Retrospective: Transitioning River Geomorphology and its Impact on Habitat Management

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Abstract

Since the early 1900s, the US government and state-level agencies throughout the southwest have invested ambitiously and prolifically on large-scale engineering projects to mitigate risks due to alternating conditions of drought and flood. These approaches included construction-intensive methods, particularly building dams, levees, and river channelization. The combination of these structures met design goals to reduce flood risk by reducing inundated areas and improving river conveyance. However, the impacts to sediment supply and homogenization of water discharge have generated a geomorphic response that has impacted riparian ecosystems. Channel narrowing, floodplain disconnection, and streambed erosion have been common in these heavily engineered semi-arid river systems.

Due to increased prioritization of ecological function and cost of recurring maintenance challenges, government activities have shifted from hardened river infrastructure solutions to engineering with nature, habitat restoration, and channel maintenance. However, in contrast to hard-engineering projects, habitat management faces challenges in demonstrating longevity, engineering effectiveness, and quantifying habitat quality improvement.

The purpose of this paper is to characterize the geomorphic change that has occurred in one of these highly engineered river systems, the Rio Grande, and how observed trends impact assumptions about restoration effectiveness and project scales. Based on geomorphic trends on the Rio Grande near Albuquerque, NM, we discuss an alternative framework to assess long-term restoration efficacy within the context of geomorphic change. The intention is to increase project resilience and effectiveness. We discuss challenges to innovation in over-allocated and highly engineered river systems, while also demonstrating how such alternatives have economic potential and reduce liabilities by reducing recurring maintenance and improving ecological function.

Introduction

Anthropogenic impacts on large rivers, including dams regulating flow and levees disconnecting floodplains, have produced rather uniform fluvial morphological results, despite the vast range of floodplain and channel geomorphology, hydrologic regimes, and biological composition (Gore and Shields, 1995). Changing sediment loads and stream flow affect channel morphology (Schumm 1969, Lane 1955), and under current river management approaches, channel incision and narrowing are quite normal. This affects riparian environments, as floodplain disconnection is associated with reduced habitat availability and biodiversity (Flitcroft et al. 2022). Therefore, river restoration should be undertaken in light of geomorphic analysis (Gregory, 2006).

The goal of this paper is to promote a framework for assessing the efficacy of long-term restoration and flow management relative to geomorphic trends. We use the Albuquerque reach of the Rio Grande as a case study example. This is an area with multiple US Army Corps of Engineers (USACE) restoration projects that have been monitored for change over the course of several years. Our specific research objectives are to: A) articulate the role of geomorphic change in efficacy of large-scale river restoration actions; B) integrate geomorphic change into project formulation and adaptive management frameworks; C) identify a framework on how to manage habitat in a dynamic fluvial environment; and D) discuss social implications of an alternative approach to habitat management.

Background: Changes in MRG Geomorphology and Impacts to Restoration Sites

The Middle Rio Grande (MRG) extends from northern New Mexico to the spillway of Elephant Butte Dam in Truth or Consequences, NM (WEST 2022). The major flood control dam on the main stem of the Rio Grande upstream of Albuquerque, NM is Cochiti Dam, although there are numerous dams that control the movement of water and sediment on tributaries to the Rio Grande, as well as upstream dams that have affected the streamflow and sediment supply (Scurlock 1998; Schmidt et al. 2003; Makar and AuBuchon 2012).

Reduced Stream Flows

Peak stream flow changes on the MRG have been noticeable since Cochiti Dam's closure in 1973 with estimates of the peak streamflow reduction as much as 38% in Cochiti, NM and 4% in Albuquerque, NM (Schmidt et al. 2003). Cochiti Dam and other dams also impacted the duration of peak flows, which have increased by 60%. Water operations at Cochiti and other tributary dams have increased duration of low flows, reduced sediment inputs, and decreased the magnitude of peak runoff events.

Hydrologic analyses (Greimann and Holste 2018) show episodic fluctuations of the discharge that cause wet and dry cycles over multi-year periods. The drier cycles have longer durations than the wet cycles. The MRG still had recorded episodes of drying until the mid-1980s, even with the influence of the dams leveling the hydrographs, although the river did not dry from the 1980s-2018 (Harris 2022). In 2022, however, drying of the MRG reoccurred south of Albuquerque (Pratt 2022).

Between 1849 and 1942, there were at least 50 major floods in the MRG greater than 9,000 cfs and in the 1800s, almost twice as many floods were documented compared with the 1600s and 1700s Schmidt et al. (2003). Riparian ecosystems, which support a variety of functions such as food, bank stability, and diversity in aquatic habitats, are impacted by changing flow regimes (Wilding et al. 2014). The physical disturbance and inundation from floods create riparian vegetative structure, and the lack of floods generally empower exotic vegetative species to dominate (Greet et al. 2007).

