive, scientific framework for ecosystem restoration project planning, intended to explicitly address and reduce uncertainty associated with ecosystem projects (Fischenich et al. 2012; USFWS 2003a; USACE 2010). Basic steps in the AM cycle include planning, design, implementation, monitoring, evaluation, and adjustment (Figure 13) (Fischenich et al. 2012). Considering that the bulk of planning, design, and implementation is covered in previous chapters, this chapter broadly addresses modeling, monitoring, evaluation, and adjustment steps in project planning, implementation, and management. Each project will necessarily differ in component parts and details of these steps, most effectively determined and agreed to by a multi-disciplinary team within the framework provided by AM (Fischenich et al. 2012).

Figure 13. Steps in adaptive management (AM) (adapted from Fischenich et al. 2012).



A central theme of AM is learning by doing — carefully designing project goals and objectives, recognizing there will be uncertainty in anticipated ecosystem response (and associated ecosystem benefits), accounting for this as part of targeted predictive or descriptive modeling, monitoring, and assessment of implemented measures and alternatives, and finally, modifying management decisions and actions based on the outcomes of monitoring programs to explicitly reduce uncertainties. AM can be effective when the following conditions are satisfied: there is uncertainty in ecosystem response to management actions, monitoring data can provide enough information to allow worthwhile learning, and the ecosystem management framework (specific measures, the project or program, decision-making authority, etc.) allows adjustments to be made (Fischenich 2012).

Sandbar and island restoration elements, projects, or programs, undertaken in the context of compliance with USACE policy per Sections 2036 and 2039 of the Water Resources Development Act (WRDA 2007), the Endangered Species Act (1973), biological opinions and other regulatory authorities, can typically satisfy these conditions, allowing PDTs to improve practices and increase success through adaptive management. For example, the Middle Rio Grande Endangered Species Collaborative Program developed a comprehensive AM plan to protect and improve endangered species along the Middle Rio Grande, New Mexico, in the context of existing and future water uses, and as a vehicle for explicit coordination between 16 agency stakeholders of New Mexico while simultaneously protecting existing and future regional water uses (Monfort 2012). Defined objectives, associated hypotheses and experimental design, working conceptual and numerical models, and clearly identified components that can be adaptively managed under this framework are articulated in this plan. This plan illustrates the complexity and care required to incorporate critical elements in project planning and implementation, monitoring and evaluation, and decision-making in an organized, deliberate framework that allows numerous potentially disparate organizations to agree on a single set of clearly articulated goals and objectives.

AM principles have been incorporated in developing habitat-based population models with a flow-dependent relationship to assess long-term trends and effects of flow management for sandbar and island habitats on the Missouri River[*]. This program is based on clear objectives and measurable metrics to gage success and help meet project goals of providing sufficient habitat to support self-sustaining populations while improving project models and reducing uncertainty in ecological outcomes, with suggestions for improved designs, implementation, operations, and maintenance being the expected long-term outcome. The following sections illustrate an example using data from a Missouri River project to show how this process is applied and suggests how it might adapted to other regions with similar issues.

### 5.1.2 Services provided by bars and islands

Though sandbars and islands provide many ecosystem services, those of particular interest in habitat restoration on large rivers tend to center around species of concern and Threatened and Endangered (T&E) species. For example, on the Missouri River, sandbars comprise the preferred nesting habitat for federally endangered Interior Least Tern (described above in numerous sections). As noted, least terns prefer bare land or sparse vegetation, above high-flow elevation, and some distance from the shore to protect against predation.

An example of a specific ecosystem service ascribed to sandbar habitat quality is provision of sufficient nesting habitat to support and sustain least tern populations (USACE 2010). The property of greatest apparent causal impact to population success is nest density and its impact on fledge ratios, assessed by comparison with species-specific requirements from the literature and/or locally or regionally relevant data. Nest density affects fledge ratios because competition increases when nests are closer together. To protect and improve the status of this species is the objective associated with nesting habitat enhancement. To increase successful fledging, increased habitat acreage is needed. Construction of new sandbars should theoretically result in relatively high rate of increase in initial fledge ratios, with declining increases as crowding ensues, to some natural population limit. However, this process should be more clearly characterized by the appropriate monitoring, and incorporated into any needed adjustments in

[*] Fischenich J., J. Tripe, D. Meier, D. Pridal, S. Givson, J. Hickey, and T. Econopouly. 2014. Unpublished. *Models, Data and Literature to Support Habitat Analyses for the Missouri River Effects Analysis*." Vicksburg, MS: US Army Corps of Engineers.

design, implementation, and potentially operation and maintenance activities required to sustain and improve ecological success.

