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Managing Infrastructure in the Stream Environment

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Research Impact Statement: We present a framework for infrastructure designers and managers to build and manage riverine infrastructure in a manner that is both resilient to hazards and more compatible with stream ecosystems.

ABSTRACT: Riverine infrastructure provides essential services for the operation and development of the world's nations and their economies. When much of this infrastructure was built in the United States, fluvial processes and stream ecology were not well understood, putting it in conflict with and at risk from the stream environment. High maintenance costs are often required to keep such infrastructure viable and some of it has led to the degradation of aquatic and riparian ecosystems. This commentary paper lays the foundation for infrastructure designers and managers to build and manage infrastructure in a manner both resilient to riverine hazards and more compatible with aquatic and riparian ecosystem needs. We introduce fundamental fluvial geomorphic and ecosystem concepts and provide a decision-making framework to replace or repair existing infrastructure or build new infrastructure. Common management challenges associated with 11 riverine infrastructure types are discussed and we provide suggestions on how each infrastructure type can be better built and managed within stream corridors. We close with a discussion on managing infrastructure under future hydrologic uncertainty and in response to natural disasters.

(KEYWORDS: rivers; aquatic ecology; riparian zone, sustainability; resiliency; restoration; floods; natural hazards.)

INTRODUCTION

Government agencies, along with private citizens, have worked to construct and manage a vast network of infrastructure within stream corridors. This riverine infrastructure and associated activities includes channel and floodplain works (channelization, large wood management, and floodplain encroachment), streamside infrastructure (roads, pipelines, levees, streambank protection), and stream crossing infrastructure (bridges and culverts, pipelines, grade control structures, dams, reservoirs, and surface water diversion structures). We define riverine infrastructure broadly herein to include a spectrum of human activities in the stream corridor that fall under the umbrella of public works, stream engineering, and stream management. Riverine infrastructure provides vital services but is frequently detrimental to stream ecosystems and can pose a liability in terms of public safety and maintenance costs (Doyle et al. 2003; Nilsson et al. 2005; TRB and NRC 2005).

A large proportion of the infrastructure in the United States (U.S.) was built in the early and middle 20th Century and is nearing the end of its

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design life (Doyle and Havlick 2009), defined as the time period infrastructure is designed to function assuming routine maintenance. During this construction boom, impacts to the stream environment from infrastructure, as well as impacts of dynamic streams to infrastructure, were not often considered as modern environmental and floodplain regulation either did not exist or was nascent (H. John Heinz III Center for Science, Economics and the Environment 2008; Doyle and Havlick 2009). Furthermore, infrastructure designers did not benefit from the current scientific understanding of stream processes and hazards. Some existing infrastructure is not compatible with the stream environment and unsustainable without high maintenance costs and ongoing degradation to stream ecosystems (Pielke 1999; Levine 2013). Failure of riverine infrastructure due to aging and stream hazards is a threat to public safety (ASCE 2017). Given these issues, the U.S. is currently at a juncture where infrastructure management and ecosystem rehabilitation may find mutual solutions (Doyle et al. 2008). As new infrastructure is built and old infrastructure is replaced, repaired, or decommissioned, we have an opportunity to increase both infrastructure resiliency and improve (or reduce impacts to) aquatic and riparian ecosystems by building stream-compatible infrastructure.

In this paper, we present foundational concepts and a decision-making framework for infrastructure designers and managers to understand how to build, maintain, or repair infrastructure in a manner that is both resilient to riverine hazards (i.e., erosion during floods and channel migration) and aligned with local stream ecosystem needs. We first introduce concepts relating to physical and ecological stream processes. We present common problems as well as stream-compatible design approaches for 11 types of riverine infrastructure. We then present steps for replacing, repairing, removing, or building new infrastructure within the stream corridor. We conclude with a discussion on managing infrastructure under hydrologic uncertainty and rebuilding after a natural disaster. We provide managers and designers with the knowledge and tools to begin the conversation about how to best manage riverine infrastructure, increase their resiliency, and improve stream ecosystems. This paper follows the recent publication of a comprehensive guidance document for managing riverine infrastructure, published through the Advisory Committee on Water Information, Subcommittee on Sedimentation, Infrastructure and Environment working group (Sholtes et al. 2017, https://acwi.gov/sos/pubs/managing_infrastructure%20_in_the_stream_environment.pdf). Design and management guidance documents specific to the various types of riverine infrastructure discussed herein can be found in this companion document.

FUNDAMENTALS OF PHYSICAL AND ECOLOGICAL STREAM PROCESSES

Stream corridors are dynamic and complex systems that support aquatic (within the stream), riparian (adjacent to the stream), and terrestrial (land-based) ecosystems. In this paper, we use the term stream to refer to all linear waterways from creeks and washes to rivers. Stream corridor refers to the stream and adjacent lands within a stream valley and active floodplain. Streams continually change at rates related to their position within a watershed and the erodibility of their bed and banks (Lisenby and Fryirs 2016). Alluvial streams are those which are able to modify their bed and banks via erosion and deposition of sediment.