Impacted Sediment Loads

The Rio Grande has traditionally carried a large annual sediment load with an estimated mass of 33 million short tons delivered to the Gulf of Mexico in the 1700s (Schmidt et al. 2003). As agricultural development and populations increased, so did soil erosion due to over grazing and clear-cutting (Scurlock 1998). The disturbed soil, coupled with a wetter period, caused an arroyo downcutting cycle in the mid-1800s through the early 1900s throughout the southwest (Friedman et al. 2015), resulting in sediment deposition along the main stem of the Rio Grande and aggravating flooding concerns in populated areas. By the mid-1900s the lower portions of the arroyos were beginning to fill in and the sediment supplied to the Rio Grande began to decrease, mirroring a cycle of arroyo downcutting and subsequent infilling observed in the sedimentary record (Friedman et al. 2015).

By 1980 the annual sediment supply delivered by the Rio Grande to the Gulf of Mexico was around 0.9 million short tons. The mean annual suspended sediment concentration at the USGS gage in Albuquerque, NM (USGS ID 08330000) reduced by 78% after the closure of Cochiti Dam in 1973 (Schmidt et al. 2003). The sediment supply reduction is not caused solely by anthropogenic factors, however, as decreases in the suspended sediment record are observed upstream of Cochiti Dam (Makar and Aubuchon 2012) and along the Rio Puerco, which may be attributed to the arroyo infilling process observed by Friedman et al. (2015).

Bed material along the MRG have coarsened since installation of Cochiti Dam. The bed material had a median size in the sand fraction (0.0625 to 2 mm) as late as 1962 (Greimann and Holste 2018). Bed material samples collected during the 2019 spring snow melt runoff at the USGS gage in Albuquerque, NM (USGS ID 08330000) showed that the bed material was still primarily in the sand fraction (AuBuchon et al. 2022; Richards and Harris 2022). Since 1972, however, gravel is increasingly evident in the bed material of the MRG north of the confluence with the Arroyo de las Cañas around Socorro, NM (Greimann and Holste 2018). The presence of coarser materials in the bed helps stabilize the channel morphology. This translates into larger floods needed to mobilize the bed materials and affects larger scale morphological changes.

The preponderance of sand in the bed material in Albuquerque and further south suggests that sand substrate remains mobile. Measurements of suspended sediment on the MRG during the 2019 spring snow-melt runoff, however, found a large variation in the amount of suspended sand across a cross section (AuBuchon et al. 2022). This suggests that sand is mobile at larger discharges and may preferentially settle in lower velocity settings across the cross section, causing sediment deposition in lower velocity and depth regions that are desirable morphological zones for habitat. McComas et al. (2022) found that sandbar formation on other fluvial systems is connected to the sediment supply availability of the bed material size class and that sandbar formation is dependent upon local hydraulics that induce changes of velocity or shear stress.

A combination of reduced sediment load and constrained floodplain extent due to levees and vegetation encroachment has reduced the channel's ability to migrate and meander. The coarsening of the bed material also restricts the vertical freedom of the alluvial channel and makes vegetation establishment more likely to preclude erosion of the banks. Historically, meanders and sediment deposition would provide nutrients and dynamic change, such as a channel avulsion, which increases habitat diversity by creating abandoned oxbows or backwaters (Crawford 2003).

Change in Vegetation

Following flood control and water operations projects throughout the valley, vegetative patterns have changed. Drainage and diversion projects have reduced the water table, and dam and river channelization has reduced the flushing of nutrients in the floodplain – leading to more alkali conditions (Scurlock 1998). This has increased the dominance of invasive species such as salt cedar (*Tamarix ramosissima)* and Russian olive (*Elaeagnus angustifolia)*, replacing native cotton woods (*Populus fremontii*), willow (*Salix spp.)* and sedge (*Carex spp.)*.

Much of the MRG is surrounded by a cottonwood gallery known as the “Bosque”. Prior to channelization, flood control and levees setting the MRG in its current place, cottonwood riparian habitat would cycle in formation and destruction, with significant flows leading to their destruction, and receding flows supporting sapling recruitment. However, due to flow regulation and floodplain disconnection, the Bosque does not experience the same turnover, with maturing cottonwoods of relatively the same age experiencing senescence, and the inundation patterns for cottonwood recruitment happening less frequently.

