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Viewpoint

Riverscapes as natural infrastructure: Meeting challenges of climate adaptation and ecosystem restoration

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ABSTRACT

Rivers have been diminished, simplified, and degraded globally by the concentration of agriculture, transportation, and development in valley bottoms over decades and centuries, substantially limiting their ecological health and value. More recently, climate change is steadily increasing stress on aging traditional, gray infrastructure. Recent trends in river management present an opportunity to address both the ecological degradation and climate stress. A strategic focus on riverscapes as critical natural infrastructure can serve as ecosystem-based adaptation to improve resilience to climate change and restore river ecosystem health. As traditional, gray infrastructure ages and fails under increasing climate stress, there is opportunity to rebuild with improved understanding of the value of the ecosystem services that healthy riverscapes provide. River valley bottoms, including source-water wetlands and riverscape floodplains, are the critical natural infrastructure areas deserving of protection and restoration to build resilience to increased frequency and severity of fires, floods and droughts associated with climate change. Since healthy riverscapes need space and water, the long-standing focus on restoring natural flow regimes makes sense. Equally crucial to restoring river health is to give rivers space and freedom to exercise (i.e., flood and adjust their channels).

1. Introduction

Society has relegated rivers and streams to constrained channels and remnant riparian corridors as agriculture, transportation and development have concentrated in valley bottoms. While a robust river restoration industry has emerged, it has been too limited and costly to meet the scale and scope of degradation challenges. The concept of "natural infrastructure"—natural areas managed to provide both ecological and societal benefits by allowing for dynamic, natural processes— presents an opportunity to address increasing climate change stress on aging gray (i.e., traditional, engineered) infrastructure and to improve the effectiveness of restoration. Using examples of process-based river restoration, community response to hurricane-driven flood impacts, and watershed restoration to reduce water treatment costs, this Viewpoint article highlights the potential of natural infrastructure to meet the challenges of climate change and diminishing ecosystem services in riverscapes.

2. The challenges humanity faces: loss of riverscape space coupled with climate crisis

Up to the early years of the 19th century, Native Americans and explorers navigated and drew sustenance from streams and rivers that hardly resembled those of today. Those stream ecosystems would have consisted of networks of beaver-dam ponds, rivulets and riparian wetlands spreading across valley bottoms and flowing into similarly complex and dynamic riverscapes and floodplains (Cluer and Thorne, 2013, 2021).

By the end of the 19th century, to meet the European demand for fur and to drain valley bottoms for agriculture, beavers had been systematically trapped throughout the United States, fundamentally changing the character of stream ecosystems (Wohl, 2020; Dolin, 2010). Timber splash damming and wood jam removal for navigation also made them more efficient conveyors of flow. Streams transitioned from hydraulically inefficient mosaics of wetlands and multi-thread channels to higher energy, single-thread channels that cut down into their floodplains, draining alluvial aquifers and desiccating valley bottoms (Rieman et al., 2015). Paradoxically, hydraulic inefficiency is a hallmark of a healthy

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riverscape (Wohl, 2016; Covino, 2017; Wegener et al., 2017; Bartelt, 2021; Wheaton et al., 2019). Without the structure of beaver dams and log jams, an era of "structural starvation" of riverscapes (sensu Wheaton et al., 2019) unfolded and has continued into the 21st century.

"Structural starvation" is one of many mechanisms that have diminished the values and services associated with historical, healthy, complex river ecosystems. Riverscapes have also been impacted by the loss of space within their valley bottom and freedom for dynamic processes of flooding, erosion and deposition. Across the incredible diversity of riverscapes, nearly all have been systematically trammeled over decades and centuries by encroachment of agriculture, transportation, and development of the floodplain (Fig. 1 A, B and C). Walled in by levees, pinched down at transportation and utility crossings, and stabilized, once hydraulically complex channels (Fig. 1D) have been substantially simplified, driving the steady decline of river ecosystems health (Brown et al., 2018; Wohl, 2021). Further, the regulation and reduction of river flow by dams, reservoirs, and diversions have impacted flow regimes (Nilsson et al., 2005; Poff et al., 1997) such that

