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Applying Resilience Concepts to Inland River Systems

Katherine F. Chambers and Waleska Echevarria-Doyle

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Abstract

As environmental uncertainty increases, incorporating resilience into project assessments, research recommendations, and future plans is becoming even more critical. This US Army Engineer Research and Development Center special report (SR) demonstrates how the concepts of resilience can be applied in a uniform framework and illustrates this framework through existing case studies on large inland river systems. This SR presents the concepts of resilience in inland river systems, the application of these concepts across disciplines, basic parameters of a resilience assessment, and the challenges and opportunities available for incorporating a more holistic approach to understanding resilience of the US Army Corps of Engineers mission areas on inland rivers. Finally, these concepts are demonstrated in several case studies in the United States to exemplify how these parameters have been applied to improve the overall performance of the system.

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Preface

This study was conducted for the US Army Corps of Engineers (USACE) under Program Element No. 031391; Project No. WIC7839F5; Funding Acct Code U4368911; AMSCO Code 031391. The technical monitor was Ms. Katherine Chambers, USACE Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Flood and Storm Protection Division, Coastal Processes Branch. Report development was funded by the USACE Navigation Systems (NavSys) Research Program, Project No. 462579, “Coastal Systems Resilience Initiative.”

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1 Introduction

1.1 Background

River systems are molded by natural and anthropogenic factors. A river channel is created by the eroding force applied by concentrated flowing water with the capacity to mobilize the earth material (Schumm 1984). River systems respond to changes in climate, land use within the catchment, and channel alignment as well as the placement of training structures, floodwalls, levees, dams, etc. Schumm (1984) notes that the decrease of vegetative coverage due to increases in urbanization, fires, and drought can reduce erosional resistance within a river valley floor. The resulting constriction and concentration of flow, increase in the energy slope and discharge, and decrease in sediment loads can increase a river channel's energy forces (Phillips and Van Dyke 2016). However, disruptive events are not always negative. In some cases, the system depends on flooding as a part of the seasonal cycle so that changes driven by rainfall events can produce a minor state change and a short recovery to pre-event conditions (Glenn et al. 2017; Phelps et al. 2015). In other cases, fluvial geomorphologists use the term dynamic equilibrium to describe a system that is not experiencing substantial changes in aggradational or degradational patterns, channel geometry, meander growth, etc. (Biedenharn et al. 2017; Little et al. 2017).

An understanding of dynamic equilibrium can be used to estimate the severity of a disruptive event. When the dynamic equilibrium in a river system or reach within the river is disrupted, the river may experience significant changes in these and other important morphological parameters (Verstraeten et al. 2017; Schumm 1977). The response of rivers to disturbance events is directly related to intensity, frequency, and duration of the event (Wolman and Gerson 1978). If the event deviates in these three variables from historical expectations, the system is vulnerable to complete alteration (Fryirs et al. 2016). The disruption may be small enough that the river returns to dynamic equilibrium in a short amount of time or might be substantial enough to cause river conditions to shift back to a previous dynamic equilibrium condition or force the system to reach dynamic equilibrium for an entirely new system condition.

These effects can be compounded by human factors like population growth, urbanization, increased runoff, and increased demands on river water levels for navigation and water supply (Sabater et al. 2018). Natural river systems have been modified by humans for multiple purposes including navigation, flood protection, water supply, hydropower, and recreation, which now provide essential economic, social, and ecological benefits. River dynamics of these natural systems have been influenced by the myriad new requirements and man-made infrastructure constructed to support those requirements, creating new conditions or equilibriums within the river system (Poeppel et al. 2017; Goudie 2006; Verstraeten et al. 2017). These new conditions have also interfered with natural ecological processes (i.e., migration of fish upstream of a dam, decrease or loss of habitat, etc.) (Richter 2010; Beechie et al. 2010; Dynesius and Nilsson 1994).

The maintenance of these benefits through river management practices has become a subject of intense scrutiny because of increasing variability in extreme weather events, available water levels, and growing human demand (Bouwer 2019; Dottori et al. 2018; Arnell et al. 2016). Over the past several decades, the United States has experienced several environmental disturbances that have demonstrated the vulnerability, or exposure, of the inland river navigation systems, most notably the increased frequency and intensity of droughts, infrastructure outages, coastal and winter storms, and major rainfall events (NOAA 2019a,b). In 2019, unprecedented and prolonged flooding in the upper Midwest impacted the entire Mississippi River Basin from the Dakotas to Louisiana. The flood season was added to the National Oceanic and Atmospheric Administration (NOAA), National Centers for Environmental Information (NCEI), list of billion-dollar weather and climate events, causing widespread slowdowns to supply chains that rely on barge navigation and nearly 20 million acres of farmland to go unplanted (NOAA NCEI 2020; USDA 2019). Future projections for increased intensity and intervals of flooding for the Midwest and South have resulted in new federal funding for studies and upgrades to flood controls and navigation infrastructure (Angel et al. 2018; Frank 2020). Understanding how to increase the resilience of inland river systems and the economic, social, and ecological benefits they provide has become a major concern for waterways managers and stakeholders.

1.2 Objectives

This special report (SR) demonstrates how the concepts of resilience can be applied in a uniform framework and illustrates this framework through existing case studies on large inland river systems. This SR presents the concepts of resilience in inland river systems, the application of these concepts, basic parameters of a resilience assessment, and the challenges and opportunities available for incorporating a more holistic approach to understanding resilience of the US Army Corps of Engineers (USACE) navigation mission on inland rivers. Finally, these concepts are encapsulated in several case studies in the United States to exemplify how these parameters have been applied to improve the overall performance of the system.