In 1962, vegetation cover ranged from 10% - 80% along the entire MRG (Greimann and Holste 2018) . By 2012 the vegetation coverage had increased to 48% - 98%. The largest vegetation coverage increases occurred south of Arroyo de las Cañas, between Cochiti Dam and Angostura Diversion Dam, and between Belen, NM and the confluence of the MRG with the Rio Puerco. The vegetation encroachment has also reduced dynamic fluctuation in bank erosion. For example, around Cochiti Pueblo there was on average about 88 ft (27 m) of bank erosion on the MRG per year in 1918 which had reduced to 16 ft (5 m) by 1992 (Schmidt et al. 2003).

Geomorphic Change

The Rio Grande has been characterized as a series of wide alluvial valleys, or basins, separated by sections of the river that flow through narrower valley areas (Schmidt et al. 2003). The wider valley or basin areas tend to be where large volumes of alluvium have been stored over millennia and for which the current incision is not yet significant in comparison to the accumulated alluvium depth. Channel progression from a wide, braided channel in the 1800s to the narrow, stable channel of today is presented in Figure 1 as an infographic.

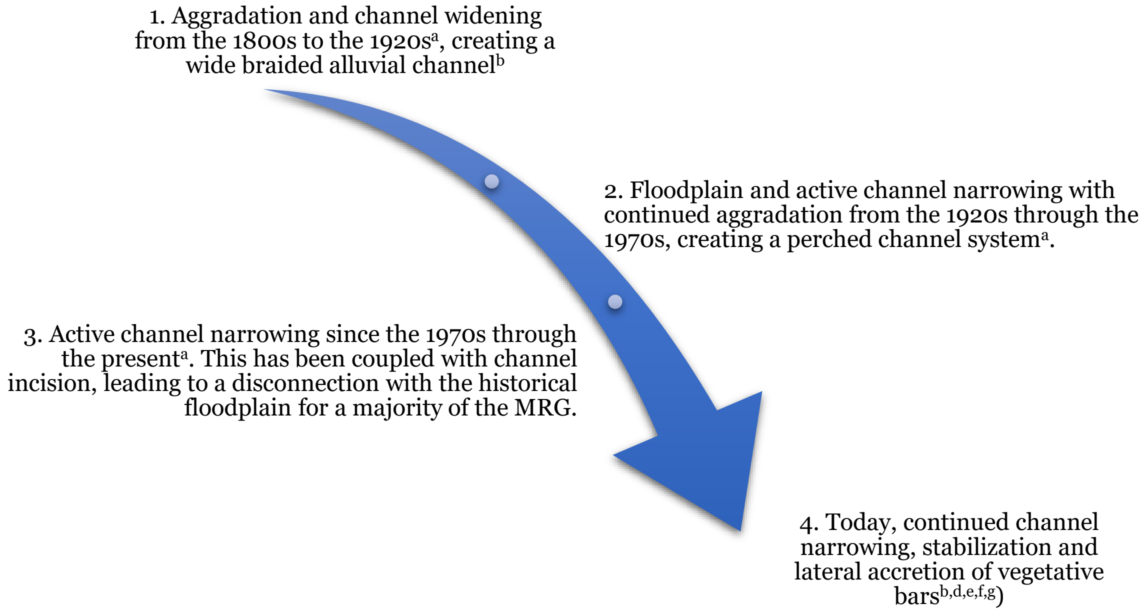

Figure 1. *Historical timeline of geomorphic change for the Middle Rio Grande, Albuquerque Reach.* [a]*Harris 2022,* [b]*Schmidt et al. 2003,* [c]*AuBuchon et al. 2022,* [d]*Harris 2022,* [e]*Harris et al. 2018,* [f]*Makar and AuBuchon, 2012,* [g]*Tetra Tech 2013*

Specifically for the Albuquerque area, the reduced sediment load and reduced peak streamflow have contributed to the following trends (from Harris et al, 2018):

- Decrease in width to depth ratio while the channel bed incises (from 1971 to 2017) and width narrows (from 1918 to 2018).
- Increase in river sinuosity since 1972.
- Transition from a wide braided channel (1918) to a meandering single thread channel, with the presence of vegetated islands increasing as one travels downstream.
- Decrease in suspended sediment concentration and a coarsening of the bed material.