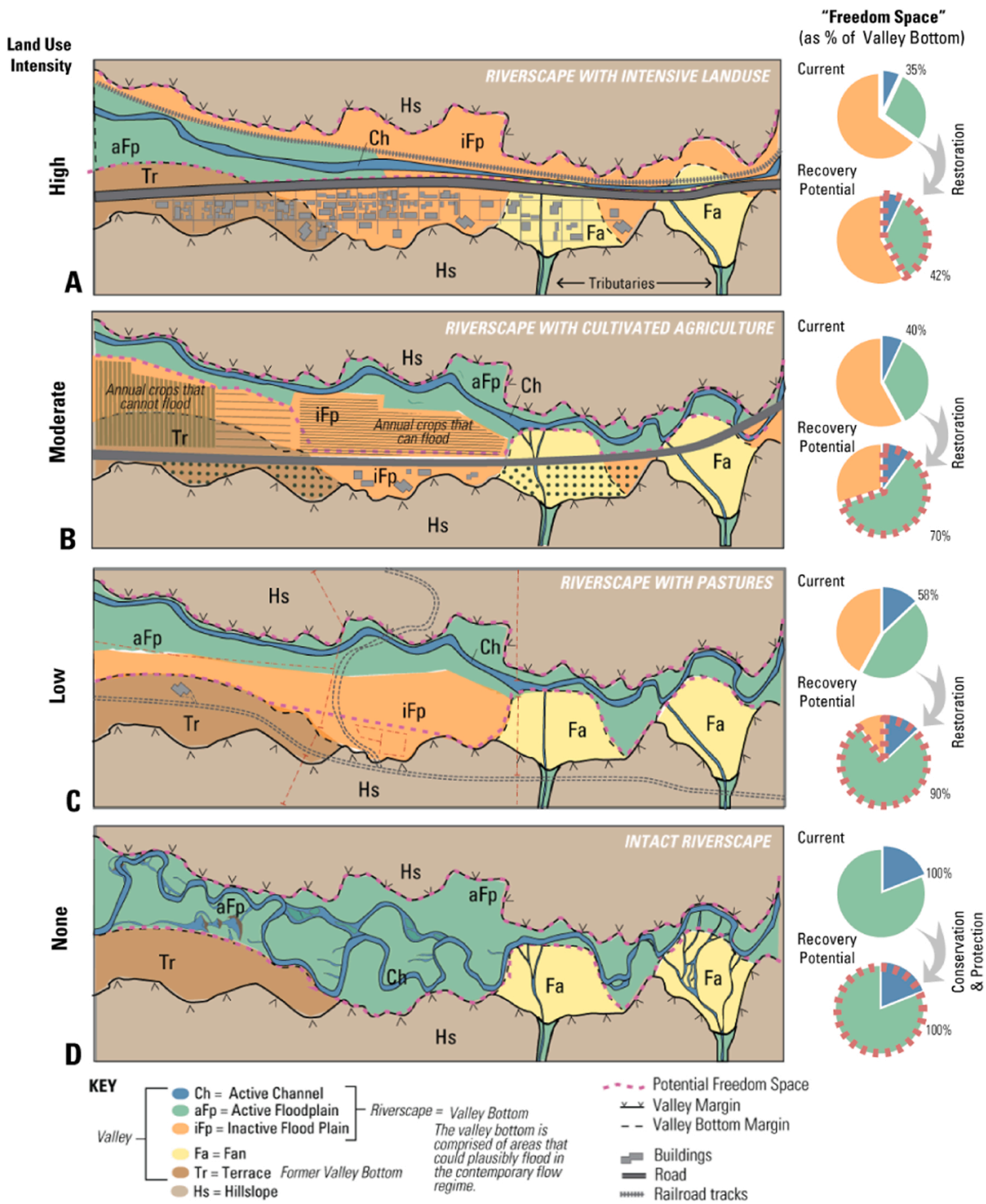

Fig. 1. Natural infrastructure for riverscapes can be expressed as the degree of freedom space (encompassed in red dashed lines) achieved through restoration or protection and available for flooding or adjusting. Hypothetical examples of varying land use intensities (A, B, C) are contrasted with an intact riverscape (D). Some land uses and gray infrastructure can be shared with natural infrastructure. However, the greater percentage of the valley bottom that can be devoted to freedom space, the greater the resilience of that system and surrounding infrastructure will be to disturbances like floods, droughts, and fires.

ecosystem interactions and pathways have been severed or depleted, leading to a disproportionate decline of freshwater habitat and species (Tickner et al., 2020). These compounded, cumulative impacts have reduced ecological resiliency and increased society's vulnerability to floods, fires, and drought.

Water resource and ecosystem health challenges are exacerbated by the unfolding climate crisis (IPCC, 2021). As the golden age of engineered river-related infrastructure withers, climate change is amplifying the frequency and magnitude of stresses on water infrastructure. Floods are bigger and more frequent, straining the capacity of levees and reservoirs in some regions; persistent droughts leave reservoirs critically low in other regions (UNISDR, 2016; Spinoni et al., 2017; Stewart et al., 2020; Salehabadi et al., 2020). It has become impossible to ignore the limitations of aging gray infrastructure to address growing challenges or the extent to which it has accelerated the decline of river ecosystem health and biodiversity. While gray infrastructure was historically justified as an economic engine for many communities and regions (Fox and Smith, 1990), new perspectives informed by ecosystem services economic theory and analysis expose long-held misconceptions of its economic viability when ecosystem services have been left off the balance sheet (Reisner, 1993; Bunse et al., 2015).

3. Current restoration paradigms don't meet the scale and scope of challenges

Recognizing the precipitous loss of riverine biodiversity and ecological values and services, governments have responded for half a century by funding innumerable, opportunistic acts of restoration (Bernhardt et al., 2007). Traditional stream restoration approaches are too expensive and small in footprint to match the scale and scope of challenges. In the United States, the river restoration industry has implemented a preponderance of piece-meal, project-scale tactics that emphasize static habitat and channel reconstruction rather than restoring ecosystem processes that can sustain values over time (Lave and Doyle, 2020; Ciotti et al., 2021).

