A Science Strategy to Support Ecosystem Management Decisions in the Mississippi-Atchafalaya River Basin

Discussion Draft for Stakeholders in the Mississippi-Atchafalaya River Basin

Environmental Defense Fund

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"The river has great wisdom and whispers its secrets to the hearts of men."

Mark Twain, Life on the Mississippi

“A holistic approach to ecosystem management in River basin planning and management framework is vital to achieve sustainability of natural resources and socio-economic development.”

Survey participant

“To put your hands in a river is to feel the chords that bind the earth together.”

Barry Lopez

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Executive Summary

The Mississippi-Atchafalaya River Basin (MARB), which encompasses nearly 40% of the United States, is an extraordinary resource. It produces a significant proportion of the world's food supply, is a major source of drinking water, supports an inland transport system, and provides recreation to millions. It also provides clean water, regulates water flows and sustains habitat – services which are critical to both the ecosystem and to communities within its extensive watershed. However, its health is in decline, and – to date – it has not received the level of attention or investment in restoring ecosystem health that other nationally-important regions have received. We anticipate that this will change within a decade. To ensure that this investment delivers results, science will need to be integrated with management across all scales from the local to the whole Basin.

In this white paper, we propose a pathway to developing the robust science program needed for investment to be successful. Our proposed pathway is informed by conversations with scientists already tasked with managing large-scale ecosystem restoration programs and by conversations with scientists currently working within the MARB.

The good news is that stakeholders within the MARB are eager for an increased science presence within the Basin. The challenge is that much of the current science is fragmented across institutions, topics and geographies and it is not always directed to addressing the management questions that inevitably arise at sub-basin or Basin scale.

Drawing on the experiences of existing large-scale, publicly supported ecosystem management efforts, we propose a holistic science framework for management of the MARB that is oriented towards guiding management decisions at the scale of the whole Basin and individual sub-basins. Recognizing that it will take both time and external funding to develop such a framework, we also propose a series of low-cost steps that can be taken in the next 3-5 years by scientists and stakeholders in the MARB to help build out this framework.

While this report focuses on the role of science and scientists, we recognize that science does not operate in a vacuum: it must be connected to the interests of stakeholders and the needs of managers. We hope that our report will stimulate discussion about how best to connect science to these interests and needs.

Preamble: Why this paper matters

If you are one of the 70 million people who live, work or play in the Mississippi-Atchafalaya River Basin (MARB), you know what a wonderful place this is. You also know that – especially in the last two decades – the Basin has faced major challenges. For example, in the past two years, barge operators had to restrict shipments due to low water levels, while elsewhere there was extensive flooding. Invasive carp can cause the destruction of habitats for native fish, potentially reversing progress made towards ecological restoration. Last year the EPA found that Iowa's major urban drinking water supplies are contaminated with high levels of toxic nitrates. The 2023 Kansas wheat harvest was the worst in more than 50 years.

While these problems may seem to be separate, they are in fact connected. All are symptoms of a larger underlying issue: our communities' quality of life depends on the health of the ecosystem, and the MARB ecosystem is severely stressed because of human activities. The way that the Basin is currently managed has largely failed to improve the situation. What is needed is a better approach to reducing those stresses and finding a way to adapt to emerging challenges.

That will require both new approaches to governance that include non governmental organizations and a massive increase in public funding. This has been done elsewhere, for example in the Everglades, Chesapeake Bay and the Great Lakes. It could happen here in the MARB. However, new governance structures will only succeed if they inspire people to action, and if those actions are guided by the best available science.

Our vision is that, in the next decade, large-scale investment in the MARB will begin to turn things around, improving ecosystem health and making all of our lives better. For that investment to be successful, it must rest on a robust scientific foundation.

That's what this white paper is about: what kind of scientific foundation will be needed to make the best use of those dollars. We will need science to diagnose the problems and identify solutions. We will need science to help us understand what will happen if certain management changes are made. We will need science to monitor ecosystem health, so we can tell whether or not management changes worked as we hoped.

We've drafted this white paper in consultation with scientists. Now it's your turn to think how best to meet the challenge of ensuring that management actions are informed by the best available science. We look forward to hearing from you.

Introduction: The need for new investment in the MARB

The Mississippi-Atchafalaya River Basin (MARB) (Figure 1) is of national and international importance. It is the largest watershed in the U.S., draining 40% of the United States and supporting an economy worth more than $400 billion per year in the Upper Mississippi River Basin alone. However, the MARB's ability to continue providing an array of ecosystem services of value to the general public[1] is increasingly under threat. Degraded water quality threatens public and ecosystem health throughout the Basin; soil degradation puts agricultural production at risk; decline and degradation of habitat threatens multiple species and associated recreational activities; and worsening droughts and floods threaten communities and important industries. All of these challenges are anticipated to grow as a result of climate change. Despite its importance the MARB has not seen the kind of dedicated, long-term investment in restoring ecosystem health[2] enjoyed by other regions in the United States.