This is only one set of components and feedback processes in effect related to this ecosystem objective — other factors, such as foraging habitat or vulnerability to predation, are also in play for population success, so additional parameters or entire models may be required to adequately capture distinct populations or life-stage-specific requirements. Decreased predation, for example, can be achieved using vegetation management and island placement away from the main shoreline. Species survival increases with improved foraging success, reduced nest density, and reduced human disturbance.

Each ecosystem service or benefit can be articulated as such (e.g., provision of sufficient foraging habitat to support and sustain least tern populations or provision of sufficient cover or separation from predator populations to reduce predation risk to least tern populations). An adaptive management framework would include multiple factors in species and habitat models, monitoring plans, and hypothesis testing to reduce scientific uncertainty in ascertaining the extent to which differing amounts, configurations, timing, etc., achieve the population objectives.

## 5.2 Monitoring, maintaining, and adaptively managing bars and islands

As noted previously, Section 2039 of WRDA 2007 requires a monitoring plan, prepared as part of the AM plan, for ecosystem restoration projects. USACE guidance explains "Monitoring includes the systematic collection and analysis of data that provides information useful for assessing project performance, determining whether ecological success has been achieved, or whether adaptive management may be needed to attain project benefits." By contrast, operation and maintenance (O&M) describes routine activities not designed to evaluate hypotheses or performance or to reduce uncertainty, though O&M activities might be included in possible actions that could be adjusted following evaluation and decision-making based on monitoring data collected as part of the AM plan.

Monitoring is conducted to assess project performance based on metrics matched to specific project objectives and often used to parameterize, validate, test, or update quantitative models that are critical to forecasting conditions in large rivers or complex systems. Monitoring plans are additionally designed and justified by optimizing the type, amount, and cost of data required to assess project and restoration feature performance against stated project objectives and make decisions to adjust monitoring, O&M, modeling, management, or other project components that can be adaptively managed.

### 5.2.1 Monitoring informing objectives and performance measures

For a given restoration project, program, or river system, tangible metrics are needed to gage performance of management measures and determine the degree to which project objectives have been achieved — this forms the basis of an efficient and coherent monitoring plan. A metric can be defined as a measurable system property that leads to defining success of achieving project objectives (McKay et al. 2010). Effective metrics are chosen to correspond with each project objective. For example, if the objective is to “meet or exceed bird productivity target,” where the target is a performance measure — “fledge ratio” — the metrics are number of chicks and number of breeding pairs per year (additional detail below). Metrics should always be associated with a specific project objective, with performance measures that are measurable, predictable, responsive to management actions, and for which monitoring data can be used to verify hypotheses (Fischenich 2012 et al.).

An example set of objectives, associated performance measures, and metrics for sandbar and island habitat monitoring related to bird populations was developed for the Missouri River and serves as a good starting point to illustrate the way in which these factors are organized to serve a monitoring-plan framework (USACE 2010):

1. Objective: Meet or exceed bird productivity targets.
    a. Performance Measure: Fledge ratios are calculated by dividing the number of chicks by the number of breeding pairs; a 3 yr running average is used.
        (1) Metric(s): Annual observed count of chicks and breeding pairs.
2. Objective: Increase and stabilize population.
    a. Performance Measure: Annual population growth rate, steady or increasing trend.
        (1) Metric: Using annual census data, the growth rate for year *t* is the population size of *t*+1 divided by *t*.
    b. Performance Measure: Adult population size, steady or increasing trend.

        (1) Metric: Measured by collecting an annual census.
3. Objective: Meet emergent sandbar habitat acreage targets.
    a. Performance Measure: Acreage and elevation.
        (1) Metric: Aerial and satellite imagery interpretation and digital measurement.
4. Objective: Minimize negative impacts of construction activities.
    a. Performance Measure: Extent of human disturbance.
        (1) Metric: Cubic yards of sand moved each year.
5. Objective: Improve model projections.
    a. Performance Measure: Declining trend in coefficient of variation of the model.
        (1) Metric: Comparison of current data with updated habitat and population targets.

#### 5.2.2 Monitoring informing maintenance

A brief example showing how monitoring, maintenance, and potential AM adjustments might fit together concerns emergent sandbar habitat for least tern constructed as a series of sandbar complexes within channels, as long as sediment placement areas are kept away from the thalweg. Larger areas of bare sand on established sandbars can be achieved using a combination of vegetation management and the filling of selected low elevations with sand.