Ironically, the most common river restoration efforts have focused on re-creating simplified streams with only modest and temporary gains to show for their efforts (Wohl et al., 2015). Because streams have persisted in these altered and simplified states for so long, little conceptual awareness of historical stream condition remains (Goldfarb, 2018a; Wohl, 2019). By the time river scientists began measuring and classifying streams, they were already dramatically changed, distorting even the scientific assessment of natural condition and potential. A generation of restoration practitioners were limiting restoration effectiveness by relying too heavily on current simplified river conditions as "natural" templates for restoration (Wohl, 2011). Such reference-based restoration was routinely criticized for failing to account for the critical importance of dynamic process, system complexity, and resiliency as core objectives for restoration and ecosystem sustainability (Tullos et al., 2021).

In the past decade, however, an emerging awareness of the ecological potential of historical, structurally and hydraulically complex stream conditions suggest opportunities to correct course in restoration practice. Increased emphasis on process-based approaches to restoration (Beechie et al., 2010; Wohl et al., 2019; Powers et al., 2018; Ciotti et al., 2021) presents both a vision and a path for restored ecological potential.

4. Process-based restoration paradigms provide solutions

The Decade on Ecosystem Restoration (U.N. Environment Agency, 2019) begins with a hopeful intersection of insights into the advantages of new restoration paradigms (Young and Schwartz, 2019). First among these insights is an improved understanding of the highest ecological potential of riverine ecosystems and recognition that common approaches to restoration have still left conditions well below historical potential. Process-based restoration strategies offer an alternative approach with improved outcomes (Ciotti et al., 2021). Such approaches have restored complex riparian wetlands at or near historical ecological potential that now function as a filter and sponge to retain sediment and runoff, recharge distributed alluvial aquifers, and store and slowly release clean water through dry seasons and drought to support fisheries (Fairfax and Small, 2018).