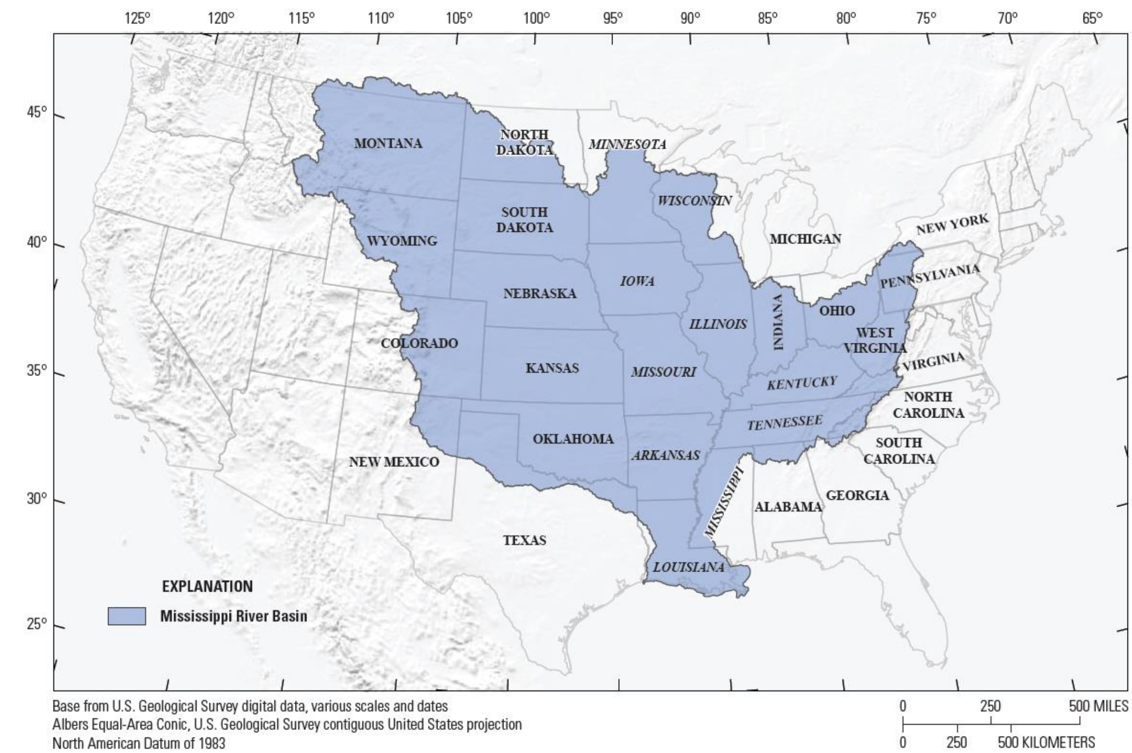


Figure 1 - Location of the Mississippi-Atchafalaya River Basin.

[1] "Ecosystem services" refers to the benefits that humans receive from healthy ecosystems. In the MARB, important ecosystem services include clean air and water, flood control, food production and recreation.
[2] "Restoring ecosystem health" means restoring critical ecological processes that provide ecosystem processes; it does not imply restoring the ecosystem to a specific historic condition.

Although some science-based programs in the Basin have a long history, these programs are limited in geographic scope or issue focus[3]. There is a growing constituency advocating for increased attention and more wide spread participation to the MARB as a whole. The Mississippi River Watershed Partnership has brought together a broad coalition of stakeholders to advocate for needed funding and has facilitated conversations about improving coordination across multiple federal and state agencies. The Mississippi River Cities and Towns Initiative has also raised awareness of the unique challenges for local governments within the Basin and the need for significant funding to address them. The nonprofit One Mississippi (formerly Mississippi River Network) has been highlighting the need for legislation to provide dedicated funding for river restoration. The Nature Conservancy has been convening state and federal agencies, together with NGOs, to identify priority needs and locations for a sentinel monitoring network at the scale of the Basin.