Several performance measures can be associated with the objective of increasing sustainability of emergent habitats for the least tern, centering on increasing or steady trends in total area of bare sand, target increases in wet to dry sand and edge to area ratios, and targets for areas, extents and density of edge vegetation. Metrics associated with objectives and performance measures include (1) ratio of wet to dry sand, (2) edge to area ratio and (3) amount of light vegetation close to the edge, which deters the effects of erosion (USACE 2010). Due to the broader timeframe of riverine and bird habits on a generally seasonal/annual cycle, annual monitoring of habitat acreage and populations might be slated to begin prior to implementation (baseline), proceed immediately following implementation (to confirm as-built conditions), and continue even if or after the initial acreage targets are achieved to document habitat sustainability following additional annual cycles.

Monitoring and model results should point to management actions that could be employed to maintain optimal habitat acreage/population levels as part of O&M, if not already being implemented, or could suggest modifications in design or implementation, even to performing adjustments, repairs, or even replacements of structures in place or vegetative management methods in use if these are shown to be ineffective or do not meet targets, for example.

Management methods during a maintenance or replacement phase could involve vegetation controls if sediment and flow processes are not in phase with expectations and could include the use of herbicides in spring to prevent growth of vegetation, mechanical removal of early successional vegetation in the fall, and removal of debris following vegetation removal. The critical decisions here will revolve around what type of vegetation problems are revealed by monitoring and whether these are trending toward or away from anticipated objectives or whether these show a gap in implementation or maintenance activities. Again, the information provided can reduce uncertainty in management of these measures. Maintenance measures may also involve, add, or eliminate ongoing actions such as application of clean sand to low elevation areas, reshaping sandbars to provide increased forage habitat, and complete replacement of important sandbars lost due to erosion (USACE 2010). Updated model results as well as cost/rate of return ratios would be used to select optimum management methods.

### 5.2.3 Monitoring informing modeling

Success of construction methods to create reliable emergent habitats, such as chevrons and dikes, can be measured using acreage evaluations over time and by comparing the size and vitality of the bird population on these features (see Objective -> Performance Measure -> Metric framework above). The metrics that form the bulk of a monitoring plan for these structures and resultant emergent habitat would be designed to help the PDT evaluate success and reduce uncertainty in assessments or models related to forecasting or predicting fluvial and other processes impacting persistence of these habitats over time.

Physically based metrics could include age of sandbar, size, elevation, location of the feature within the reach (including whether attached, unattached, adjacent shallow water habitats, etc.), flow variability during nesting season, and bird population and dispersal. Monitoring organized to capture these parameters should be based on the anticipated nature and timing of sediment transport and deposition processes, bird life-cycle usage and requirements with appropriate timing of these cycles, and other characteristics influenced by predictable or stochastic processes with monitoring planning set up to capture these changes, update the models used to predict or represent reach-wide processes, and possibly update monitoring itself to adjust to unanticipated cycles or processes newly identified through monitoring. Updating the model input to reflect annual changes, for example, gives managers a tool to assess the management methods required using a matrix similar to Table 2 and make any necessary changes. Effects of additional management actions, such as predation control and vegetation management, could also be predicted by updated model results, further refined by better targeted monitoring and evaluation.

Making use of the literature and local and regional data collection efforts, with previous management or implementation efforts, is critical for success of monitoring activities in the context of expected riverine processes. Descriptive or predictive models used to site and design appropriate solutions given the best available science — literature, data and models — is put to the test in the monitoring stage, potentially leading decision-making in unexpected directions, requiring adaptive management solutions or confirming hypotheses for improved species habitats, population status, and forecasting models. The positive impact of constructed habitats on population growth has been documented in the literature. Caitlin et al. (2011) reported that piping plovers preferred engineered habitats to natural and managed habitats. Sherfy et al. (2008) reported that nest survival was twice as high on constructed sandbars when compared to natural sandbars. The paper also indicated that nest selection was sensitive to slight changes in habitat features, suggesting management efforts should be carried out to optimize suitable habitat conditions. Finally, Strucker et al. (2011) reported that constructed habitats were comparable to river-created habitats to support fish communities.