Monitoring of recent restoration projects has started to expand understanding of what works. Continually monitored since 2005, Bridge Creek (Oregon, USA) became one of the first carefully documented experiments and demonstrated successes of partnering with beaver in restoration (Bouwes et al., 2016; Goldfarb, 2018a, 2018b). In Bridge Creek, installation of stick and post dams led to the expansion and persistence of beaver dam activity, a dramatic increase in the quantity (i.e. space) and quality of aquatic habitat, and increased juvenile abundance, survival, and productivity of endangered steelhead trout (Oncorhynchus mykiss). The Bridge Creek restoration came at a time of enlightenment within the community of river scientists and restoration practitioners. In concert with case studies and research documenting the ecological benefits of preserving or reintroducing in-channel wood in forested streams and floodplains (Grabowski et al., 2019; Swanson et al., 2019), scientists also began to understand the full-potential river ecosystem state. The perception of natural condition for streams began to shift from picturesque, meandering, single-thread channels to hydraulically inefficient, wetland-stream complexes (Fig. 2) where "messy" is a virtue and an indicator of habitat value (Wheaton et al., 2019). With the increase in beaver dam building activity (a key process), Bridge Creek has recovered the functional use of more of its riverscape. Although monitoring revealed improvements in habitat quality, the dramatic expansion of habitat helped to explain the positive population response. Cluer and Thorne (2013) captured the essence of this space argument with what they termed *Stage 0* – a pre-disturbance condition representing a multi-thread channel network occupying the entire valley bottom.

Stage 0 was just one part of an expansion of a long-standing, conceptual channel evolution model that switched the focus to the possibility of messier, more connected riverscapes and captured the imagination of many in the restoration community (Powers et al., 2018). Although not the first to suggest such ideas, Cluer and Thorne (2013) captured a growing sentiment within riverscape literature on engaging natural processes to expand the proportion of the valley bottom that could be "active" and to do so using "structural forcing" (wood, beaver dam structures, vegetation; see also Gurnell et al., 2019; Chin et al., 2021). A greater active proportion of the valley bottom (i.e. active channels and floodplain) provides substantially greater ecological value for wildlife and can be initiated with low-tech, low-cost tactics at broad scale in most types of streams (Wheaton et al., 2019; Ciotti et al., 2021). There is growing evidence that in addition to self-sustaining, durable fish and wildlife benefits, *Stage 0* restoration can provide such critical services as carbon sequestration (Sutfin et al., 2016), nutrient capture (Puttock et al., 2018), the provision of persistent streamflow (Puttock et al., 2017) and moderated stream flow and temperature in the face of drought and climate warming (Brazier et al., 2021). The story of Bridge Creek, among other recent and ongoing *Stage 0* restoration efforts (Powers et al., 2018), highlights the potential for restored wetlands, stream systems and floodplains (collectively riverscapes) to serve as natural infrastructure.

A second insight is in the awakening to the value of healthy river ecosystems (Yeakley et al., 2016) and the cost to communities of limited and lost ecosystem services. Though ecosystem markets valuation is indeed emerging, markets have been narrow in scope and rarely efficient enough to entice traditional financing or shifts in policy. But we have reached a pivot point. Payment for ecosystem services models have produced enough functioning examples to shift policy to accommodate the valuation of services provided by nature (Busch et al., 2021). There is increasing acknowledgment among resource managers and impact investors that these services and costs deserve to be part of resource and

Fig. 2. Illustration of the process of encouraging beaver dam activity with beaver dam analogs (BDAs) and how this can lead to (on right) self-sustaining Stage Zero conditions (anastomosing or multi-threaded channels around island complexes).
(Source: Goldfarb, 2018b).

infrastructure valuation. Where cost-benefit analyses required for public funding of infrastructure or resource extraction projects once ignored the ecosystem functions and services impacted or lost, some now require such valuation (e.g., 115th Congress, 2018).