1.3 Approach

This report utilizes the USACE definition of resilience as a means to construct a framework for integrating resilience into assessments of inland waterways.

Resilience is a term that includes four general concepts: *prepare*, *absorb*, *recover*, and *adapt* (Figure 1). These four concepts have been adopted as the official definition of resilience for the USACE because of their flexibility in application across business lines and their ability to provide a life-cycle perspective for actions and change over time (USACE 2016). The resilience cycle is derived from relatively recent strides in understanding disaster resilience, where the resilience principles are applied to systems that involve diverse components, including communities, built infrastructure, and the environment (Ayyub 2019; NIST 2019; Hosseini and Barker 2016; Schultz and Smith 2016). Analyzing these diverse components requires a deep understanding of their relationships to each other (e.g., scale, connectivity, dependencies) and their reactions to a disturbance.

Figure 1. The resilience cycle includes the ability to prepare, absorb damages, recover quickly, and adapt to better respond to the next disturbance (Rosati et al. 2015).

Resilience is a concept that has been applied across a variety of scientific fields including engineering, ecology, and environmental science (Park et al. 2013). River management is an interdisciplinary field that requires input from hydrologists, engineers, fluvial geomorphologists, ecologists, and economists (Cohen 2018). Therefore, a definition of river systems resilience can be challenging since this term is often described for specific components within the system but not the system as a whole. For example, for engineers, resilience is generally applied to describe a system state near equilibrium and is measured by the speed at which the system returns to its equilibrium after a disturbance (Pimm 1984). Holling (1996) describes the application of resilience in ecological science as the capacity of a system to adapt to a wide range of disturbances and shocks to maintain ecological functions. In the context of commodity distributions systems, DiPietro et al. (2014) mentions that the concept of resilience applies to physical infrastructure that facilitates movement (e.g., the locks and dams of the inland waterways) as well as to the entities that represent the supply and demand forces in the system (the mines and power plants) and, more broadly, the integrated energy system. From the flood management perspective, Liao (2014) refers to “flood resilience” as the capacity to tolerate flooding, and maintain essential functions when disruption occurs. It would be ideal to have a deep understanding of the relationship of these diverse components with each other (e.g., scale, connectivity, and dependencies) and their reaction to a disturbance. However, managing of a complex system for resilience instead of optimizing a single resource function brings its own uncertainties due to complex interactions and feedbacks within the system (Holling and Gunderson 2002; Cosens and Williams 2012). Therefore, adaptive management is perceived as an approach to allow adjustments in the system, recognizing that changes will occur in the future (Holling 1978; Folke et al. 2005; Cosens and Williams 2012).

As climate uncertainties increase, it is important that the management of river systems promotes the capacity to minimize the negative consequences of disturbances, recover quickly, and adapt so that the benefits that rivers provide to communities, the environment, and the economy can continue to exist in the future.

2 A Framework for Applying Resilience Concepts

The resilience of a system is increased by incorporating adaptive actions while recognizing that conditions change over time and disruptions are bound to occur (USACE 2016). Figure 1 shows how these concepts are integrated via a cycle triggered by an event or disruption. Over time, iterations of this cycle will increase the overall resilience of a system as it recovers and utilizes lessons learned from a particular disruption to adapt and prepare for the next event (Figure 2). Resilience assessments can take a wide variety of forms and are key to incremental improvements to the system. They are the means by which the system prepares for the next event and incorporates adaptive management practices. This SR embraces this four-phase cycle as a framework to conduct a resilience assessment in the section below.

Figure 2. In a resilient system, the cycle of resilience is applied over time so that the next time a particular disruption occurs, less functionality is lost because the system is better able to absorb impacts and recover quickly

2.1 Prepare

The first phase of the resilience cycle, *prepare*, is a time to conduct a resilience assessment and ensure that the system is well understood, the stakeholders are involved, future risks are anticipated, and response and recovery actions are prioritized. The first step in the preparation phase is for the project team to specifically define the assessment's purpose. The purpose can often be defined by the decisions and actions that the study findings will inform. These decisions can vary widely — a study can be used to increase preparedness through a general awareness about disruptions and their impacts in a watershed; to identify and prioritize future investments, research, and actions; or to aid in the design selection for a specific project. The next step is to identify and involve the correct stakeholders. These stakeholders should include those directly involved in the operation and maintenance of the systems that provide and support any critical functions and those that can provide their experiences and knowledge to provide boundaries and objectives for the assessment and ground-truth any results.

Resilience assessments can take a wide variety of forms, but in general, each study must first identify which critical functions are priorities for the system of interest and what infrastructure and organizational components support those functions. The critical functions of a system are defined herein as the main activities or purpose(s) that the system is envisioned to provide. These functions may be supported by and have an impact on both natural processes and man-made infrastructure. For the critical function of safely and effectively facilitating navigation on a waterway, a diverse set of components needs to be utilized including channel training structures (e.g., revetments, dikes, chevrons, weirs), water transportation infrastructure (e.g., locks and dams, canals), dredging maintenance, and flood control (e.g., levees, floodways, spillways). A thorough characterization of these components can provide insights into how the system provides the desired function in an equilibrium (or steady state). Finally, the study team must envision how these functions and components are going to fare in the future, given potential disruptions. While natural or man-made disasters can be random and unpredictable, historical precedent can inform system managers and stakeholders on what they need to prepare for (e.g., flooding, unplanned infrastructure outages, barge accidents at a difficult turn in the river). An awareness of threats, combined with an understanding of the likelihood of each threat scenario and the impacts when that threat occurs, is necessary for making

informed decisions about how to reduce the consequences of an event. These concepts may be familiar as they are considered three components of risk management (i.e., what can happen, how likely is it to happen, and what are the consequences [Kaplan and Garrick 1981]).