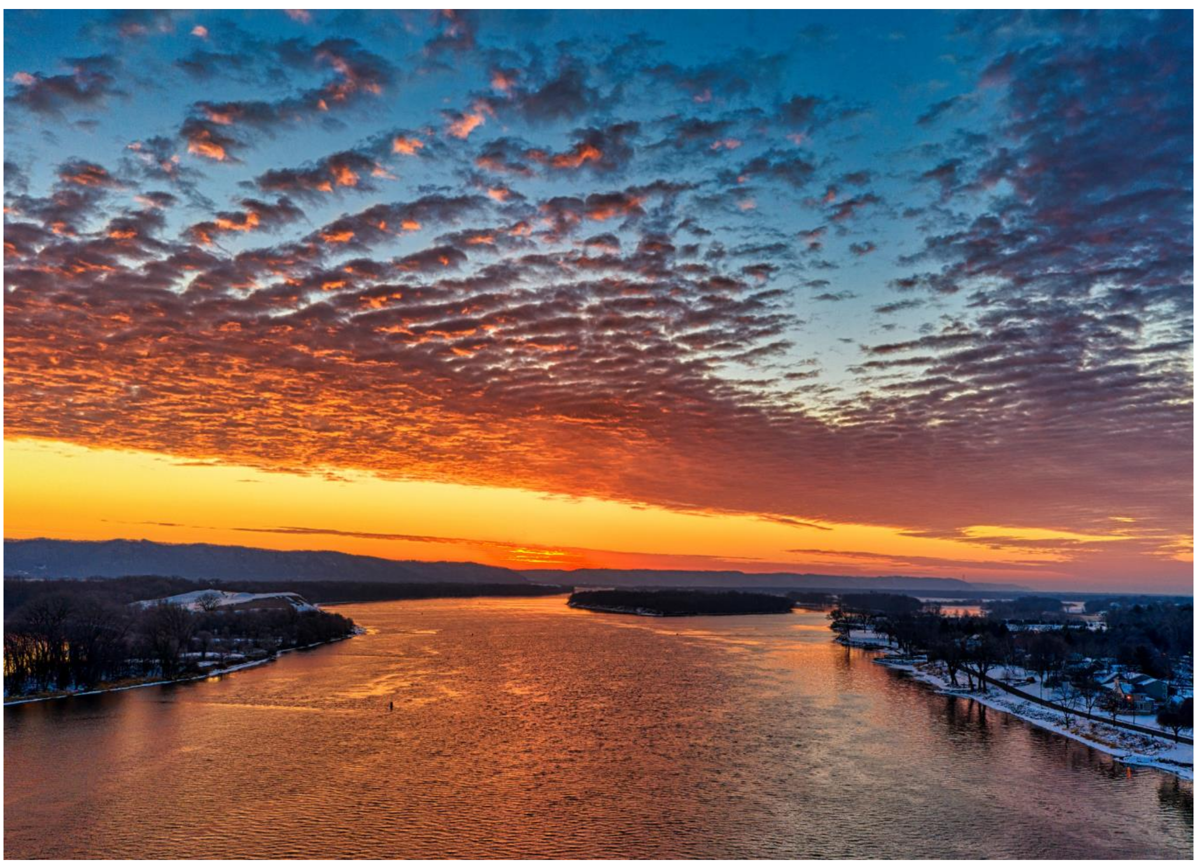
In response to growing interest in the Basin, in 2021 Congressional appropriators requested the U.S. Environmental Protection Agency (USEPA) to inventory existing federal and state investments in the MARB and identify significant policy gaps. The resulting report, published in 2022[4] provides a very useful compendium of all the federal programs that support activities in the MARB, together with recommendations for policy changes to make these programs more effective. Also in 2021, appropriators requested the U.S. Geological Survey to assess the current state of the science in the MARB, including data gaps. The USGS report[5], published in 2024 following an online Science forum which drew participants from across the Basin, makes clear the need for a more comprehensive and coordinated science program across the entire MARB, a need we re-emphasize in this paper.

> **"The Mississippi River supports a strong and energetic stakeholder community eager for an increased science presence in the …Basin."**
> **USGS Mississippi River Science Forum report**

[3] For example, the Army Corp's Upper Mississippi River Restoration Program dates to 1986; the founding legislation that led to the Hypoxia Task Force dates back to 1998, but the Hypoxia Task Force does not have the structure or funding to be considered as a restoration program on the same level as these others.
[4] The Mississippi River Restoration and Resiliency Strategy, available at: https://www.epa.gov/nps/mississippi-river-restoration-and-resiliency-strategy.
[5] U.S. Geological Survey Mississippi River Science Forum—Summary of data and science needs and next steps, available at: https://www.usgs.gov/publications/us-geological-survey-mississippi-river-science-forum-summary-data-and-science-needs.

Although early actions by the current administration seek to de-emphasize federal support and spending, the need for increased resources and support will continue to grow as the impacts of global changes become more intense and widespread. What is already clear and will grow over the the next decade is the need for a significant investment in improving the health of the MARB system to deliver benefits for the ecosystem and local communities.

To grow and support continuing investments in the Basin will require regular assessments of "success", defined as measurable progress towards stakeholder-informed goals. This Science Framework (including both biophysical and socio-economic aspects) outlines the need for establishing meaningful and realistic goals, providing guidance on the best approaches to meeting those goals, and helping decision-makers evaluate progress. Efforts to restore the health of the MARB and its associated communities must put science at their heart, and in this paper we recommend how that can be accomplished.



The Current State of Science in the MARB

To gain an understanding of the current state of science in the MARB, we conducted interviews with scientists from federal agencies and academia who work in the Basin and supplemented this effort with a survey of water resource professionals. Survey respondents included scientists working for federal and state agencies, academia, non-governmental organizations and private entities.

We learned that a wide array of institutions are engaged in generating scientific understanding of the MARB and the influence of human activities on the Basin's health. These institutions include: Federal agencies[6]; state environmental and natural resource agencies[7]; tribal entities[8]; academic institutions (both large research universities and smaller undergraduate colleges); non-governmental organizations at national to local scales; and private companies (including representatives of agricultural and shipping interests). A further set of institutions play a role in coordinating scientific investigations at regional or sub-regional level[9]. Some institutions focus on one issue, like the Gulf Hypoxia Task Force; others focus on specific geographies.