## 5.3 Modeling growth and decay of bars and islands

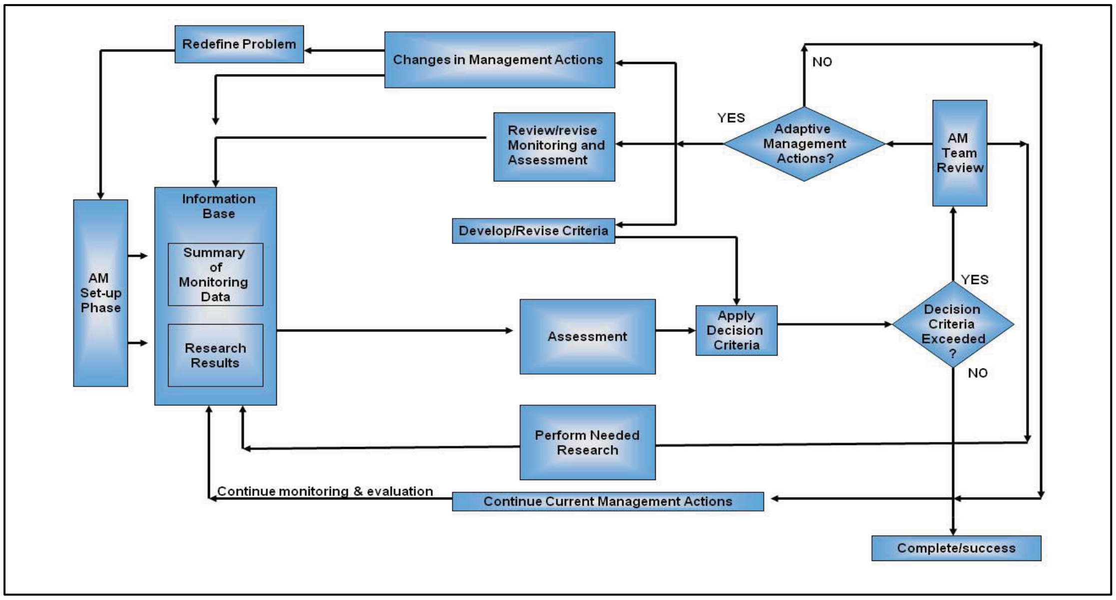
The results from the bird models are used in the flow manipulation model to indicate potential changes in management strategies. A copy of a matrix used to guide acreage targets for the least tern in a Missouri River reach is shown in Table 3 (adapted from USACE 2010).

Table 3. Decision matrix for adaptive management

| Population Status | Population Target | Acreage < Target | Acreage ≈ Target |
|---|---|---|---|
| **Growing population** | | | |
| Fledge ratio > equilibrium | Population ≥ target | Unexpected (target too high). Much less density dependence than expected.<br>*Actions:* Maintain habitat and reduce acreage target. | Overbuilding (target too high).<br>Less density dependence than expected.<br>*Actions:* Maintain habitat, consider reducing acreage target. |
| Growth rate > 1 | Population < target | Optimal (growth)<br>System responding as predicted.<br>*Actions:* Continue with current habitat creation plan. | Overbuilding (building too fast). Population growth limited by factors other than habitat.<br>*Actions:* Maintain acreage and monitor population response. |
| **Stable population** | | | |
| Fledge ratio ≈ equilibrium | Population ≥ target | Overbuilding (target too high).<br>Less density dependence than expected.<br>*Actions:* Maintain habitat, consider reducing acreage target. | Optimal (stability).<br>System, responding as predicted.<br>*Actions:* Maintain habitat. |
| Growth rate ≈ 1 | Population < target | Underbuilding (building too slow).<br>*Actions:* Continue habitat creation; consider increasing pace. | Underbuilding (target too low). More density dependence than expected.<br>*Actions:* Increase acreage target or improve habitat quality. |
| **Declining population** | | | |
| Fledge ratio < equilibrium | Population ≥ target | Reversal (not maintaining habitat). Habitat was sufficient but quantity is now declining.<br>Actions: Reconstruct habitat, improve maintenance. | Reversal (not maintaining habitat). Habitat was sufficient, but quality is decreasing.<br>*Actions:* Improve habitat quality or increase acreage target. |
| Growth rate < 1 | Population < target | Underbuilding (building too slow).<br>*Actions:* Increase pace of habitat creation. | Unexpected (target too low) Much more density dependence than expected.<br>*Actions:* Increase acreage target, and/or improve habitat quality. |

The fully regulated flow model and bird population models were used to model the growth and decay of bars and islands in a Missouri River reach. An illustration of the implementation phase of the AM process is shown in Figure 14.

Figure 14. Implementation of adaptive management process (Fischenich et al. 2012).




The steps used to determine model results are listed below.