Steps for preparation

1. Identify the purpose and problem of a resilience assessment.

Throughout this section, an illustrative example to walk through each proposed step of a resilience assessment will be provided. This illustrative study's goal is to increase the resilience of a river system by providing reliable navigation and increasing the environmental health of the river. However, there are other purposes that can be defined for a resilience study. For example, how much dredging capacity should be planned to meet future needs for draft depth? What training structures are most effective at minimizing dredging cost and providing maximum navigation benefits? What are the short-, mid-, and long-term effects of these structures in the channel? How is the health and resilience of the river affected by policy decisions at the watershed level?

2. Identify and organize stakeholders of the system.

It is important to identify key stakeholders that contribute to or manage the critical functions of interest. The thoughtful identification of stakeholders is a critical step as study managers must find the optimum balance between the benefits of a wide public participation (e.g., trust in decisions, increased understanding of projects and issues with local knowledge, integration of various interests, public acceptance of decisions) with the risks (e.g., increased complexity and cost, empowerment of particular stakeholders over others, misrepresentation, conflict [Luyet et al. 2012]). In general, the best practice for water resources projects is to identify and characterize potential stakeholders and to structure them into different degrees of involvement (Arnstein 1969). These degrees of involvement have been heavily debated in this topic area and range from informational (being made aware of the study and its aims) to co-decision (cooperation towards an agreed upon solution) and empowerment (making decisions about the project [Luyet et al. 2012; Daniels and Walker 2001]). The appropriate level of involvement depends upon the project's specific objectives and time restrictions. For more information on this

process, there are many examples in the literature of how existing river basin projects have approached stakeholder involvement (e.g., Orr et al. 2006; Collins et al. 2007; Comino et al. 2016; Hassanzadeh et al. 2019). As mentioned earlier in this section, river management includes multiple disciplines and each discipline can contribute to establish alternatives that could support critical functions. For the illustrative study, hydraulic and river engineers, hydrologic modelers, restoration ecologists, and navigation operations professionals are needed.

3. Scope the system of interest.

The scoping step of a resilience assessment is to identify the critical functions or services of concern, the natural processes and man-made infrastructure that supports those functions, potential future risks, and bound the extent of the system. For example, for inland waterways, navigation is considered a critical function. Proper channel depths are considered an important component that support navigation along the river. Dredging is a typical operation used to remove accumulation of sediments inside the channel that may affect the channel depth needed for navigation. This also must coincide with a natural level of water flow high enough to support navigation. Prolonged drought and flooding pose a risk to navigation operations. Dikes have been constructed on some of the larger waterways in the United States to capture most of the river's flow within the navigation channel and mobilize more bed sediment material and therefore reduce the need of dredging operations. However, deposition of the presence of dikes and other river engineering structures could potentially represent a risk to critical habitat areas (Hood 2004; Fischer et al. 2018). From the environmental perspective, this loss of habitat disrupts critical ecological functions. Some alternatives including dike notching, the use of chevrons, and other off-bank revetment have been considered to offer habitat complexity (Braun et al. 2016). The implementation of such alternatives is considered only if there is a minimal effect on the purpose and intent of the authorized projects such as navigation and flood risk management. This example shows that reliable navigation and the provision of critical habitat are considered critical functions along navigation waterways. The evaluation of alternatives to improve both navigation and ecology can potentially preserve critical functions across disciplines. The infrastructure and natural processes that interact with these functions include the dikes themselves, the navigation channel and its use, and the ecological factors

that allow for the existence of critical habitat. Some examples of future risks to these critical functions are prolonged drought, flooding, and habitat loss due to sediment deposition and loss of ecological complexity.

A system of interest must also be defined by selecting the appropriate geographic and temporal scales of interest. On inland waterways, these scales can quickly become quite large because of changes in the watershed, upstream and downstream effects of a particular project, and the timescales at which impacts occur. The illustrative example requires an understanding of sediment transport, trends of sediment movement, and the long-term impacts of training structures on navigation and endangered species habitat. Conducting the necessary geomorphic assessment may require decades of data to evaluate the system response for long periods of time. This type of assessment can be performed for a reach of interest within the river or the entire watershed system. If the problem in question requires a more immediate plan of action (e.g., lock and dam repair, revetment repair), a shorter temporal scale may be required to restore the damage or make faster decisions that will maintain critical functions of the system in operation.

2.2 Absorb and Recover

The resilience cycle extends beyond the definition of risk, threats, and consequences to include the ability of the system to withstand disruptions according to set performance requirements and then recover within an acceptable timeframe (Aven 2011). To use resilience as a management paradigm, a systematic understanding of how the system is able to *absorb* and *recover* from disruptions is necessary. Once an understanding of the system is established during the *prepare* phase, the next step is to set general goals for performance and recovery (McAllister 2015). This can be accomplished by working with stakeholders and experts to determine critical functions and set requirements on how those functions should be maintained during and after a disruption. This should also include prioritization of what recovery actions should happen first. Once these associated performance and recovery goals are defined, the performance of the supporting infrastructure and/or natural processes can either be tested through scenario-based modeling or through an after-action review post disruption (e.g., what infrastructure has been incorporated into the project of interest to absorb and recover from the main stressors and disturbances? What data and analysis were used for the projects current design? Are the interactions between components of the project?).