Scientific research within the Basin covers a spectrum from the collection of monitoring data to detailed investigation of ecological processes. This research has helped identify the over-riding problems facing the Basin: degraded water quality at local and regional scales; unsustainable use of surface and groundwater; limited ability to adapt to more frequent and intense droughts and floods; loss of charismatic species and widespread decline in species diversity and numbers; loss

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[6] Relevant Federal agencies include: U.S. Environmental Protection Agency; U.S. Geological Survey; U.S. Department of Agriculture; U.S. Fish and Wildlife Service; National Oceanic and Atmospheric Administration; Federal Emergency Management Agency; and the U.S. Army Corps of Engineers.
[7] For example, in Iowa, relevant agencies include: Iowa Department of Agriculture and Land Stewardship; Department of Homeland Security and Emergency Management; and the Department of Natural Resources.
[8] In the MARB there are 115 federally recognized U.S. Tribes and 5 Tribes recognized by the Canadian Government. Examples include: Bad River Band of Lake Superior Ojibwe; Prairie Band Potawatomi Nation; Fond du Lac Band of Lake Superior Chippewa; Jena Band of Choctaw Indians; Great Lakota, Dakota, Nakota Nation; Red Lake Nation.
[9] For example, the Upper Mississippi River Basin Association coordinates state-level water quality monitoring in the Upper Basin and the Lower Mississippi Conservation Commission coordinates efforts related to improving fish and wildlife stocks and habitats in the Lower River.

and degradation of habitat; increasing challenges posed by invasive species. Research has also shown that the relative importance – and even directionality - of these problems varies from sub-basin to sub-basin across the MARB; for example, some portions of the Basin are particularly vulnerable to floods and others to droughts.

Much of the scientific effort in the Basin is devoted to routine monitoring, particularly water quality and flood stage monitoring. As others have noted[10] the lack of coordination across these programs in terms of types of data collected and collection methodologies, together with the lack of a centralized data repository, make it difficult to detect trends in environmental conditions across space and time within the Basin. Perhaps more importantly, there appears to be no systematic effort to use monitoring data to inform socio-ecological models of the system or to test the impact of management actions.

The sheer size of the Basin (1,239,000 square miles) poses a challenge to coordination, both of monitoring and of broader scientific research. The scientists who we interviewed or surveyed acknowledged the lack of, and need for, scientific assessment at the scale of the whole Basin. However, they also pointed out that local communities may be more concerned with localized problems that need detailed investigation at a smaller scale.

We also learned that most scientists working in the Basin have at best limited interaction with other scientists working in the Basin: 24% said that they "rarely or never" interact with other MARB scientists. Again, this is understandable given the size of the Basin and the specialization of most scientists' work. However, it does mean that most scientists' view of the MARB is confined to a limited region and issue area, and that there is little understanding of the Basin as a system.

[10] National Research Council. 2008. *Mississippi River Water Quality and the Clean Water Act: Progress, Challenges, and Opportunities*. Washington, DC: The National Academies Press; U.S. Geological Survey Mississippi River Science Forum report (see footnote 4); The Nature Conservancy https://www.nature.org/en-us/about-us/where-we-work/priority-landscapes/mississippi-river-basin/monitoring-the-mississippi/

Challenges with the current approach

Lack of clear goals

> **"We have to have an end goal in place. We have to know where we are going." "We don't want random acts of science but [we] want a goal and target."**
> **Panelist from AWRA forum**

At the scale of the Basin, the only clear goal is the nutrient reduction target established by the Hypoxia Task Force.[11] The existence of this target has served to foster coordinated action by all of the mainstem states in the Basin. Unfortunately, it's not clear that this target resonates with all of the stakeholders in the Basin; people tend to care more about their local water quality than downstream. In contrast, in at least two of the large-scale ecosystem restoration programs we examined, clear goals serve to drive action on multiple issues (such as restoration of iconic species and removal of toxic chemicals) across the entire ecosystem.

> **"[We] need … a clear message that resonates with stakeholders, focusing on habitat, fish, and clean drinking water. [These] priorities should drive the science, rather than the other way around. For instance, the Chesapeake Bay program emphasized bringing back sea grasses and blue crab harvests, which meant that water quality would need to be improved, rather than stressing the water quality itself"**
> **Scientist in a federal agency interview**

Lack of system perspective

The MARB is a vast and complex system, ranging from semi-desert landscapes in its far western tributaries to a complex delta system at its mouth. Like the apocryphal blind men grasping parts of an elephant, almost every scientist working in the Basin sees only part of the system; this is not a criticism of individual scientists, but rather a note that opportunities are missed when nobody is tasked with seeing the bigger picture.

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[11] The Task Force target is to reduce the area of the Gulf of Mexico hypoxic zone to less than 5,000 km^2 (approximately 1,930 square miles). The Task Force also agreed to reduce the nutrient load by 20 percent by the year 2025, as a milestone toward reducing the hypoxic zone to less than 5,000 km^2 by 2035.

As a result, efforts to, for example, treat problems of excess sediment in the streams of the upper part of the Basin are disconnected from efforts to increase sediment flows in the lower part of the Basin. Likewise, with a few notable exceptions[12], little attention is paid to the ways in which management of the land affects conditions in the River, or how activities in the upper portion of the Basin affect communities all the way to the Gulf. As noted in the 2024 USGS report: "The focus now and into the future needs to include the entirety of the Mississippi River Basin". This would include the River corridor itself, the tributaries and indeed the entire watershed, from Minnesota to Louisiana and from Montana to West Virginia.