1. Specify the habitat acres required to be constructed annually to reach target acreage. Flow creation is assumed at this point.
2. Randomly choose a sequence of consecutive years of historical flow and storage data for each model replicate.
3. Add the amount of acreage constructed previously.
4. Using flow data from the models, determine mean monthly flows for the period and calculate changes to baseline emergent sandbar habitat.
5. Calculate the sandbar acreage that is safe from inundation using daily flow. The amount of sandbar above water during a year is determined using values from historical data of the maximum river stage in May – July. The acreage safe from inundation during these maximum river stages is determined using stage-area curves estimated for each reach.
6. Adjust nesting habitat acreage values to account for available acreage due to stage variation (low or high flow, flooding).
7. Provide nesting habitat acreage to bird population models.

The models calculate the nesting habitat acreage as a function of mean monthly flow and ambient nesting acreage values using the updated information. Any acreage losses are incorporated into the flow-based model, and changes in available habitat acreage can be changed at any step in the model to account for current flow conditions.

For application to Garrison reach of the Missouri River, this model was modified using shear stress and hydraulic characterization. The model could be modified to account for the dominant processes in other reaches as well.

Several assumptions are made within the models: (1) there is a loss of sandbar habitat annually and the percentage of annual sandbar loss increases with the total acreage of sandbars in a reach (higher acreage usually requires sandbars to be constructed in sites that are more susceptible to erosion, resulting in increased habitat loss), (2) each reach has its own table of estimated loss rates by total acreage, which are independent of flow values, and (3) the baseline amount of nesting habitat is assumed constant within each nesting season (i.e., erosion and vegetation do not affect nesting during a given season).

# 6 Summary and Recommendations

Sand bars and islands provide nesting and foraging habitat for birds (including listed species) and important shallow water habitat for many aquatic species. In incised channels lacking floodplain connectivity, instream habitat becomes even more important, with channel bars providing an important riparian habitat component. However, most managed rivers have more sediment capacity than supply, causing these features to erode and disappear. There are management actions that can create and maintain these important habitats.

Four groups of management methods were described that could be used to meet specific project goals, as listed below:

- Spur Dikes, Groins, Wing Dams, Jetties – used for bar formation, and to reduce erosion
- Bendway Weirs, Stream Barbs, Bank Barbs – used for flow management, bar formation
- Rock Vanes, Submerged Vanes – used to reduce erosion, bar formation
- Chevrons – used for flow management, bar formation.

Fourteen construction materials were listed in the report; some were deemed more suitable than others. When selecting a construction material, factors such as the flow obstruction effectiveness, removal success, public safety, constructability, and a damage/risk assessment should be considered.

A conceptual model was described that used historical flow data, habitat acreage estimates derived using aerial and satellite imagery and population census data to calculate the habitat acreage that should be created to achieve target acreage values. The models embraced the principle of AM that allows modification of management actions in response to changing environmental and population conditions. The models use clear objectives and measurable metrics to gauge success and help provide adequate habitat to support self-sustaining populations. The models include specific factors related to the species of concern, such as bare sand or slightly vegetated habitat, habitat elevation, and fledgling ratios, to reduce model uncertainty. Used with updated input, these models can be used to maintain and monitor existing habitats after initial acreage targets are reached.

This report discusses much of the work completed on the Missouri River and documents many of the lessons learned to convey the theories and methods implemented. The methodology can be applied to various systems with consideration of differing T&E species, sediment characteristics, and project goals.

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# Abbreviations

| | |
|---|---|
| ADDAMS | Automated Dredging and Disposal Alternatives Modeling System |
| AM | Adaptive management |
| BMP | Best management practice |
| CDF | Confined disposal facility |
| CEM | Channel evolution model |
| ELJ | Engineered logjam |
| ESA | Endangered Species Act |
| ESH | Emergent sandbar habitat |
| LWD | Large woody debris |
| O&M | Operation and maintenance |
| PDT | Project delivery team |
| T&E | Threatened and Endangered species |
| USACE | US Army Corps of Engineers |

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**14. ABSTRACT**
Sandbars and islands provide important nesting and foraging habitat for birds (including listed species) and shallow water habitat for many aquatic species in riverine ecosystems. In-stream habitat is especially important in incised channels lacking floodplain connectivity, with channel bars providing important riparian habitat. However, some river management practices significantly alter and sometime eventually eliminate these important habitats. Several US Army Corps of Engineers districts are planning or actively building instream bars and islands using flow management and/or instream structures. Sister agencies (e.g., US Bureau of Reclamation) have similar initiatives downstream of their reservoir structures. This report outlines considerations for establishing and managing sandbar and island features. It presents a compilation of proven techniques for promoting sandbar and island development and for reducing erosion of these features.

**15. SUBJECT TERMS**
Ecosystem management, Islands, Rivers—Management, Sand bars, Streamflow--Management

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