Steps for response and recovery

1. Set performance and recovery objectives for a disruption.

In previous steps, the risks to the system were identified, and the services and supporting infrastructure were assessed. In this step, the project team considers these risks and identifies how the system would ideally react. For the navigation and habitat example, the project team must identify the minimum draft depth of the navigation channel and the amount of critical habitat that needs to be available for the endangered species in the area (e.g., 9 ft^{*†} of depth, 17 acres of habitat). Next, they set goals for how fast the system should recover from disruptions and what level of service the recovered system should provide. Questions that might guide this process include the following: if a flood event deposited a large amount of sediment into both the primary channel for navigation and the secondary channels needed for critical habitat, how will the sediment deposited along the primary channel affect navigation and how soon could the navigation channel be restored to normal operations? How long would it take for the critical habitat to recover to its full extent? Would training structures need to be repaired or replaced and how soon? Is it acceptable for the sediment to move out of the river reach naturally, or would dredging be required to reach desired depths faster?

2. Prioritize response and recovery actions.

Given the desired critical functions and recovery goals already identified, the study team then has the opportunity to create a plan for response and recovery to a future disruption scenario. This plan should identify the most efficient and effective means to accomplish the performance and recovery goals. For the navigation channel example, after a large flood event, what would be the first actions necessary to assess the damage to the navigation channel and infrastructure (e.g., inspections, surveys), how fast would these actions have to be taken, what is their priority order, and are there actions

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

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

that depend on the completion of other actions? Then, how fast do these required actions have to be completed to reestablish the pre-flood conditions along the navigation channel? After that, the project team would prioritize any longer-term repairs within the system with ecological needs in mind. Finally, the team would make sure that conditions to re-grow or regain critical habitat are present. Ecological timescales are usually long, and therefore critical habitat may take several years to re-grow after total destruction, even with the appropriate environmental conditions.

3. Assess the response of the system to a disruption.

In the assessment step, the project team can use models, lessons learned, or expert opinion to gauge the effectiveness of their recovery goals and to identify where the system needs to be improved. For a flooding event that limits navigation, the model would need to include frequency of flooding, the duration, secondary effects that may affect the project's needs (e.g., a levee breach or overtopping), and the failure mechanisms themselves. What caused the failure of a dike or levee? Is the failure also related to maintenance issues? How much sediment can be expected to deposit in the area? How frequent is the storm event? Would that event become more frequent with climate change?

2.3 Adapt

The insights gained during the absorb and recover phase of a modeled or real-life disruption are the foundations for the final step in the resilience cycle: *adaptation*. Adaptation is defined herein as the ability to change practices so that the system is better able to function in the future. This learning phase is the most critical aspect of increasing resilience over time because it allows room for change and uncertainty in management practices and assumptions, which is inevitable in large and complex systems (Holling 1978). A familiar management practice that fits into this step is adaptive management, which has been integrated into USACE practices for decades and was codified in agency practices in the early 2000s (Fischenich and Vogt 2012). Adaptive management is a complex concept that is summarized below in a definition adapted from the National Research Council as follows:

Adaptive management [is a decision process that] promotes flexible decision making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better

understood. Careful monitoring of these outcomes both advances scientific understanding and helps adjust policies or operations as part of an iterative learning process. Adaptive management also recognizes the importance of natural variability in contributing to ecological resilience and productivity. It is not a “trial and error” process, but rather emphasizes learning while doing. Adaptive management does not represent an end in itself, but rather a means to more effective decisions and enhanced benefits. Its true measure is in how well it helps meet environmental, social and economic goals, increases scientific knowledge, and reduces tension among stakeholders. (Williams et al. 2009, p. 4)

The adaptation phase, while undoubtedly critical, is often neglected from traditional resilience assessments, which focus instead on the disruption itself and the ability of the system to recover quickly. These sorts of assessments tend to rely strongly on assumptions, calculations (with associated uncertainty), and stakeholder inputs. These results are important in informing preparation and recovery practice, and they can be made even more effective if they are integrated with adaptive management practices (Benson and Garmestani 2011). Adaptive management does not happen on its own; it must be thoughtfully incorporated into any study or project plan. This can be accomplished by reassembling stakeholders after an event or disruption in their area and discussing the event itself, the results of management actions, the ability to meet performance and recovery goals, and their impressions of success or failure. During this review, the results of any former preparation actions including critical functions, boundaries, models, and assumptions about disruptions and their impacts on the system can be revisited. Any new data, knowledge, or developing technologies can also be leveraged to provide better insights into system behavior, and the plans for preparation, response, and recovery can be improved.

Steps for adaptation

1. Use the results of the disruption to identify key areas to improve the ability of the system to meet performance and recovery goals.

For this step, the response of the system to a disruption is utilized to identify actions to overcome vulnerabilities. This step allows stakeholders to evaluate alternatives to improve the system’s ability to absorb disruptions in critical function. Given a suite of potential options, which of

these options provides optimal impact across all of the functions of concern and is attainable given cost and time restrictions? For example, after evaluating multiple alternatives on how to repair the levee that has been damaged during a flood event, is there an alternative that could make the system more resilient to flooding but also provide ecological benefits? Can the new alternative also support the recovery of critical navigation components, such as barge traffic and lock and dam operations?

Then, there are questions related to repairs: should the levee be repaired to reach the pre-failure design? Should the pre-failure design be modified so that the levee can resist the same event or a larger event? If this is a feasible alternative, should the levee be raised or set back to allow more room for flood water? The incorporation of floodways to the system may also help relieve pressure for the levee system for current and future conditions.

2. Develop and prioritize resilience enhancements.

After these actions are identified, they need to be prioritized and verified to ensure that they will improve the system performance and meet present and future needs. For example, is the system performing as expected under present conditions? Does it need improvements to absorb and recover from potential disruptions in the future? What decisions have to be made today so that the system can recover from disruptions caused by potential changes in climate, population, land use, navigation needs, etc.? What kind of infrastructure needs to be improved? Can a combination of natural features and traditional infrastructure support the system adaptation to future conditions? Integrating new knowledge gained from the resilience assessment into project planning or future operations is essential to evaluate alternatives that can prepare the system for future changes.