Physical Processes

Streams are not naturally static features, but are rather in an active state, capable of transporting, storing, and remobilizing sediment, wood, and nutrients. The prevailing flow regime and sediment supply mediated by local geology and vegetation are the dominant controls influencing unaltered channel form and geometry (Leopold et al. 1964). Over a relatively short time period (years to decades), streams may adjust their width and channel position due to continuous or abrupt lateral migration resulting from frequent to infrequent floods. Their meander bends typically migrate downstream and across the valley bottom. Over longer time periods (decades to centuries), assuming stationary flow and sediment regimes as well as no anthropogenic channel alterations, these streams may be in dynamic equilibrium (Schumm and Lichty 1965). Streams in dynamic equilibrium maintain average values of width and sinuosity over time, but can be expected to temporarily widen or deepen in response to short-term disturbances (i.e., floods, drought, or fires) (Knighton 1998).

When changes in the flow regime or sediment supply occur, a channel falls out of equilibrium and begins to adjust away from its original form. Channel adjustment to disturbances often follows the channel evolution model, which characterizes this adjustment through a series of stages ultimately resulting in a new dynamic equilibrium (Schumm et al. 1984; Hupp and Simon 1991; Cluer and Thorne 2013). Disturbances may include changes in the magnitude and frequency of floods due to urbanization or physical changes to the channel such as channelization and confinement by floodplain encroachment. Understanding if a channel is adjusting to an anthropogenic disturbance and where it may be in these stages of evolution can better inform infrastructure siting, design, and riverine hazards and guide the rehabilitation of degraded aquatic and riparian habitats.

Floods, and the resultant physical response of stream corridors, are the primary hazard of concern to riverine infrastructure. This hazard primarily relates to inundation of the valley bottom and hydraulic forces from floodwaters, which may damage infrastructure such as bridges, diversion dams, and roadway embankments. Other flood-related hazards include stream channel movement, erosion, and deposition of sediment in the stream corridor, and erosion of adjacent hillsides (Piégay et al. 2005; ASFPM 2016). Channel migration and floodplain transformations during floods may force flood waters to encroach outside of the regulated or mapped floodplain and cause damage in unexpected locations. The channel migration zone is defined as the area within which the channel currently occupies, has historically occupied, or could occupy or influence in the future (Rapp and Abbe 2003; Jagt et al. 2016).

The magnitude and frequency of floods may change over time, often due to urbanization or other land-use changes. Urbanization and associated increases in runoff typically amplify the peak flow rate, especially of frequent to moderately frequent flood events (Konrad and Booth 2002; Vogel et al. 2011). Changes in climate are expected to lead to greater magnitude and frequency of extreme weather but projected trends vary by region, and there are large uncertainties in projections (Sillmann et al. 2013; Melillo et al. 2014). Nevertheless, flood-prone areas in the continental U.S. are predicted to increase throughout the 21st Century as a result of climate change (FEMA 2013). This trend, coupled with continuous development in the U.S., results in an increasing amount of infrastructure and property located in hazardous areas (Pielke 1999).

Ecological Processes

The ecological health of a stream system is complex and dependent on interactions of a variety of components and processes, some of which are discussed in this section. Fundamental to ecological theory is the presumption that habitat heterogeneity and biodiversity are coupled (Kerr and Packer 1997; Palmer et al. 2010). Physical complexity in stream form, known as a "messy stream," provides a diverse range of physical habitat that supports a diverse array of species and their life stages. Messy streams are loosely defined as streams with natural deposits of large woody material, bank erosion, and sediment bar deposition. Messy streams may exhibit a multi-threaded planform, which is often induced by the presence of woody vegetation, large wood in the channel and floodplain, as well as beaver dams (Wohl 2016). In many systems, a variety of human impacts have simplified streams with multiple active channels (multi-threaded) into single channel streams resulting in a loss of habitat heterogeneity and ecosystem diversity (Walter and Merritts 2008; Cluer and Thorne 2013).

The longitudinal and lateral connectivity of water, sediment, wood, and organisms are factors in the ecological health of stream systems (Ward 1989; Kondolf et al. 2016). For example, a flood control project may separate the stream from its floodplain, or a dam with reservoir storage may disrupt the continuity of water and sediment downstream along with the passage of aquatic organisms. Dams and reduction in inundated areas also create barriers for fish accessing headwater or floodplain habitat for spawning and rearing (Olden 2016). Streamside infrastructure, such as riprap-protected banks, can decrease lateral connectivity to the floodplain by limiting a stream's ability to migrate and maintain dynamic floodplain habitat necessary for many aquatic species life stages. Armored banks are cited as an important limitation to the generation and maintenance of habitat for endangered salmonids in the Columbia River Basin (NMFS 2014). Indeed, erodible corridors (Piégay et al. 2005) and intact riparian zones are critical components of a healthy stream ecosystem as they provide food for the aquatic insect food base (Gregory et al. 1991), physical habitat for fish (Fausch and Northcote 1992; Marcarelli et al. 2011), and buffer nonpoint source pollution (Osborne and Kovacic 1993; Dosskey et al. 2010). Agriculture and urban development have drastically reduced riparian forest cover in North America which has had adverse effects on water quality, channel stability, and aquatic and riparian habitat (Welsch 1991).