> **"There are a lot of questions and not enough time and resources to address them all – a holistic approach would help identify the scope of the problem, synthesize existing data, and provide a guide to where and what to sample to address key gaps."**
> **Scientist from the survey**

Monitoring not strategically integrated with a larger scientific framework

> **"[Even] if you looked at the abundance of monitoring you couldn't actually infer the goals of the program, and you should [be able to]. You should be able to look at what's being monitored and say, "I get what you're after'".**
> **Scientist from AWRA forum**

While a considerable amount of monitoring is done throughout the MARB, it's not clear how this monitoring relates to a larger scientific framework. Monitoring by itself can be helpful in communicating the current state of the ecosystem and – if designed well – can be used to communicate changes in ecosystem health over time. However, to be most useful, monitoring must be tied to programmatic goals, and designed to measure progress towards specific environmental, social and economic targets. If there are goals related to, for example, changes in species abundance or flood damage, then there needs to be associated monitoring of changes in specific indicators of species abundance or flood damage. Goals should drive indicators, which determine what is to be monitored, rather than monitoring driving goals.

[12] Mississippi River/Gulf of America Hypoxia Task Force https://www.epa.gov/ms-htf; SERA 46, The Framework for Nutrient Reduction Strategy Coordination, https://northcentralwater.org/partnerships/sera-46/

> **"Monitoring [by itself] isn't a scientific framework. It has to be a part of it. That means you need models … that can help you understand the way the system is now and how it may change."**
> **Scientist from AWRA panel**

To be most useful, monitoring should also be connected to models of how the system operates. Ecosystem management relies on models that describe how different parts of the system connect to one another; this enables managers to use models to predict the impact of changes in management actions. Monitoring then plays a critical role in evaluating whether the change in management led to the desired result: did the monitored change in environmental conditions align with the change predicted by the model? If not, this implies that the model needs to be re-evaluated.

> **"Often you don't realize what you don't know until you try to model the whole system."**
> **Scientist from a university interview**

Lack of clear processes to connect science to management and stakeholders.

What is clearly missing at the moment in the MARB is a synthesis of what we have learned from research to date, including identifying where there is conflicting information and where there are gaps, and a process for resolving contradictions and filling gaps. It's also clear that there is a need to better explain to stakeholders what is known about the causes of the Basin's problems; stakeholder perceptions often differ from scientific understanding, and progress will not be possible until there is broad agreement on causes and solutions.

> **"Having worked in both the Mississippi and Great Lakes Basins, I think the former can learn much from the latter in terms of integrating science throughout the management community."**
> **Scientist from the survey**

Lack of coordination.

Each of the scientific entities within the MARB has specific topics of interest (often prescribed by authorizing legislation or mission statements), works in discrete geographies (often prescribed by political geography rather than ecology), and is usually staffed by scientists from a subset of scientific disciplines. Given this reality, it is not surprising that there are often overlaps and gaps in research questions, data collected, and analysis undertaken. More troubling is that failure to consider the interactions between issues such as water quantity, water quality and habitat risks creating unintended trade-offs between various environmental (and other) outcomes.

> **"We have a need for better coordination and reduced duplication among federal agencies to achieve more effective results."**
> **Scientist in a federal agency interview**

Lessons learned from other large-scale ecosystem restoration programs

Anticipating a significant influx of funding to the MARB, we decided to learn how science is integrated into existing large-scale, publicly supported ecosystem restoration programs. Many of these programs have developed robust science programs whose primary purpose is to guide decision-making at a large spatial scale. Seeking to understand "what works" we began with a literature review of materials from the Chesapeake Bay Program; the Great Lakes Restoration Initiative; the Comprehensive Everglades Restoration Plan; and the RESTORE program in the Gulf of Mexico. In addition, we looked at how science is incorporated into other regional ecosystem restoration efforts (the Puget Sound Partnership and the California Bay-Delta program). In each case we reviewed the science plan or framework (if any) used to guide management decisions, as well as the institutional arrangements for connecting science and management to one another. In addition, we read programmatic reviews conducted by, among others, the National Academy of Sciences and the Government Accountability Office, which identified additional needs and opportunities for integrating scientific input into decision-making.

In all cases it was clear that science played an important role in setting overall programmatic goals, in evaluating strategies and projects needed to achieve those goals, and in documenting the impact of selected strategies and projects. In the case of the Chesapeake Bay Program and the Great Lakes Restoration Initiative, scientific assessments of the state of the ecosystem – demonstrating that human stressors were impacting the ecosystem and the communities that depend on it – were instrumental in securing the initial investments that established the programs as well as for ongoing and increasing program support.

Following this literature review, in October 2024 we hosted a panel discussion at the annual meeting of the American Water Resources Association (AWRA), titled "Developing a scientific framework for ecosystem restoration in the Mississippi River Basin". Panel members[13], all scientists responsible for managing the science programs in large ecosystem restoration efforts,

[13] Panelists are listed in Appendix A

offered lessons learned on how best to ensure that science is at the heart of ecosystem management. Although the programs they described varied with respect to authorizing legislation, overall goals, and governance structures, the panelists were unanimous in calling for strategic integration of science into all aspects of the program, from setting overall program goals and objectives to identifying priority restoration projects and tracking program impacts.

The importance of collaboration

Across all programs, our panelists stressed that the most important factor that led to success was trust and accountability: trust that all partners were committed to the same goals, and that they would collaboratively work together and be accountable to each other to achieve those goals, prioritizing the success of the effort over advancement of any individual or institution.