3. Socialize these results with decision makers and identify key areas where new knowledge can be integrated.

Key to any progress in increasing the resilience of rivers and watersheds is to make sure that stakeholders are highly engaged in the planning, execution, and validation of the study. This heavy emphasis on stakeholder engagement is critical because at the end of the assessment, they will be responsible for translating the study results into action. The next section will discuss selected case studies where stakeholder engagement was paramount to the process of applying these resilience framework parameters.

3 Case Studies

Case studies are an excellent means to illustrate how resilience analyses can be conducted on inland waterways. This section describes efforts led by the USACE to bring stakeholders together in two major river basins: the Lower Mississippi River (Bouska et al. 2018, 2019) and the Ohio River (Drum et al. 2017). These case studies both utilize a stakeholder-driven process that leads to a better understanding of how the river systems of interest function. The studies' end goals are to provide management solutions. These solutions aim to improve the ability of river systems to absorb floods, increase or restore environmental benefits, provide reliable navigation and movement of commodities, and adapt to changes in climate over time. These real-world systems have constraints and limitations both in the study scope, natural processes, and operation of the waterway. Policies, funding, data availability, modeling limitations, and study costs all create unique situations and challenges for conducting a resilience assessment, and provide a great opportunity to apply the proposed resilience framework to existing successful study designs.

3.1 Developing a shared understanding of the Upper Mississippi River: the foundation of an ecological resilience assessment

The Mississippi River is one of the world's major river systems with a drainage area of approximately 1.2 million mi², including all or parts of 32 states and 2 Canadian provinces (LMRCC 2015). USACE divides the river into three main reaches: the Upper Mississippi River (UMR) from Minneapolis, MN, to St. Louis, MO; the Middle Mississippi River from St. Louis, MO, to Cairo, IL; and the Lower Mississippi River (LMR) from Cairo, IL, to Head of Passes, LA. Each of these reaches presents its own set of unique characteristics and management challenges. As climate patterns become more uncertain, understanding how the ecological functions of the system relate to the goods and services that society depends on has become an important challenge. This case study focused on an effort undertaken by an interagency group to understand more about the UMR to increase its ecological resilience. The effort is documented in two journal articles by Bouska et al. (2018, 2019).

3.1.1 Prepare: identify purpose and problem

The Upper Mississippi River System (UMRS) is a large and dynamic floodplain ecosystem that spans multiple states and jurisdictions of federal agencies. In recent years, the Upper Mississippi River Restoration (UMRR) Program managed by the USACE adopted a strategic plan with a vision for “a healthier and more resilient ecosystem that sustains the river’s multiple uses” to guide its activities (UMRR 2015). To achieve this objective, the UMRR partnership endeavored to undertake a resilience assessment. Bouska et al. (2018) detail the chosen approach to the assessment adapted from several available frameworks that included three primary steps: (1) system description, (2) assessing the system, and (3) adaptive management. The follow-on study (Bouska et al. 2019) described how three general resilience principles (diversity and redundancy, connectivity, and controlling variables) can be linked to qualitative indicators to provide insights on drivers and, subsequently, potential alternatives for increasing the resilience of the system.

3.1.2 Prepare: identify stakeholders

For a river system as large as the Mississippi River, management objectives are as broad as the mission areas of the many state, federal, and local agencies that have jurisdiction within the system. To coordinate these objectives, the USACE manages a multiagency partnership called the UMRR. The UMRR consists of the USACE, US Geological Survey (USGS), US Environmental Protection Agency (EPA), the US Department of Agriculture (USDA), the US Department of Transportation (DOT), and various natural resource agencies from each of the five UMRS states (Illinois, Iowa, Minnesota, Missouri, and Wisconsin).

3.1.3 Prepare: scope the system

In the past, resilience assessments have emphasized interactions within a social-ecological system, but the missions, expertise, and resources of the UMRS partnership resulted in an ecological focus for the system. The study leads emphasized the importance of establishing a study scope as the key foundation to an accurate resilience assessment. This holistic and accurate ecological system scope was co-developed between science and management communities of the UMRR during a 3-day workshop and focused on four critical aspects: (1) the scale and boundaries to be examined, (2) important historical changes, (3) what is valued by users of

the system, and (4) known drivers including controlling variables and feedbacks.

As far as study scale, the UMRR is authorized to operate within the boundaries of the UMRS or the “commercially navigable portions of the Mississippi River main stem north of Cairo, Illinois” and the commercially navigable tributaries (i.e., the Illinois River). Because the resilience assessment is focused on the ecological system, the working group decided to divide the UMRS into four reaches with distinct characteristics based on aquatic vegetation, geomorphology, and levee distribution: the Upper Impounded Reach, the Lower Impounded Reach, the Unimpounded Reach, and the Illinois River Reach. To understand the impacts of modifications of the basin, floodplain, and river to the river’s modern hydrogeomorphology, Bouska et al. (2018) reviewed changes to the UMRS and landscape during the past 200 years — beginning in 1820 with rapid deforestation, cultivation, installation of river training structures to improve navigability, and levees for flood risk reduction.

Finally, the group focused on the function of the UMRS, or how the fluxes of water, materials, and the movement of biota interact across the diverse landscape. To identify these controlling variables, the study partners conceptualized the river as being composed of three interacting subsystems: lotic (flowing) channels, lentic (or relatively still) off-channel aquatic areas, and floodplains. These subsystems were not intended to be comprehensive; instead they simplified the system to better identify the variables of interest to stakeholders, their role in the function of the ecosystem, and the resources that support those variables. For each of these subsystems, the UMRR working group identified major resources, controlling variables, and external drivers. For example, for the lotic channels, major resources are water quality, fish community, and mussel community. These resources are controlled by a group of nine controlling variables and five external drivers (Figure 3).