Communities and resource managers are also recognizing the ecosystem service value of natural floodplains. Ten years ago, Hurricane Irene struck the northeastern United States. Floods and debris flows wiped out homes, businesses, and communities (Baird, 2021). As floodwaters receded, powerful diesel machines descended to reclaim livelihoods and shore up flood defenses. But again, the confluence of evidence and new ideas spurred alternative responses in some communities that recognized the folly of rebuilding within flood prone areas (Inside Climate News, 2016). Resource agencies and scientists teamed up to develop RiverSmart Communities guidance (Vogel et al., 2016). Rather than fortifying against floods with engineering and rigid structures, some communities are now avoiding flood damage and reducing costs by providing space for rivers to migrate across and inundate their floodplains (Buffin-Bélanger et al., 2015). As the frequency and magnitude of devastating storms and floods increases, some U.S. local and state governments (Colorado, Montana, Oregon, Washington) are now mapping channel migration or flood hazard zones to inform planning and development (Warner et al., 2018; Blazewicz et al., 2020). Communities are recognizing the practical limits of traditional infrastructure and are reconsidering the strategy of "controlling" floods. Once novel concepts of setting levees back to provide space for floods, relocating structures out of the floodplain, and re-configuring bridges and crossings to accommodate dynamic channels are now recognized as viable components of infrastructure management. These community-driven, adaptive responses can reduce vulnerability and build resilience to climate change and generate substantial ecological recovery as a byproduct, if not as an intentional companion goal.

A third insight is that where popular restoration practice has too often focused on creating carefully designed, static habitat features within simplified and stabilized river channels, opportunity is available to refocus restoration on removing constraints wherever possible – setting levees back, concentrating infrastructure into fewer pinch points, removing or limiting channel-stabilizing features, and renewing native riparian vegetation communities. Removing constraints on river processes provides greater return on investment than constructed habitat features whose benefits are temporary at best (Ciotti et al., 2021; Wohl, 2021). River ecosystems have a tremendous capacity for passive restoration if given the space for dynamic interactions between the channel and floodplain (Kondolf, 2011). *Freedom Space* (Biron et al., 2014), the valley bottom floodplain area for rivers' dynamic processes of flooding and meandering, is emerging as an important principle guiding river restoration (Ciotti et al., 2021) and is well-aligned with flood resilience guidance for communities (Naturally Resilient Communities, 2021). Incentivizing *Freedom Space* for rivers within the valley bottom (Fig. 1A-D) benefits both the human community, in the form of natural infrastructure, and the river ecosystem.

5. Allowing freedom space for riverscapes is an investment in natural infrastructure that provides climate resiliency

The environmental strains of expanding human populations are exacerbating the impacts of a warming climate (IPCC, 2021) and straining the capacity of gray infrastructure to provide water security and mitigate increasing floods and drought (Vigerstol et al., 2021). News cycles are overloaded with pronouncements of risk to once secure water treatment and delivery systems and scenes of tragedy stemming from increasingly common floods, fire, and droughts (Reichstein et al., 2021). Water quality is declining where increases in precipitation and floods wash more pollutants into rivers; droughts are depleting reservoirs that sustain cities and farms. Traditional, gray infrastructure developed under different climate regimes can no longer practically address the contemporary scope and scale of these stresses. These events and threats expose the obsolescence of many 20th century projects that may now cost more to remove than they did to build.