> **"Collaboration is extremely important in whatever framework you are working in. If you are going to start any kind of project, having a mechanism for people to work together, to agree and have that constant commitment to meeting together and holding each other accountable is super, super important."**
> **Panelist, AWRA Forum**

How to build that atmosphere of trust? This is the critical question for all partnerships, and the answer always seems to be that it takes a willingness by all partners to keep showing up to meetings, to learning together, to working side-by-side on small projects, and time[14]. Successful programs did not appear, fully-fledged, from the void. They grew out of small groups and small projects, growing over time – time that is measured in years.

Scientist responsibilities

Panelists identified that, for programs to be successful, scientists must take on a variety of responsibilities, as listed in Table 1.

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[14] See, for example, "Making Collaboration Work: Lessons from Innovation in Natural Resource Management", S.L. Yaffee and J.M. Wondolleck, Island Press, 2002.

Table 1. Scientist responsibilities

Scientist responsibilities
Working with stakeholders and managers to translate stakeholder interests into meaningful, realistic, and measurable goals.[15]
Creating a model of the biophysical system.[16]
Identifying the key stressors which need to be addressed in order to restore desired ecological processes and functions.
Modeling the impact of changing stressors (e.g., climate change) and changing management scenarios on desired environmental outcomes.
Helping decision-makers evaluate different options for improving ecosystem health.
Quantifying the relative benefits of different management scenarios in terms of desired environmental outcomes, so that managers can prioritize funding to the most effective projects and approaches.
Testing scientific assumptions about how the system behaves by comparing modelled results with monitoring data.
Identifying circumstances in which actions can lead to trade-offs across desired outcomes.
Recommending experiments to reduce scientific uncertainty and so increase confidence in proposed solutions.
Working with managers in an adaptive process to refine (and as needed, redirect) management actions in light of evolving scientific understanding (e.g., if monitoring impliess that system models need to be updated).
Translating monitoring data to help stakeholders and decision-makers understand the impact of – and limitations to - restoration efforts.

The role of a coordinated science program

A key question centers on the need for and value of a coordinated science program. In each of the case studies we examined – in the Chesapeake Bay, Great Lakes, Everglades and Gulf of Mexico – scientific research, including state- and locally-led monitoring programs, was already underway when the program was established. However, as is the case in the MARB today, this research was not necessarily tied to ecosystem-scale goals, nor was it coordinated to ensure that resources were used most efficiently. In addition, critical elements of science programs, such as ecosystem models, were lacking. Each of the programs that we reviewed had developed a coordinated science program which served both to coordinate existing work and to develop the tools and processes necessary to support integrated, ecosystem-scale decision-making. In this way, a coordinated science program adds value to existing smaller-scale programs, enabling the development of tools (such as ecosystem models) that benefit existing programs.

[15] For example, in the Chesapeake Bay, stakeholders identified particular species whose decline they wanted to reverse; scientists quantified the habitat needs for these species, such as acceptable levels of turbidity and dissolved oxygen; policymakers then translated these habitat needs into specific water quality goals.

[16] All panelists agreed that it will be important, going forward, to move beyond models of the biophysical system to broader modeling efforts that include social and economic aspects of the system

Critical elements of science programs

Panelists also identified what we might think of as the "nuts and bolts" of making science work in this context – critical elements that need to be funded as part of the ecosystem management program and institutionalized within it.

A set of guiding principles

A set of guiding principles, such as a recognition of the need to integrate biophysical science with socio-economic concerns, a commitment to scientific integrity, a commitment to addressing scientific uncertainty, and an emphasis on science that is relevant to decision-making.

A set of tools to connect science to management (and vice versa)

These would include:

- Metrics (goals, targets, and indicators) developed in collaboration with stakeholders; they would be used to define desired future conditions and to track whether or not management activities are moving the system towards those conditions;
- A socio-ecological model (or set of interconnected models) that reflect current understanding of the system, and how changes in one element of the system affect other elements. For example, it may show how changes in policy affect fertilizer use, and how changes in fertilizer use may affect water quality and farm income. It might show how changes in dam operations affect river flows, how changes in river flows affect aquatic habitat and species, and how changes in habitat and species affect recreational activities. A model is critical to predicting the impact of management actions.
- A comprehensive monitoring program that tracks both leading and lagging indicators, in order to provide insights into the impacts of management actions on environmental, social and economic outcomes[17]. A monitoring program is critical in testing how well the model(s) describe reality.

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[17] For more on the topic of leading and lagging indicators, see McLellan, E.L., Suttles, K.M., Bouska, K.L., Ellis, J.H., Flotemersch, J.E., Goff, M., Golden, H.E., Hill, R.A., Hohman, T.R., Keerthi, S. and Keim, R.F., 2024. Improving ecosystem health in highly altered river basins: a generalized framework and its application to the Mississippi-Atchafalaya River Basin. *Frontiers in Environmental Science*, *12*, p.1332934.

A set of processes to connect science to management (and vice versa)

- A process for ensuring regular communication between scientists and managers, so that scientists can understand managers' questions and managers can hear scientists' concerns.
- A process for analyzing and synthesizing scientific results and translating them into materials that are useful to managers
- A process for competitively funding management-relevant research.
- A process for independent scientific review, as needed to address significant dissent within the scientific community.