MRG Restoration Strategies

The Middle Rio Grande Endangered Species Collaborative Program has developed habitat restoration areas to improve conditions for endangered species. Several species of interest for this system have habitat requirements in the active channel and/or the floodplain. These include the Rio Grande silvery minnow (*Hybognathus amarus*), the southwestern willow flycatcher (*Empidonax traillii extimus*), and the yellow-billed cuckoo (*Coccyzus americanus*). These habitat areas provide food in the form of large insects (MRGESCP 2021b), flying insects (MRGESCP 2021a), and macroinvertebrates/algal/diatom communities (MRGESCP 2021c). In addition, these habitat areas provide shelter through the riparian vegetation, requiring vegetation diversity (MRGESCP 2021b), multi–age vegetation (MRGESCP 2021a), and aquatic shelter both in the active channel and the floodplain (MRGESCP 2021c).

About 1200 acres of floodplain habitat has been constructed on the MRG since the late 1990s (this doesn't include exotic vegetation removal acreage). The three most common features are backwaters, bankline terracing, and high flow channels, which are typically constructed via earthwork excavation. Backwaters create a low velocity inundated area with a single connection point to the MRG wherein streamflow enters and exits. High flow channels contain two connections to the MRG, allowing streamflow to move through and connect with the floodplain. Bankline terracing involves lowering of bank edges parallel to the MRG to providing more frequent inundation opportunities at various streamflow stages. Some design criteria, such as USACE's Bosque Restoration sites in Albuquerque, are based on incipient inundation. Incipient inundation is a design flow that is reached before the restoration site begins to inundate. The USACE Bosque Restoration sites have incipient inundations varying from 1500 to 3000 cfs (Richards and Harris 2022). Other site designs were selected based on a balance between how many of acres of habitat are created at a given flow, relative to the excavation volume, which has a removal cost to spoil (USFWS 2016).

Key morphological responses at the restoration sites, based on feature type, are as follows (McKenna 2022; Richards and Harris 2022; Stark et al. 2022)

- Sediment deposition in restoration features was primarily observed following the first large event after construction, typically associated with a peak streamflow of 3000 cfs or greater. Subsequent peak streamflow events of the same magnitude or greater were observed to deposit sediment at a lower accretion rate.
- High flow channels tend to fill and narrow from their constructed state. There are fluctuations in the bed topography (about a foot) in the streamflow direction along the entire high flow channel with more dynamic adjustments (on the order of a couple of feet) observed at the inlet and outlets.
- Backwaters were observed to have the largest amounts of sediment deposition, whether isolated or in connection with a high flow channel.
- Bankline terraces had some deposition with more associated at the edge closest to the mainstem with target incipient inundation thresholds continuing to be met over time.
- Sediment accumulation (or lack thereof) does not seem associated with whether the site was constructed on the inside or outside of a meander bend of the MRG.

When taken in context with the geomorphic trends for the main channel, the combined effects of geomorphic change in the channel and restoration sites culminate in reduced floodplain and restoration site inundation without reduction of the fluvial morphological trends that created the need for habitat restoration efforts in the first place. The challenge with this trend is two-fold, where both restoration site effectiveness is reduced, and risks to instream and river-adjacent infrastructure (i.e., levees, water diversion structures) are increased over time.

Limiting Restoration Goals

The current methodology for habitat management has weaknesses relative to prevailing geomorphic trends. Sediment deposition and vegetation recruitment on restoration sites eventually returns the form and function of constructed sites to the pre-project environment, creating the need for continued restoration activities in order to sustain desired habitat features. We posit that the critical limitations of restoration management approaches are that 1) habitat management goals have a narrow focus; and 2) project development does not incorporate geomorphic change, leading to recurring maintenance costs that may otherwise be avoided.

A primary step in restoration planning is to inquire "what has changed" as it links to reduced ecosystem function and species prevalence. In the MRG, a wide, shallow channel would provide the diversity of hydraulic conditions to support various habitat structures, but the vertical incision and floodplain disconnection is moving away from this condition. Prevailing trends of channel incision are more likely to cause channel meandering, and if uninterrupted, would eventually create a wider, inset floodplain (Schmidt et al 2003). However, channel meandering causes concerns with existing infrastructure since considerable damage can ensure if left unchecked – i.e., levees – requiring hardened interventions, such as bank stabilization via riprap revetment. Therefore, a planform that could potentially improve habitat structure cannot be achieved unless adjacent infrastructure is also reassessed.

Too Narrow of Focus

Ecosystems are remarkably complex. Despite this, MRG habitat restoration projects often focus on just a few of the habitat requirements of a single species. Endangered and threatened species garner a lot of attention, and though these are often keystone species, life cycle processes of non-listed flora and fauna require some attention as well.