MANAGEMENT OPTIONS

Management challenges and solutions associated with 11 types of riverine infrastructure and channel or floodplain modifications are presented in Table 1. Figure 1a provides examples of riverine infrastructure that are at a higher risk of damage from fluvial hazards and result in greater negative ecological

TABLE 1. Management challenges and options pertaining to riverine infrastructure.

Riverine infrastructure	Management challenges	Management solutions
Channel and floodplain modification		
Stream channelization is defined as the straightening and shortening of a reach of stream. It is practiced as a local flood control measure and means to drain wetlands for agriculture	Channelized reaches increase flooding downstream because less flow is stored locally in the floodplain. Local steepening from channelization often results in channel incision and widening. This leads to streambank failure, introducing excessive fine sediment to the stream (Nakamura et al. 1997). This can also draw down the groundwater table, leading to die off of riparian vegetation (Bravard et al. 1999)	Restoration of channelized reaches may involve rerouting the stream back into its historic channel, or excavating a new channel with greater sinuosity. In-channel structures may introduce some physical complexity, meet channel stability goals, and improve habitat (Newbury and Gaboury 1993; Bernhardt and Palmer 2007)
Large wood in streams results in more abundant and complex habitat for aquatic species. Wood recruitment occurs within forested riparian zones from tree fall and bank erosion	Natural wood recruitment is limited by bank armoring and riparian clearing. Wood poses a hazard to infrastructure by racking during floods, reducing flood conveyance of stream crossing infrastructure, and compromising navigation channels. As such, it has historically been removed from streams (Wohl 2014)	Risk analysis can aid managers in deciding where and when it is acceptable to leave large wood in streams (Wohl et al. 2016, Mazzorana et al. 2018). Engineered wood structures are increasingly used for habitat restoration and channel stability (Brooks et al. 2004; Pess et al. 2012). These structures can be designed to mitigate risk (BOR and ERDC 2016). Riparian buffer protection, revegetation, and removal of bank armoring is necessary to reestablish natural wood recruitment (Abbe and Brooks 2011)
Floodplain encroachment occurs with development and earthen fill in the floodplains and bridge and roadway embankments that cross or parallel a river	Infrastructure within floodplains is exposed to flood hazards including inundation and fluvial scour or deposition. Floodplain encroachment reduces a floodplain's ability to naturally store and convey floodwaters, which can increase flooding downstream, resulting in local and downstream channel instability and impacting sensitive riparian habitat (Jordan et al. 2010; Ndabula et al. 2012)	Floodplain development should first be avoided by removing obsolete infrastructure, relocating old or damaged infrastructure, and siting new infrastructure outside of the floodplain (Pottier et al. 2005). Infrastructure within the floodplain should be designed for flood resiliency (Lennon et al. 2014). Mitigation measures should focus on rehabilitating neighboring floodplains along the same water body
Stream crossing infrastructure		
Grade control structures are typically constructed in channels that are experiencing or could experience incision, which would otherwise progress upstream	Grade control structures can limit downstream movement of sediment and boats and upstream passage of aquatic organisms (Litvan et al. 2008). The stream can laterally migrate around or flank the structure, resulting in downstream scour and bank erosion	Grade controls should be designed and constructed appropriately for the channel type and geomorphic context (Snyder 2012). Where applicable, multiple lower height grade control structures or rock ramps are generally preferred over a few larger structures to allow upstream migration of aquatic species (NRCS 2007a)
Dams create reservoir pools for a wide variety of purposes including municipal and industrial water supply, irrigation, flood control, hydropower, recreation, and providing downstream minimum flows for navigation	Dams can change the quantity and timing of streamflows and trap sediment. Changes to downstream flow and sediment regimes can lead to changes in the stream corridor such as incision, bank erosion, and bed armoring (Hadley and Emmett 1998; Brandt 2000). Trapped sediment reduces water storage capacity of the reservoir and can clog intake infrastructure. Dams act as longitudinal barriers to aquatic organisms and boats	Environmental impacts of dams can be mitigated through a variety of actions including: establishing minimum streamflows for aquatic habitat, providing periodic high flows to reset and restore physical habitat, releasing water from different reservoir elevations to achieve the desired water temperature, providing fish passage infrastructure, reservoir operations or retrofits to pass the upstream sediment supply through or around the reservoir, and dam removal (Richter and Thomas 2007; Tullos et al. 2016; Randle and Bountry 2017)
Surface water diversions redirect water from streams for agriculture, municipal, and industrial use. They are typically much smaller than storage dams	Diversion structures raise the water surface upstream. These small structures typically block fish passage, locally trap sediment, and can create hazards for boaters. Active diversions at lower flow periods may result in higher than normal water temperatures and less available aquatic habitat (Meier et al. 2003)	Rock ramps or bypass channels constructed as retrofits or replacements for diversions can provide passage for target organisms (Mooney et al. 2007). Diversion weirs constructed from natural materials (i.e., cobble and boulders) or infiltration galleries can provide the same diversion needs while reducing maintenance costs and boater hazards