An adaptive management framework

All of our panelists stressed the importance of an adaptive management framework that allows for course corrections based on lessons learned. It is simply not possible, at the start of any program, to fully understand the system (ecosystem or socio-ecological system), how stressors impacting the system (such as climate change) will change through time, or how management actions will affect the system. This creates uncertainty, and uncertainty can serve to inhibit action. To avoid this problem, scientists use a "learning-by-doing" approach, beginning with hypotheses about how the system works, formalizing those hypotheses into models, and testing those hypotheses with real-world data. Adaptive management is a structured approach that involves continuous learning, monitoring and adjusting strategies based on the measured (monitored) outcomes of (management) actions.

Figure 2 below presents a simplified example of an adaptive management framework. It begins with defining the problem (for example, in the Everglades, the problem was fundamental changes to the hydrology of the system driven largely by agricultural production) and building a simplified model to show how human activities change environmental (and other) outcomes. A management action is selected and implemented along with monitoring that will test the results of the management action. Then the monitoring results are evaluated and communicated to stakeholders. The final step is learning from what worked or didn't work based on the modeling and monitoring results and adapting the next management action and/or models and monitoring based on that learning. This is the most critical part of "learning-by-doing" to incorporate what is learned into the next iteration of the process.

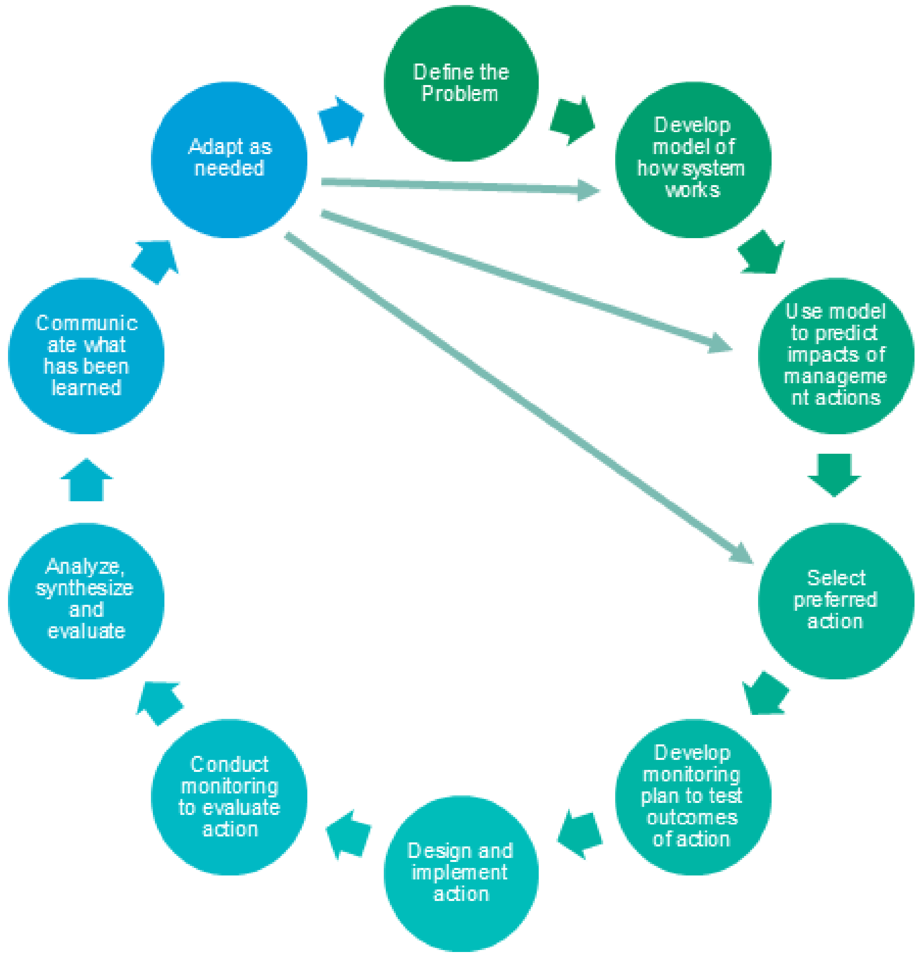

Figure 2 - A simplified adaptive management framework.

The most important - and challenging - part of an adaptive management framework is the final step: the willingness to make changes in response to new data. Monitoring data may show that changes in management have not led to changes in outcomes that the system model predicted. This may mean that the model needs to be revised; it almost certainly means that management actions must be halted or changed.

> **"Adaptive management is fundamentally about getting management smarter based upon our best understanding and the realities of what's happening on the ground and tying those together. So I think start with that and build a framework around it."**
> **Panelist, AWRA Forum**

> **"What came out of that effort was a periodic and disciplined effort to reevaluate major portions of your program as it matures."**
> **Panelist, AWRA Forum**

A scientific infrastructure to facilitate communication and collaboration between scientists

This could include the following:

- A widely accessible data repository containing standardized monitoring data, a model (or linked models) simulating the system, and results of model runs simulating different management (or other, e.g. climate) scenarios. It might also support a research library which compiles peer-reviewed and grey literature relevant to the region;
- Funding support for annual conferences to allow scientists to meet one another, present the results of recent research, and discuss implications for management;
- A process for collaborative work planning that allows federal and state agencies, academics and scientists from NGOs and industry to work together in answering management-relevant questions; this could include incentives that reward scientists for inter-disciplinary and cross-institutional work.