Given the diversity of imperiled species and the homogeneity of the regulated river system, habitat management approaches should be focused on providing a mosaic of different habitats which evolve and change dynamically through time. Conditions that are unchanging are going to migrate to a homogeneous habitat condition, whereas natural systems promote habitat destruction and habitat regeneration. Therefore, for anthropogenic change via restoration projects to restore ecosystem function, the fluvial changes that would occur in a natural system should be assessed in a holistic way. This includes looking at the timing and magnitude of various environmental flows, not only for desirable habitat conditions but also for encouraging dynamic fluvial morphological processes.

There is no need for design criteria to reflect a single streamflow. Given empirical studies and widespread availability of USGS monitoring gages, it is possible to calculate or assess flow frequency in any river reach. Computational hydraulics, such as those in SRH-2D or HEC-RAS, can then be used to simulate a range of potential stream flows for restoration design alternatives. Much like an effective sediment discharge curve, the percent likelihood and the area of suitable inundation conditions can be quantified for comparison among possible restoration approaches. Multiple impacts, whether it be inundation frequency to support riparian vegetation, duration of inundation to support fauna life cycle milestones, appropriate shear stresses for food sources or substrate placement, etc. can be assessed in this approach. Long-term trends, such as river degradation, can also be implemented in the modeled reach to assess site efficacy due to geomorphic change.

Habitat management efforts are often treated as standalone projects and constrained to a subset of organizational goals. In reality, agencies responsible for habitat management may also be responsible for or affect other river management priorities, including erosion protection, flood control, and water conveyance. Conversely, if both habitat management and other critical missions are approached congruently, there may be opportunities to reduce overall operation costs and develop more sustainable engineering projects.

Short-term Project Development Plan

Ultimately, the inadequacy of the current approach can be evaluated by project effectiveness. The magnitude of areas impacted and their performance over time, the natural succession of geomorphic form at these sites, and the quality of habitat and food provided are all measures of habitat restoration performance. While projects used to have a one-and-done approach, adaptive management for iterative improvement has become an accepted management approach on the MRG. However, habitat design is still focused on maintenance/self-maintaining design, which ultimately fights against natural site progression and leads to recurring costs for re-excavation or reconstruction or diminishing function of these restoration sites. If project planning were to evaluate how the site is expected to change over time, e.g., via vegetation encroachment or deposition, then interventions may not be needed as frequently or at all.

In addition, prevailing geomorphic trends should be considered during the alternatives analysis and the "No Action" alternative. "No Action" alternatives are often the baseline condition that is compared to potential improvements presented by the proposed alternatives. In these changing systems, "No Action" does not necessarily mean that the existing condition will remain the same. For example, in areas where habitat is degrading due to channel incision, channel incision may continue and lead to increasing decline of habitat quality. Assessing how the project site will be affected by continued trends will be necessary in order to appropriately quantify risks of "No Action".

Alternative Approaches to Habitat Management Planning

We have identified weaknesses in restoration development due to a lack of a geomorphic context. To countervail these weaknesses, we propose an alternative approach to habitat management planning, one that can be achieved by prioritizing geomorphic trends in project formulation, and by expanding the scope of habitat restoration to accommodate other missions on the MRG, such as flood risk management and effective water conveyance.

From the beginning, project development should include a conceptual model of the system and the factors contributing to the target problem. Precursors to geomorphic trends, i.e., changes in sediment supply and hydrology, have been well documented as conceptual models. Additionally, there are often historical datasets, such as USGS stream gage data and aerial photography, that can be leveraged to identify prevailing trends in hydrology, sediment transport, and channel form.

Qualitative models are helpful in generalizing drivers. There may be regional conceptual geomorphic models, such as those presented by Massong et al. (2010) or more general morphological change models, such as Lane's Balance (Lane 1954). Since changes to the sediment and water supply are drivers of geomorphic adjustment, the impacts from sediment retention and controlled water operations should be assessed. Actions that exert a control on the fluvial morphological response, such as recurring management actions in the floodway, should be assessed as well. Considering that anthropogenic actions on the MRG are very recent in geologic time scales, it is warranted to conceptualize how their impacts will continue to influence geomorphic adjustment into the future.

Ecological processes are also conceived as a conceptual model, and likely include finer temporal and spatial resolution than processes described in a geomorphological model: seasonal timing and habitat conditions. If a specific project area is in mind, it is warranted to include adjacent ecosystems, particularly vegetation, as construction activities will likely impact areas surrounding the project area.

Once the existing system is characterized with an integrated geomorphic and ecosystem model, the effects of the restoration project through its life cycle, such as site succession and long-term performance can be effectively elucidated. The "No Action" alternative, or the status quo condition, can be better described based on how current geomorphic trends are likely to continue, and habitat management challenges are exacerbated. It is also prudent to consider competing mission goals (e.g., effective conveyance of water and sediment and ecosystem function) and how these are also impacted by geomorphic and ecosystem processes.