(continued)

TABLE 1. (continued)

Riverine infrastructure	Management challenges	Management solutions
Bridges and culverts allow transportation networks to cross streams, conveying streamflow underneath	Upstream flow constrictions at bridges and culverts and ineffective energy dissipation downstream may endanger these structures due to scour or sedimentation and clogging with debris upstream (Richardson et al. 2001; Gschnitzer et al. 2017; Schmocker and Weitbrecht 2013). Downstream scour and high flow velocity through these structures may block fish passage and decrease habitat for the aquatic insect community (Blakely et al. 2006; Anderson et al. 2012)	Wider spans that, at a minimum, are sized to bankfull flow width and proper placement and alignment of bridges away from actively migrating reaches of a channel reduces scour potential. As an example, the "Stream Simulation" approach for designing road-stream crossings restores geomorphic and ecological function, provides aquatic organism passage, and improves infrastructure flood resiliency (Cenderelli et al. 2011; Gillespie et al. 2014). Driftwood bypass or retention structures can be another effective way to decrease blockage at stream crossings (Schmocker and Weitbrecht 2013)
Streamside infrastructure		
Pipelines carrying water, waste water, fossil fuels, and hazardous chemicals cross or parallel streams	Pipelines can become exposed by gradual or abrupt stream movement and then subjected to hydraulic forces and debris racking during floods leading to ruptures and risks to aquatic and habitat and species (Castro et al. 2015)	Appropriate lateral setbacks and vertical burial depths for new pipelines are necessary to mitigate the potential for pipeline exposure and rupture. Event-based scour and long-term channel incision along with lateral migration should be evaluated by a fluvial geomorphologist (NRCS 2007b; PHMSA 2016)
Levees, embankments, and dikes have been constructed to protect agriculture and development in otherwise flood-prone areas	By reducing the hydrologic connection with the floodplain, levees increase flood levels elsewhere, increase stream velocity, and reduce available floodplain and riparian habitat. Levees reduce flood attenuation and concentrate flood flows within the channel resulting in higher flood stages (Di Baldassarre et al. 2009). Levees are often politically easier to build than implementing nonstructural alternatives, which may be more cost-effective and ecologically beneficial (Tullos 2018)	Given the existing development they protect, some levees are critical infrastructure. Opportunities to set back or remove portions of a levee system can both restore floodplain habitat and reduce flood hazards for other critical areas (Florsheim and Mount 2002; Dierauer et al. 2012). When a new levee is proposed, assessments should consider historical channel migration patterns (Larsen et al. 2006)
Streambank protection may be warranted where natural channel migration threatens infrastructure or bank erosion presents a water quality and habitat impairment concern	Traditional streambank stabilization incorporates hard engineering approaches such as riprap blankets and may be necessary to protect certain infrastructure or land uses. Hard engineering approaches may require continual maintenance and result in ecological impacts. Unprotected banks downstream can be made more susceptible to erosion	Though many alternatives exist, riprap is often the default streambank stabilization method. Flow deflection structures can reduce bank erosion by changing near-bank flow patterns (Radspinner et al. 2010). Bioengineering incorporates living elements within stabilization measures and provides a similar level of protection along with an ecological benefit (Sudduth and Meyer 2006; Baird et al. 2015). Removing streambank protection where natural migration is tolerable should also be considered (Florsheim et al. 2008)
Roadways are a critical piece of infrastructure. With typical planning and design approaches, roads inevitably cross and parallel streams and rivers	Roads and their embankments parallel to a stream limit natural channel movement and disconnect the channel from its floodplain (Blanton and Marcus 2009). Constricting floodplains can increase the potential for channel scour and roadway failure during floods (Yochum et al. 2017). Runoff from roads to streams can be contaminated with heavy metals, oils, salts, and other chemicals (USFS 1999)	Siting proposed roads away from channel migration zones and outside of floodplains can reduce the potential for road damage from floods and protect ecologically sensitive riparian areas. Improved drainage and grade control at outfalls can reduce the runoff volume and improve the water quality for existing roadways. Roadway needs, impacts, and benefits should be evaluated at a system scale to inform management decisions (USFS 1999)

impacts compared with more resilient and stream-compatible infrastructure presented in Figure 1b. We present real-world examples of stream-compatible infrastructure in Figure 2. Additional details on fluvial processes, infrastructure examples, and management and design guidance associated with each infrastructure type can be found in Sholtes et al. (2017).