Figure 3. Ecosystem services for lotic channels are represented by major resources and include water quality, fish community, and mussel community. These resources are impacted by nine controlling variables and five external drivers (from Bouska et al. 2018).

3.1.4 Absorb and Recover: consider desired goals for absorbing impacts and recovery

The first half of the study (Bouska et al. 2018) characterized the UMRS into three subsystems that provide major services or resources that are controlled by a number of variables. This provided the stakeholder group a collaborative forum to agree on how the system should be defined and which components are of most importance to its resilience. The objective of the second half of the study (Bouska et al. 2019) was to develop a set of indicators for the following three main resilience goals that were identified by the UMRR: (1) maintain diversity and redundancy, (2) manage connectivity, and (3) manage controlling variables and feedbacks.

3.1.5 Absorb and Recover: assess response of the system to disruption

These three resilience principles were utilized to develop a set of 10 indicators that could be quantified by available ecological datasets and previously published reports. These indicators were then assigned a positive (+) or negative (-) relationship with resilience that was used to scale the indicators to each other (Table 1). The indicators were then quantified (e.g., Simpson's diversity index (a measurement of species abundance and diversity), hectares per river kilometer of impounded river, total phosphorus concentration) for four reaches of the UMRS (Figure 4). Non-reach-scale indicators (like connectivity, diversity, and redundancy) were

rescaled by dividing the indicator value by the maximum value of that specific indicator. For example, longitudinal connectivity was divided by 100 to scale it from 0 to 1. The indicators were not weighted based on their relative contributions to resilience — they were considered to be equal.

Table 1. Ten groups of resilience indicators were identified and their positive or negative (+/-) relationship with three general resilience principals (Bouska et al. 2019).

General Resilience Principal	UMRS Resilience Indicator	Relationship with resilience	Rationale and Assumptions
Maintain diversity and redundancy	Aquatic habitat diversity and redundancy	+	Provides a wide range of options for responding and adapting to disturbances
	Floodplain inundation diversity	+	
	Fish functional diversity and redundancy	+	Provides a wide range of community functions and back-up species with similar functions in the case of species loss
Manage connectivity	Longitudinal connectivity	+	Provides access to a wide range of thermal and hydrogeomorphic conditions and supports native species
	Lateral connectivity	intermediate	
Manage controlling variables and feedbacks	Water surface elevation ranges	+/-	Variability that better approximates historic (pre-lock and -dam) conditions and supports native species
	Total suspended solids	-	Low water clarity may negatively impact native species
	Nutrient concentrations	-	Eutrophic conditions may negatively impact native species
	Sedimentation rates	-	Loss of deep low-energy off-channel areas may negatively influence native species
	Aquatic invasive species	-	Presence may negatively affect native communities

3.1.6 Adapt: identify key areas for improvement and work with stakeholders to develop and prioritize actions

The study was intended to provide a generic assessment of resilience across four reaches of the UMRS. Figure 4 provides a graphic summary of how these resilience indicators contribute to resilience for each reach; the differences in their environmental characteristics are clear. For example, the Upper Impounded Reach of the UMRS had very little longitudinal connectivity when compared with the Unimpounded Reach. This understanding allowed the study leads and participants to gain better insights into the trends and drivers of resilience across the river system

and to begin a conversation about potential management options to address these issues at the reach scale. To proceed through the following recommended steps, the analysis would need to become more specific. For example, Bouska et al. (2019) identified the need to include climate projections into the analysis, and that specific indicators are well suited for correlation with increased temperatures and more variable precipitation. To identify specific local action, any study users would also need to understand thresholds for these indicators or the point at which the underlying structure of the system would change.

Figure 4. A cross-indicator synthesis of contributions to general resilience derived from rescaled indicator values. Values near the center indicate lower contributions to general resilience and values near the edge reflect greater contributions (Bouska et al. 2019).

The resilience assessment was intended to provide a coarse description of a multitude of factors that contribute to the resilience of a large watershed. Utilizing qualitative data also provided an opportunity for natural resource managers to discuss actions that are necessary to influence resilience. The study is a detailed and valuable account of the way partnerships can generate a shared understanding of how large and complicated systems operate, and derive great value from the process. This critical step provides strong working relationships and buy-in for partners as they continue with the resilience assessment steps — assessing the impacts of disruptions and envisioning resilience enhancement options and adaptive management techniques.

3.2 Formulating climate change mitigation/adaptation strategies through regional collaboration with the Ohio River Basin alliance

The Ohio River is located in the Midwestern United States and carries the largest volume of water of any of the Mississippi River tributaries (LRD 2020). Its drainage area is approximately 204,000 mi² including parts of Illinois, Indiana, Kentucky, Ohio, Pennsylvania, and West Virginia, and its length is approximately 981 mi (LRD 2020). This section addresses an interagency effort to improve the climate resilience of the Ohio River watershed through adaptive management strategies.

3.2.1 Prepare: identify purpose and problem

The USACE Institute for Water Resources Response to Climate Change Program funded a study entitled *Ohio River Basin – Formulating Climate Change Mitigation/Adaptation Strategies through Regional Collaboration with the Ohio River Basin Alliance* (Drum et al. 2017). The study was conducted over 7 years and was led by the USACE Huntington District in collaboration with the Ohio River Basin (ORB) Alliance, the USACE Institute for Water Resources, the Great Lakes and Ohio River Division (LRD), and numerous other federal agencies, non-governmental organizations (NGOs), research institutions, and academic institutions. The ORB is a complicated watershed with numerous major rivers and navigation infrastructure owned and operated by federal and state agencies. These systems have experienced episodes of flooding and drought over time. The agencies that operate and manage the facilities within the ORB (USACE, Tennessee Valley Authority, and Natural Resources Conservation Service) have plans for these events to minimize

their impacts. However, there is concern that as the disruptive events become more frequent, extreme in duration and potency, and harder to predict, the operating schemes and infrastructure designs will be unable to accommodate these changes and meet expected demands. Any proposed solutions must be able to address the concerns of equity, equality, public services, and social and economic impacts.