Change Influence and Project Impact

Once the conceptual ecological and geomorphological model of the system are established, there may be higher-order influences, such as sediment or streamflow management, that are obviously driving large-scale system adjustments. When considering the sustainability of a habitat management scheme, project managers may be influenced by or have some control of geomorphic change drivers. Figure 2 has alternative management actions prioritized based on drivers that are most likely to sustain desired geomorphic conditions. As one travels down the tiered list, the management actions require greater intervention, i.e. are more construction-intensive. These alternatives require construction on the onset, and are likely going to require recurring maintenance, as the restoration action may not mesh well with the dynamics of the surrounding system.

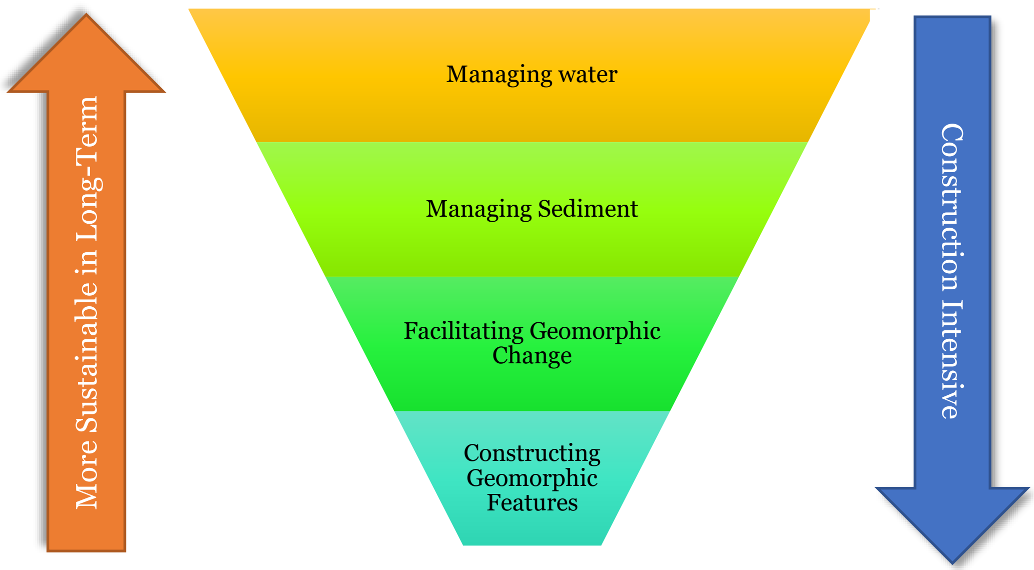

Figure 2. *Ranking of conceptually "construction intensive" and "more sustainable" approaches to working with geomorphic trends in habitat management planning.*

The foremost driver and management alternative is the management of streamflow. Streamflow affects geomorphic feature development and supports riparian vegetative species that further influence planform conditions. In some cases, managing water is not a practicable alternative for habitat management. For instance, climate and land-use change may make required water volume unavailable or water management authorities may not be flexible enough to manage water for habitat management. However, some authorities, such as flood control or water delivery, may benefit from being mindful of habitat requirements. For example, incised, meandering rivers may be a recurring maintenance issue for in-stream or river adjacent structures.

The second approach is sediment management. Sediment supply influences geomorphic change, as a river's energy will either deposit or scour sediment based on the relationship between sediment load, bed material, and transport capacity. Much of the infrastructure challenges in the MRG, whether it be from channel plug formation or increased meanders, are adjustments of the river from a human-made channel to one that can accommodate sediment inputs or lack thereof. Some sediment retention structures may have had design intentions to reduce flooding risks, but as tributaries reach these structures, they lose the energy needed to transport the sediment supply into the MRG and thus cause maintenance issues where the sediment deposits. There are opportunities to reduce sediment retention, either by passing sediment through flood control structures or by reusing dredged materials in beneficial ways, such as filling in low areas of the floodplain that cause flooding concerns.

In areas where sediment has been retained for a long time, i.e., dams, there may need to be testing to determine whether the retained materials contain contaminants. Sediment release may also affect bed substrate, water quality, and channel form. In the MRG, sediment pulses incorporating a wide range of sediment sizes from the watersheds into the MRG are more often associated with the summer monsoons than the runoff from snowmelt. The timing and magnitude of sediment release may affect food sources such as macroinvertebrates or biofilms. Finer grained sediment deposition in overbanking areas may facilitate better growing conditions for vegetation. This is a management approach that would benefit from assessing the geomorphic history of a system, particularly the magnitude and character of change from construction-intensive interventions, such as river channelization or installation of instream structures.