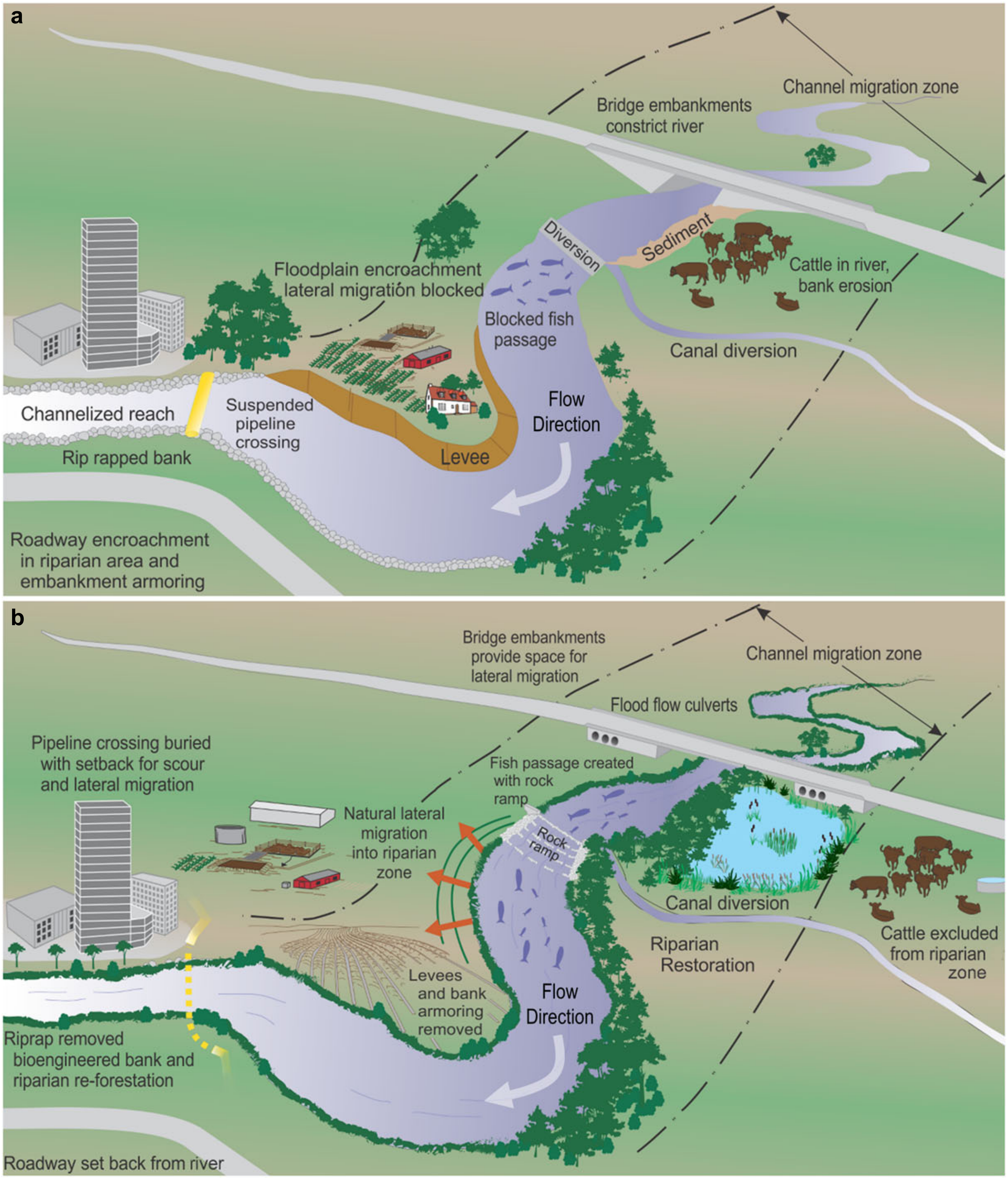

FIGURE 1. (a) Illustrations of riverine infrastructure with greater impacts to physical stream processes and ecosystems and greater exposure to riverine hazards. From upstream to downstream: a bridge abutment constricts the channel and may be exposed to channel migration hazards. Cattle with direct access to the stream can destabilize the bank and introduce fine sediment. A diversion dam blocks fish passage, and a levee within the channel migration zone blocks natural migration. Riprap along the banks protects a road adjacent to the stream and reduces channel migration and riparian vegetation. A pipeline has been exposed due to channel incision and is now more vulnerable to rupture. Finally, the stream was channelized and its banks armored to accommodate development within the floodplain. (b) Examples of more resilient infrastructure that permit a greater degree of channel movement and support ecosystem processes beginning upstream with bridge abutments that do not constrict the channel. Moving downstream, cattle have been fenced away from the stream and provided an alternate water source. A rock ramp replaces the former diversion dam allowing for fish passage. The levee has been removed or set back to accommodate channel migration. Farming continues in the floodplain. Riparian restoration has reintroduced woody vegetation along the stream. The pipeline has been buried below the estimated long-term scour depth over a width that accommodates channel migration. Finally, the roadway has been set back and riprap removed. Bioengineered banks provide stability and reintroduce native vegetation along the banks.