The central question formulated for this study is as follows:

Can regional mitigation/adaptation strategies that are collaboratively developed with the ORB Alliance and formulated using Integrated Water Resources Management principles be implemented successfully within the ORB to counter the anticipated water resources, ecological and infrastructure impacts of climate change? (Drum et al. 2017)

The purpose of the study was to identify the components of ORB infrastructure and ecosystem resources that will be impacted by future climate changes (precipitation and temperature) and to formulate mitigation and adaptation strategies that can be implemented to reduce those impacts.

3.2.2 Prepare: identify stakeholders

Beginning in 2009, LRD recognized the need to convene a wide variety of stakeholders into working groups to resolve basin issues. This was the beginning of the ORB Alliance. The Alliance Climate Change working group provided the opportunity for extensive collaboration among various federal, state, and local agencies, NGOs, academia, and institutions, allowing this pilot study to incorporate the most relevant climate change information from a diversity of regional resources and jointly formulate feasible adaptation strategies.

3.2.3 Prepare: scope the system

The study scope addressed almost the entire ORB (climate change data were not available for the Tennessee River watershed, so it was excluded) and included an extensive system of operating reservoirs that store and release water for various authorized purposes. The study embraced the concept of integrated water resource management and as such, the scope of the infrastructure and ecosystem services that were examined was very

large. The ORB Alliance Climate Change working group developed the study with the goal to take a holistic approach to water resource management. For the environment, that meant considering ecosystem services, environmental concerns, water quality, water use and availability. For infrastructure and regulatory systems, the study included dams, reservoirs, local protection projects (floodwalls and levees), flood protection channels and diversion facilities, navigation locks and dams, public waterfront areas, stormwater retention, wastewater collection and treatment facilities, water extraction, treatment and distribution systems, energy infrastructure, transportation infrastructure, and communications infrastructure.

3.2.4 Absorb and Recover: consider desired goals for absorbing impacts and recovery

Past studies on the ORB had suggested that there would be threats to the USACE ability to manage the infrastructure system for authorized purposes and recommended that a future effort to make specific recommendations for alternatives to address those impacts be undertaken (USACE LRH 2009). For this study, since climate change impacts happen incrementally over decades, the goals for response and recovery were considered in a long-term context. The preliminary review of the watershed identified the monetary value and/or economic services of the system and the risks to those contributions through climate change disruption. Each component of the ORB is maintained by various agencies. Each agency has operating procedures and manuals that address both normal and extreme conditions (e.g., drought or flood). For this step of the framework, the loose definition of desired goals for response and recovery was that the system is able to maintain authorized requirements described within these manuals, including future extremes. Some of the manuals did not include future extremes, so the study team considered the ability of the ORB to provide services until 2099 and beyond.

3.2.5 Absorb and Recover: assess response of the system to disruption

To assess the response of the ORB to future climate change impacts, a downscaled model was created from nine carefully selected combinations of Atmospheric Ocean Global Climate Models (out of 77 available combinations of models and emissions scenarios). The model runs were performed using two greenhouse gas (GHG) emissions scenarios from the Intergovernmental Panel on Climate Change Special Report on Emissions

Scenarios (IPCC 2000). The nine ensemble runs were performed for three time periods and other tools were used to generate hydraulic response including stream flow, temperatures, precipitation, and snow water equivalent. The outputs of the hydraulic model included the following three measures: (1) percent change mean flow, (2) percent change maximum flow, and (3) percent change minimum flow. These three measures were calculated for the annual average, average during peak flood season in March, and average during low flow season in October.

These changes in precipitation, temperature increases, and river discharge were then compared to the categories of basin resources to characterize the impacts of climate change. The ORB Alliance Climate Change working group divided into subject matter expert-driven teams to identify the future impacts to ecosystem resources and infrastructure operations. Predictive climate data within the ORB are only available at very large spatial scales, so the teams used a combination of expert elicitation, review of existing models, and conclusions of past studies to understand and identify the most impacted ORB ecosystem and infrastructure services (freshwater provisioning for drinking, power generation, and goods transport, agricultural land, near-stream flood control, timber production, flood risk reduction, navigation, etc.).

3.2.6 Adapt: identify key areas for improvement

The results of the analysis indicated several major trends and key areas for improvement across the ORB basin. The best adaptive management options were measured against their ability to impact exposure (the present and future climate impacts), sensitivity (the impacts of the climates on systems performance), and adaptive capacity of systems (how well systems can manage the impacts) (IPCC 2014). The study team identified several *adaptation themes* and utilized the results of the climate modeling to identify options to improve resilience among these themes at five sub-basins (Table 2).

Table 2. Adaptation themes and the ecosystems services they support
(from Drum et al. 2017).