The third alternative is facilitating geomorphic change. In instances where sediment and water control alone cannot sufficiently achieve the habitat management goals, there may be opportunities to still let the river do the work by supporting geomorphic processes. One approach for identifying alternatives is to try to countervail the impacts of previous river engineering efforts directly. An interesting consideration for facilitating geomorphic change or counteracting historical engineering impacts is the scale at which a project should be conducted to be effective. For example, while consideration should be given to a larger watershed, smaller reaches may be effectively restored by considering geomorphic processes. For example, restoration of a half mile reach of the Pueblo Colorado Wash near the Hubble Trading Post, Arizona restored lost sinuosity through previous channelization actions effectively reversing lost floodplain and groundwater connections (Zeedyk 2015). This reach proved to be resilient over time, and prevails despite upstream and downstream segments remaining in a channelized state.

Some examples to counteract levee floodplain dissection and disconnection by river channelization include:

- Levee improvement or reconstruction to allow higher discharges to be released, which may enable streamflow to do the work of changing morphology.
- Infrastructure setbacks to allow for ideal floodplain inundation conditions (i.e., shallow, slow-moving water required for aquatic refugia and foraging) and provide freedom to the river to adjust (Biron et al. 2014).
- Active channel reconstruction to increase vegetated bank areas and side channels that are always wetted.
- Woody debris or other nature-based features to encourage scouring and deposition to create heterogenous channel geometry.
- Planform management for island formation (McComas et al. 2022), including using earthwork or instream structures to foster areas of large velocity/depth change or, if space allows, increasing channel sinuosity.

- Vegetation clearing to increase habitat turn-over and succession.
- Placement of temporary structures to raise the water surface elevation. These were traditionally used to divert water into irrigation canals. The purpose of their temporality is to not exacerbate flooding issues during high flow events.

The final approach is the most typical approach to habitat restoration. This includes earth work and constructed features to emulate the conditions that would be provided by geomorphic change. Excavated side-channels, backwaters, and bankline terraces are examples. Generally, these features do not have the scale or the impact to sustain themselves, and therefore would require maintenance, but they do provide temporary habitat opportunities. The habitat areas provided by these are typically proportionally to excavation footprints, requiring construction costs to increase in order to increase project benefits. Still, being cognizant of prevailing geomorphic trends may increase the resilience of such projects over time.

Overcoming Challenges

This alternative framework aids in navigating challenges presented by innovation in various ways. With any innovation, there are going to be perceived and actual risks. Developing a comprehensive conceptual framework of how geomorphology, hydrology, and ecosystem processes will interact with one another reduces uncertainties and prepares projects for adaptive management. In addition, considering other river priorities, such as flood control and effective conveyance of water and sediment, creates a more comprehensive project supported on a broad range of management objectives. Multiple priorities should always be considered contextually by planners and designers in developing river restoration projects. From a policy sense, it is important that federal teams "formulate" around the Congressionally specified purposes, as the addition of other mission areas may not be allowed.

With risks, there are also tangible economic benefits for considering an alternative habitat restoration management approach. The framework points to two dimensions of project economics which will be discussed with greater detail: 1) project function over its life cycle; 2) multi-purpose projects increasing impact or returns on investment.

First, it may be more palatable for an organization to construct many smaller restoration projects by constructing geomorphic features. However, if these are not congruent with long-term changes in the system, the projects will require recurring maintenance. In the long-term, recurring maintenance may tie up an organization's resources or eventually require the organization to abandon maintenance altogether. This results in a project that provides negligible long-term effects. On the other hand, a project with a larger footprint may require more upfront expense and coordination amongst multiple agencies to negotiate real estate, permitting, or other resources for implementation. However, if the project has a sustainable approach, the benefits cover greater areas and are longer-lasting.

In addition, designs with consideration of fluvial morphological processes: channel bed adjustments, bank lateral adjustments, sediment deposition of the feature, etc. help set realistic expectations related to the anticipated life cycle of the feature. "Project effectiveness" should be framed according to time scales that are relevant to ecosystem processes and restoration goals. In natural systems, the habitat function of a particular area may evolve overtime. Sedimentation and inundation frequencies may drive vegetative patterns that replace one another and evolve over time. Considering that a static system is not natural, having expectations of change on the outset may radically affect project objectives and acceptable uncertainty.