DECISION TOOL FOR MANAGING RIVERINE INFRASTRUCTURE

A framework for considering sustainable and resilient approaches to infrastructure design and management as discussed in Table 1 is outlined in a decision tool flowchart presented in Figure 3. At the first stage of infrastructure project planning, the following topics should be explicitly identified based on the physical scope of the project: purpose, goals, and scale. Social, economic, regulatory, and ecological values and constraints associated with the project area can be determined through stakeholder engagement and review of existing watershed studies or master plans. Watershed (master) plans provide context for infrastructure operation and management within the physical and ecological processes of that system and prioritize capital improvement and restoration work (USFS 2011). In the second stage, the project is evaluated based on the hazards it will be exposed to and its impacts on prioritized ecological and social values. A hazard assessment should identify how flood inundation and geomorphic (stream movement) hazards might impact the planned project. An experienced fluvial geomorphologist is required to perform the latter assessment. The evaluation may consider the prevalence of protected species along with existing recreational, economic, and cultural values associated with a stream corridor.

In the third stage, alternative designs or treatments are formulated. New infrastructure development should avoid or minimize impacts to the extent possible. Examples include setting a project footprint back from the channel migration zone or widening a bridge span to accommodate meander migration and flood flows. Where hazards cannot be avoided, alternatives should be considered. Each alternative should include a maintenance plan and budget. For example, should a new levee be required to protect an urban corridor, a budget to maintain the toe in case of scour should be included in project evaluation. Opportunities to restore the floodplain upstream and downstream of the project should be explored to mitigate the hydrologic and ecologic impact of the proposed project. Where ecological impacts are unavoidable, mitigation may be considered, or required, depending on the type of habitat impacted (National Environmental Policy Act, 42 U.S.C. §4321; Clean Water Act, 33 U.S.C. §1251 et seq.).

Existing infrastructure poses a different set of considerations as damaged or old infrastructure may be rehabilitated, replaced, relocated, or removed. An opportunity to restore stream and riparian habitat may exist in conjunction with these efforts. For example, local conservation organizations might partner with irrigation districts to construct fish passage on diversion dams slated for repair after flood damage or to remove an obsolete dam (e.g., Wamser 2012; Colorado Trout Unlimited 2016).

Removal of obsolete dams can simultaneously eliminate a safety concern and restore aquatic connectivity. In the U.S., state wetland mitigation programs may be willing partners in funding such a project (ACOE 2008). In the final stage, alternatives are evaluated in terms of feasibility, costs and benefits (economic, social, and ecological), hazards, and risks. Final decisions may be reached by stakeholder consensus with the aid of decision-making tools such as multi-criteria decision analysis (Martin et al. 2016).

After the devastating 2013 Colorado Front Range flood, the state of Colorado supported the development of watershed-scale master plans to guide flood recovery efforts (Colorado Emergency Watershed Protection Program, Accessed June 12, 2017, https://coloradoewp.com). These plans used the master-planning framework and process (Goodman and Hastak 2015) to identify stream corridor restoration and infrastructure alternatives with the goal of flood risk reduction, community resilience, and improved ecological conditions. The Left Hand Creek Watershed Master Plan (LWOG 2014) incorporates assessments of ecological integrity and flood and geomorphic hazards within the watershed. Stakeholder input identified the infrastructure to rebuild and the type and location of stream and floodplain restoration approaches to conduct. Examples include identifying what stream reaches should be prioritized for conservation and floodplain restoration, prioritizing road-stream crossings for improvement to avoid overtopping and clogging during floods, and developing stream-compatible approaches for rebuilding roadways in stream corridors including setbacks and realignments (i.e., Figure 2). This and other plans like it have guided the post-flood recovery effort and serve as templates for future emergency response work.

MANAGING RIVERINE INFRASTRUCTURE UNDER UNCERTAINTY

Infrastructure design in stream environments often relies on estimates of design flows and sediment yield. These estimates are subject to uncertainty due to an imperfect or relatively short data record, uncertainty in deterministic modeling, as well as changing hydrology under climate and land-use change. Faced with these uncertainties, managers may default to safety factors resulting in more conservative design.