Adaptation Themes	Basin Purposes Supported							
	Flood Risk Management	Wastewater Management	Water Supply	Navigation	Hydropower	Recreation	Aquatic Ecosystem	Land Ecosystem
Restore Wetlands	X	X				X	X	X
Reconnect Floodplains	X					X	X	X
Reduce Consumptive Uses of Water			X	X	X	X	X	X
Water Harvesting	X		X					
Drought Planning			X	X	X	X	X	
Increase Nutrient and AMD Management		X	X			X	X	
Thermoelectric Power Plant Cooling Changes ²²		X	X				X	
Nonstructural Flood Risk Management	X	X	X			X	X	X
More Water Quality and Discharge Monitoring	X	X	X	X	X	X	X	X
Land Use Management	X	X	X			X	X	X
Reservoir Operation and Structure Modifications	X	X	X	X	X	X	X	X
Managing Ecosystem Stress	X	X	X	X	X	X	X	X

3.2.7 Adapt: use results to develop and prioritize resilience enhancement options

An array of mitigation and adaptation strategies that could be deployed by water managers and users were developed to support the vision of the ORB Alliance: “to support and implement integrated management of the Basin’s resources to achieve sustainable economic growth, ecological integrity, and public safety,” (Drum et al. 2017). The Basin vision provided a metric to measure the success of measures and strategies to address potential climate change impacts. Adaptation options include a variety of options: (1) no action, (2) protection, (3) accommodation, and (4) retreat, and encouraged the incorporation of both *co-benefits* and *no-regrets* actions. Implementation strategies for these actions can occur for either individual infrastructures during normal operations based on existing protocols and manuals (e.g., locks and dams) or as an integrated system during emergency conditions. These recommended adaptation options were presented in an outreach effort described below.

3.2.8 Adapt: work with stakeholders and decision makers

One of the most successful and promising aspects of this study was collaboration with member organizations of the Ohio River Basin Alliance. The array of resources made available to the study team were instrumental in the success of the study. Other team members were either recommended by the Alliance or were already members of the Alliance, including working group leaders from Battelle, The Nature Conservancy, and physical and environmental scientists from the EPA and USGS. Collaboration through the Alliance was a positive lesson learned and may return dividends as a method for disseminating climate change data and operating as a vehicle for implementing strategies identified in the study.

The final step in the study was to identify the existing water resources development and operation policies by which the USACE operates and the implications of forecasted climate change threats to those policies. The present policies for managing the basin were designed with an expectation of sufficient water supply and constant mean annual temperatures. Climate forecasts suggest that these conditions will not remain steady and that policies should include flexibility to meet mission requirements.

4 Summary and Future Research

Resilience is a theoretical concept that has quickly become an important part of management and governance of large inland river systems. Understanding how to prepare by working with stakeholders to scope the system, analyze the system's response to risks, and identify means of improvement between disruptive events is a pattern that should be incorporated into any study aimed at improving decisions about how a system of interest is handled in the future. The framework and process identified herein (Figure 5) provide a means to formally structure studies that aim to understand more about how to incorporate resilience into future plans and development without straying far from existing project management paradigms.

Figure 5. Resilience analysis framework considering all four steps of the resilience cycle.

The case studies identified within this report present examples of how this framework fits with existing studies of resilience led by the USACE. Both studies are unique and tailored specifically to the aims of the interagency groups that participated in them. They also make remarkable headway in gathering quantitative information to generate conversation amongst stakeholders and resource managers about how to better understand their river system's ability to absorb disruptions. Critical to these important conversations is gathering the appropriate interdisciplinary teams and

garnering enthusiastic participation. For both studies, the results of each step in the framework is heavily dependent on the interaction and goals of the management agencies that participated in the study and the availability and reliability of data sources. As the number of new datasets increases and data reliability continues to improve, study teams need to ensure that they are capitalizing on the best methods and indices available for understanding complex natural and infrastructure systems in river basins.

Both studies also identified future work to build on their findings. Bouska et al. (2019) write that there are outstanding questions about how well the indicators identified represent adaptive capacity through the persistence and recovery of ecological resources. Adaptive capacity represents a different management paradigm that is challenging to grasp because of its flexibility and temporal nature. The ORB Alliance study addressed the concept of adaptive capacity head on — the objective of the study was to identify opportunities to improve the system over time given projected climate change impacts. However, the authors made note of the stark absence of any other ongoing climate change study or effort to develop adaptation strategies by other water managers or agencies operating in the basin. Adaptive management approaches have heavy requirements of time, modeling, and expert input that may not be available to many state or local agencies or non-profits. This work can also be difficult to justify financially as the anticipated future conditions may never materialize. There is an existing need for agencies like the USACE, EPA, and NOAA to take the lead in formulating strategies to reduce impacts from future threats. Additionally, the ORB study took many years to complete, from the formulation of the pilot study in 2009 to the publication of the final document in 2017. This level of effort is untenable for most agencies and stakeholders. Bouska et al. (2019) caveat their work by saying that large river systems like the UMRS must be simplified into either specific reaches or specific functions of interest (like the three resilience principles) to provide any useful findings for considering its capacity to respond to change. Further work on simplification of these river systems is necessary to generate useful findings and to lower the barrier of entry for others to begin similar studies.

The framework presented within this SR is a step-by-step explanation of studies that successfully incorporate the four concepts of resilience into an assessment of a river system. Resilience is the ability to prepare for the unexpected and to thoughtfully review past performance to make changes

and improve the system's ability to handle future disruptions. This paradigm is becoming increasingly important in a future full of climate and environmental uncertainty. Building from these concepts is a starting point for understanding how to design a study that results in stronger strategies for improving the inland river systems both now and into the future.

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Acronyms and Abbreviations

CMTS	Committee on the Marine Transportation System
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Agency
LRD	Great Lakes and Ohio River Division
NOAA	National Oceanic and Atmospheric Administration
ORB	Ohio River Basin
UMR	Upper Mississippi River
UMRS	Upper Mississippi River System
UMRR	Upper Mississippi River Restoration Program
USACE	US Army Corps of Engineers
USGS	US Geological Survey

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