Second, this alternative habitat management framework is an opportunity to assess projects outside the scopes of habitat restoration. Flood control, effective conveyance of water and sediment, and infrastructure protection are all linked to riverine processes, and therefore geomorphic trends may affect project performance over time. River meanders, disconnected floodplains, and channel incision/aggradation are all conditions that may contribute to the need for river projects. The consideration of habitat restoration within the framework of these projects may not be the primary driver of the project but ecological processes may still be beneficial in addressing the morphological issue causing the riverine process of concern. In this framework, addressing an infrastructure concern area due to erosive riverine conditions may indicate that the project occurs away from the problem area. For example, solutions may occur upstream, such as energy dissipation: either by increasing the sediment input or reducing stream power. Issues associated with deposition may need to be approached by increasing accessible areas where sedimentation is suitable, either by increasing channel area or improving floodplain connection.

Conversely, habitat restoration projects may involve the need to address flood control or effective conveyance of water and sediment, requiring a wider implementation scope or additional fluvial processes other than certain habitat feature types. For example, there may be the need to disrupt existing habitat features in order to reset the morphological form that encourages a more diverse ecological community. This disruption in the short term (1-10 years) provides the means to not only more effectively convey water and sediment but in the long term (15-20 years) may provide a richer and more vibrant ecological community. Either way, this alternative framework encourages looking beyond existing conditions and the immediate problem area, among the context of overarching trends. This increases the overall likelihood for sustainable project design and successful management planning.

There are inherent challenges to incorporating this geomorphic framework throughout project development, from planning and implementation phases. Foremost, to change water or sediment drivers requires coordination at potentially contentious regional levels, including navigating legal authorities to modify water operations or water quality concerns related to sediment flushing. Adjacent infrastructure may be impacted from changes in operations, from in-channel water conveyance capacity to levee integrity. In the case of the MRG, some agencies are required to ensure water delivery and any change in wetted channel width or riparian vegetation will need to be carefully accounted for impacts to evaporation and transpiration. In many cases, risks associated with change: flood control and water delivery; are highly scrutinized. Therefore, linking habitat management goals with reducing economic risks (i.e., property loss to fire, flood, recurring maintenance or other legal liabilities) can elevate the relevance of habitat management relative to other, sometimes competing, priorities.

Some aspects of the current environment, though unsustainable, are celebrated recreation sites. In the MRG, there is consistently pushback for any activities to occur in the cottonwood gallery adjacent to the river known as the “Bosque”. The pushback constrains converting riparian areas to better support emerging native vegetation, including young cottonwoods. Educating public about realistic habitat goals and the value of ecosystem processes is a necessary step to reduce resistance to more natural functions. Implementing design elements to encourage public ownership may help with continued community support over time. For example, MRG habitat restoration sites have been constructed in areas used by the public and thus can be designed to encourage public utilization. Creating access points and locations that provide recreation promotes long term support for these systems (Stark et al. 2022).

Another example of changing expectations from an unsustainable condition is accepting erosion as a natural process. While geomorphic trends such as incision and meander migration may create stark features, such as steep banks, this is a necessary step for planform adjustment to "reset" a connected floodplain. Erosion may be troubling near levees and instream infrastructure but does not necessarily need intervention in all instances. Additionally, working to address the causes of the observed changes helps to create a more desirable end state that supports habitat restoration and other management priorities along the river corridor, particularly flood control and infrastructure protection.

Finally, a certain challenge in changing habitat management is the fact that innovations may not achieve the ecological improvement goals as intended. Drivers of habitat degradation may be difficult to disentangle from a changing environment. Therefore, it is important to develop adaptive monitoring and management tools to provide feedback following a habitat management action. The Plan-Do-Check-Act feedback loop should be implemented throughout project development – from the feasibility to the implementation phase, ensuring that performance measures are defined and can be iteratively improved as understanding of the system evolves. Discerning between uncertainty and acceptable risk is an important consideration, as natural systems may change in complex and unexpected ways.

Conclusion

The incorporation of geomorphic change into habitat management provides opportunities to design more resilient projects. This alternative framework introduces potential economic savings in addressing other riverine maintenance issues and in reducing recurring maintenance cost. This includes allowing for natural processes such as vegetative or geomorphic succession, ultimately increasing project longevity and effectiveness. In the current habitat management approaches in the MRG, restoration efforts are patchy, as they are constrained by authorized funding, public opinion and land ownership. Expanding the perspective of habitat management and how it links to other tangible environmental risks, such as fire or flood, may be able to leverage increased stakeholder interest and buy-in. This in turn can expand project footprints in a way that also increases ecosystem function.

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