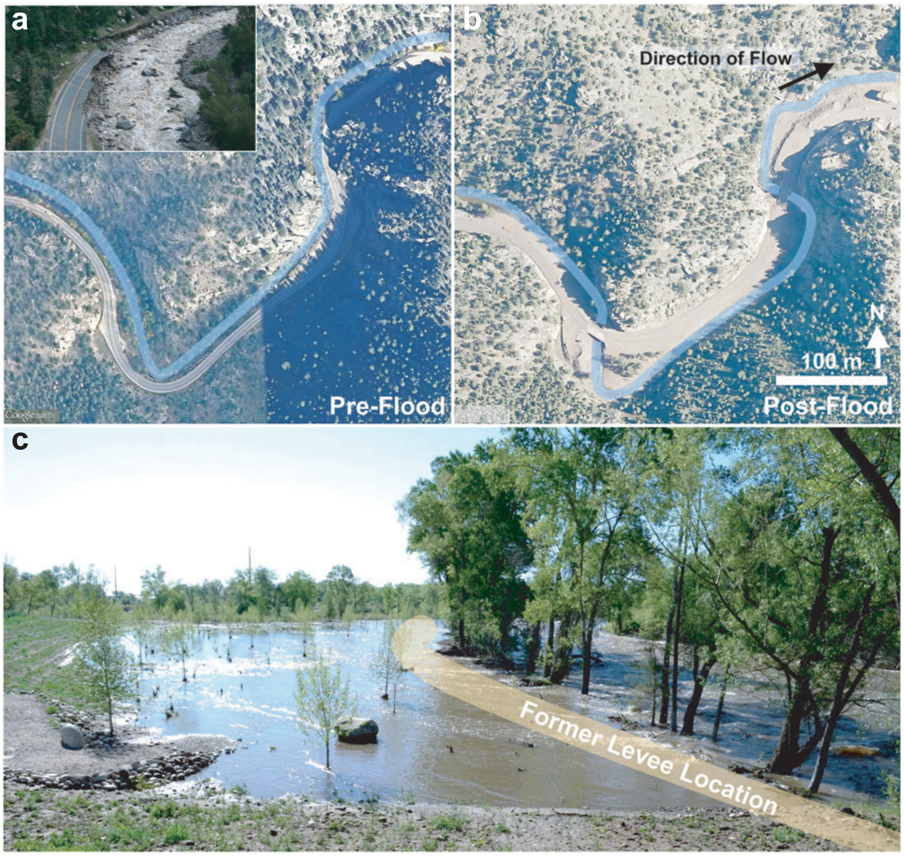

FIGURE 2. Examples of stream-compatible infrastructure and restoration projects. (a) Many portions of Larimer County Road 43 (CR43) within the North Fork of the Big Thompson River canyon near Estes Park, Colorado were washed out from a 2013 flood, especially where the road ran along the outside of river canyon bends (inset photo, Colorado Department of Transportation, used with permission). This aerial imagery shows the river (blue line) and road alignment prior to the flood (2012, Google Earth). (b) In partnership with Federal Emergency Management Agency and the United States Department of Transportation, Central Federal Lands Highway Division, Larimer County realigned CR43, bringing the roadway to the inside of river bends and away from areas the river (blue line) occupied during the flood (2016, Google Earth). Other resilient designs within the canyon include setbacks of the highway from the river, vegetated floodplain benches, and integration of vegetation into embankments. (c) A levee was removed (tan band shows approximate location of levee) and a floodplain bench excavated and revegetated to hydrologically connect this floodplain with a portion of the Poudre River, Fort Collins, Colorado that has been confined by floodplain encroachment. Abandoned gravel quarry ponds adjacent to the river were reclaimed as emergent wetlands and connected with flood flowpaths.

Safety factors that reduce hazard exposure, reduce maintenance costs, and provide for more stream processes include a taller, wider spanned bridge or culvert or a larger floodplain setback for a project footprint. Other approaches to safety factors, such as larger riprap sizing or taller levees, may be in conflict with natural stream processes and reduce infrastructure efficacy over the long term. Ultimately, risk analysis is required to balance project goals with environmental goals.

Where uncertainty in future conditions exists, robust designs, which perform well over the range of potential future hydrology and land-use scenarios, should be considered (Stakhiv 2011). In cases where significant trends exist in historic data, flood-frequency estimates may be adjusted to account for these trends (Collins 2009; NOAA 2011; Vogel et al. 2011; Salas and Obeysekera 2013). Under non-stationarity, or changing flood frequency and magnitude over time, design-flood estimates based on the most recent record may be reasonable for projects with shorter design lives but not over longer design lives. Top-down modeling using downscaled climate projections to predict future hydrologic conditions results in a cascading effect on uncertainty (Wilby and Dessai 2010) and scenario analysis may be helpful (Kundzewicz et al. 2018). Another approach to addressing non-stationarity in design, known as decision scaling, first characterizes the climatic conditions that result in project failure (e.g., levee or bridge overtopping) and then compares these to the distribution of future projected climate conditions informing the probability of failure (Brown et al. 2012). Finally, where data are scarce or uncertainty is high, an adaptive