Insights regarding the potential for natural infrastructure to provide cost-effective, self-sustaining alternatives and complements to gray infrastructure are increasingly apparent. These alternatives address challenges for urgent water resources and natural hazards problems and can simultaneously restore ecosystem health. Natural infrastructure may prove to be a critical component of a mix of solutions to complex ecological and societal challenges and as a keystone to any successful regional, national, or global restoration strategy. It requires two strategic actions to regain as much space in riverscapes as possible. First is the protection of remaining riverscapes in recognition of the value they provide as natural infrastructure. Second is a need to seize on the political opportunities created by damages from "natural disasters" by rebuilding outside of these dynamic natural spaces.

The Bridge Creek and RiverSmart cases highlight elements of a strategic pathway and guiding principles for restoration of riverine ecosystems as humanity embarks on the United Nations Decade on Ecosystem Restoration. The marriage of emerging *Stage 0* and *Freedom Space* approaches with practical climate adaptation strategies creates an opportunity to employ natural infrastructure to address the triple challenge of: (i) restoring ecosystem function and services, (ii) improving security to communities dependent on rivers for irrigation and clean drinking water, and (iii) adapting to climate change.

A natural infrastructure strategy warrants distribution of natural features on the landscape at relevant scales. In 2012, despite the far-reaching impacts of Hurricane Sandy, New York City continued to provide clean water to its municipal customers because of its previous investments in natural infrastructure. By investing ~$100 million annually in rural communities to improve forest and river health through payments for ecosystem services (derived from natural infrastructure), New York City has saved billions (U.S. dollars) and obviated the need for an additional water filtration plant (Appleton and Moss, 2017). Cities across the country are evaluating and investing in natural infrastructure to reduce capital expenditures and annual maintenance costs while providing both water security and ecological benefits (Vigerstol et al., 2021). And as dramatic fire seasons have devastated forests, areas where beaver have created "emerald refuges" (Fig. 3) reveal the resilience of those valley bottoms to fire and their capacity to capture post-fire sediment that would otherwise choke downstream water treatment plants and reservoirs (Fairfax and Whittle, 2020). Widely distributed wetland features capture, retain, and filter runoff from rain and snowmelt, modulate floods and provide cost-effective alternatives or reductions to drinking water treatment facilities and irrigation storage needed to meet current and future municipal and agricultural water supply. These features also provide complex, heterogenous wetland and riparian habitat essential to restoring ecosystem health.

Further down in the watershed, where smaller streams join to form rivers, floodplains also serve as natural infrastructure by providing storage and filtration benefits. The Bear River (River Partners, 2021) in California, where levees were set back, reconnecting 250 ha of flood-prone farmland, is just one example of a growing number of levee setback projects that have served to address traditional infrastructure limitations while also restoring habitat. The project has reduced flood risk by increasing the capacity of the floodplain, improved water quality by reducing flood-prone farmland, and provided a carbon sink and expanded habitat as the riparian forest matures. Examples of pilot-scale projects like this are plenty and critical for inspiration and demonstrating potential.

Fig. 3. Beaver ponds create an emerald refuge within a landscape recently scorched by fire in Idaho. (Photo: Creative Commons Attribution Only - Joe Wheaton 2018).

6. Conclusion

Global trends in the loss of riverscape ecosystems services and biodiversity are exacerbated by changing climate. At the same time, climate change is stressing aging infrastructure and threatening water security. Natural infrastructure, in the form of restored riverscapes, can address stresses to water security while providing co-benefits to society and nature. Protecting and restoring space for riverscapes is the cutting edge of coordinated river and resource management. Now is the time to open the door to recognizing riverscapes and natural processes as critical natural infrastructure and as the conservation and restoration pathways necessary to meet the challenges of this Decade on Ecosystem Restoration.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The second author, Joseph Wheaton is the co-owner and principle of a consulting firm, Anabranch Solutions. The company helps clients plan, design, build and adaptively manage low-tech process-based riverscape restoration projects. This potential conflict of interest is proactively managed from becoming realized with a conflict of interest mitigation plan filed with Professor Wheaton's primary employer, Utah State University, and is publicly declared here: https://www.anabranchsolutions.com/mitigating-potential-coi.html.

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