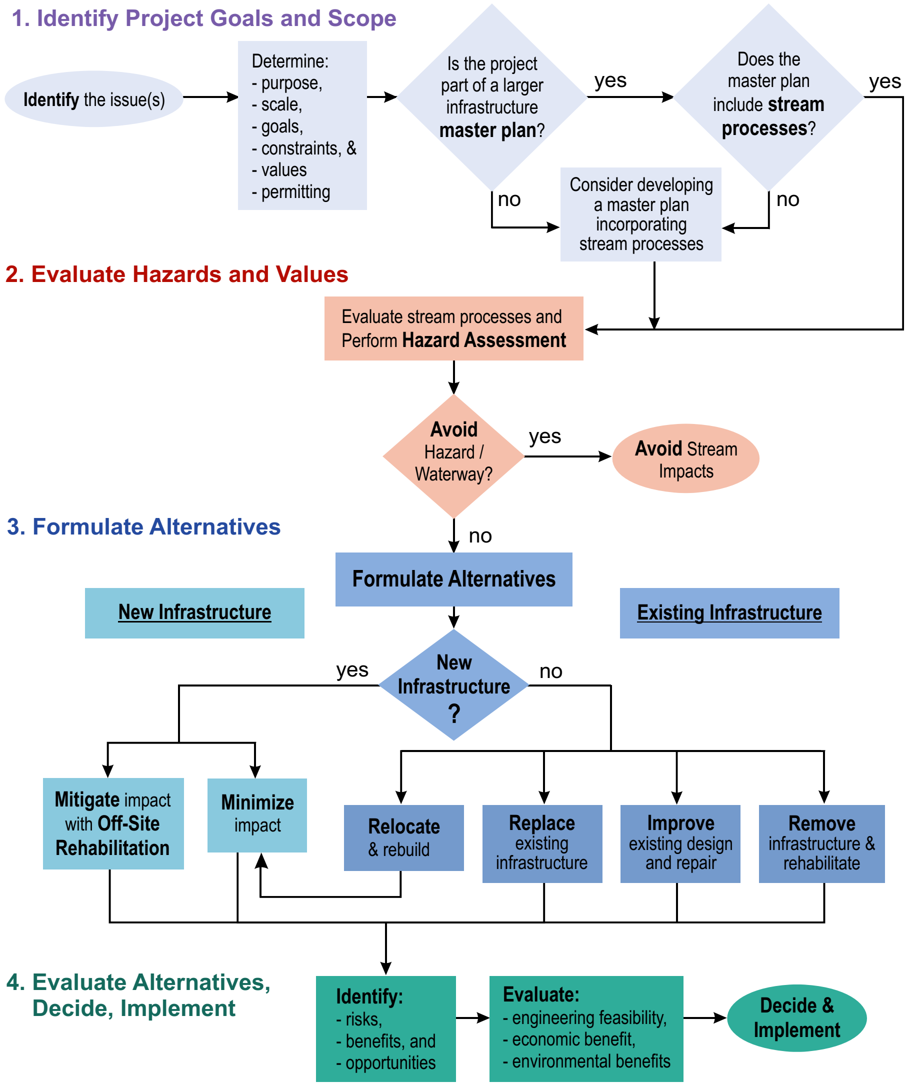

FIGURE 3. Decision tool flowchart for managing existing and planned riverine infrastructure.

management approach may be appropriate. Adaptive management involves implementing a project in phases and adapting the design as more information becomes available but requires flexibility and dedicated funding over longer time horizons (Williams 2011).

FLOOD DISASTER RESPONSE AND RECOVERY

Large floods can be destructive to infrastructure and communities along streams. Indeed, the number of flood-related federal disaster declarations continues to increase each decade (FEMA 2017). In addition to inundation, fast moving water can transport and deposit large amounts of sediment and debris, erode streambanks, and damage infrastructure. A large flood may alter the stream channel alignment. Emergency response and other community personnel in the affected area will likely need assistance from engineers and scientists who have experience with stream processes to ensure their recovery efforts do not create long-term problems for the stream environment and surrounding infrastructure. Permitting and funding agencies should be certain that new channel and infrastructure designs are compatible with natural stream processes and have the necessary resiliency to better survive future floods.

Problems and effective solutions can be unique to specific stream locations. Rigid rules associated with post-disaster recovery funding and procedures may not achieve improved post-disaster conditions nor are they cost-effective. For example, rules associated with FEMA's standard public assistance recovery funds typically limit infrastructure reconstruction to what previously existed (Olshansky and Johnson 2014). However, this infrastructure may not have originally been compatible with the stream. Opportunities and examples of funding for post-disaster betterment do exist (Consoer and Milman 2018), and changes to this policy are currently being piloted (FEMA 2018). Emergency repairs often occur in an expedited manner with abbreviated environmental permitting requirements (e.g., 33 C.F.R. § 325.2; 42 U.S.C. 5159 § 316; Consoer and Milman 2018), which may result in negative impacts to the stream environment (Richer et al. 2015). Emergency repair within the stream corridor may not consider the stages outlined in Figure 3. Pre-disaster and watershed master planning can identify stream-compatible designs and approaches to be used for emergency repairs and reconstruction. Providing incentives and funding to incorporate resiliency into the reconstruction process will enhance public safety and reduce reconstruction costs for the next flood. An overall lack of literature on regulatory limitations to "building back better" (Kim and Olshansky 2014) post-disaster indicates this is a ripe area for research and action.

SUMMARY AND CONCLUSIONS

This paper presents information and guidance for riverine infrastructure managers and designers to better understand the stream environment along with guidance to better build and manage infrastructure that is economically, socially, and environmentally sustainable. It follows the recent publication of a comprehensive guidance document for managing riverine infrastructure, published through the Advisory Committee on Water Information, Subcommittee on Sedimentation, Infrastructure and Environment working group (Sholtes et al. 2017). We present a decision tool for managing riverine infrastructure that integrates it into a watershed-scale master plan considering physical and ecological stream processes, ecological restoration goals, and hazards. Many approaches exist to enhance the compatibility of decommissioned, repaired, replaced, and new infrastructure with the stream corridor as well as to restore components and processes of the stream environment (Sholtes et al. 2017). As our 20th-Century infrastructure nears the end of its design life and as we build new infrastructure for the next generation, we have the opportunity to build stream-compatible infrastructure that is more resilient, cost-effective, and protects and restores valuable stream ecosystems.

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