Based on our panel discussion and subsequent conversations, we conclude that these same critical elements – guiding principles, tools, processes, an adaptive management framework and scientific infrastructure - will need to be built as part of investment in the MARB. A key question then is how to grow science capacity and infrastructure in the Basin over time, moving from where the science is now (primarily focused on monitoring, mostly at sub-basin or smaller scales) to where it will need to be in a decade's time (integrated into all aspects of Basin management at whole-Basin and sub-basin scale).

Recommendations for moving forward

How best to grow science capacity and infrastructure in the MARB towards the kind of sophisticated science programs seen in the Chesapeake Bay, Great Lakes, Everglades and Gulf of Mexico? And how to do this in a way that leverages the investments that have already been made in the Basin, such as the work of the Upper Mississippi River Basin Association in aligning monitoring programs across state lines, the relationships that the Hypoxia Task Force has built with Basin states, and long-term monitoring programs run by USGS and others? In this section we attempt to answer these questions, recognizing that the ability to move forward may be constrained by the political (and therefore funding) environment in the near term.

The first step is to ***formally convene a group of scientists to carry forward the conversation about growing science capacity and infrastructure in the Basin***. In this we concur with the USGS report, which called for the formation of a Mississippi River Science Team. This Team should include representation from the entire science community in the Basin: federal and state agencies, tribal entities, academia, non-governmental organizations and industry. It should include biophysical scientists, economists and social scientists. It should help to integrate existing science programs in the Basin. And it could be convened as part of the broader stakeholder engagement and Basin governance work being undertaken by the Mississippi River Watershed Partnership (MWRP). We cannot emphasize enough that the intent of convening the Mississippi River Science Team is not to replace existing science programs in the Basin, but rather to strengthen them through connection. The analogy that perhaps best describes this is the process of creating a mosaic, by taking an array of (individually appealing) fragments and arranging them to create a bigger and more coherent picture (see Figure 3). Existing programs, such as the Hypoxia Task Force, as well as emerging projects like the MRWP, would be integrated into this bigger picture, gaining strength from their new relationships with other institutions and activities in the Basin. Inevitably, as the mosaic is assembled, areas of overlap will be identified, as will gaps. Part of the ongoing work of the Science Team will be to make recommendations to managers on how best to address these gaps and overlaps.

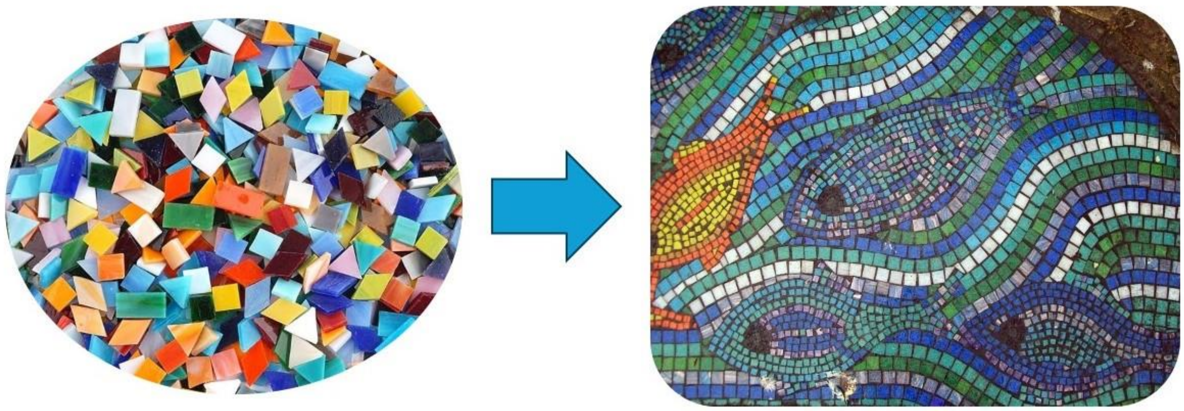

Figure 3 - Current programs are the individual tiles on the left-hand side of the diagram; when the tiles are put together, as on the right-hand side, a larger picture emerges.

We further recommend that, over the next 3-5 years, the Mississippi River Science Team (MRST) undertake five activities that, individually and collectively, would begin to address the challenges with the current fragmented approach to science in the Basin and help make the case for expanded investment in the MARB.

Convene science team! Top actions you can take:

1. Create a shared vision of what science in the Basin could look like.
2. Build on current efforts by The Nature Conservancy and others to develop consensus on monitoring needs across the Basin, develop common data collection protocols, and lay the groundwork for a data repository accessible to all scientists in the Basin.
3. Publish a science assessment of the state of the Basin for a policy audience, articulating its problems and what is at risk for the Basin and the communities it supports.
4. Organize a Mississippi River Research Forum to identify the key research questions that need to be addressed to inform effective management of the Basin; these questions can include socio-economic concerns as well as biophysical issues.
5. Work with stakeholders in a formal process to develop goals for the Basin as a whole and for sub-basins.

Create a shared vision of what science in the Basin could look like

What might the "larger picture" hinted at in Figure 3 – the vision – look like? In our conversations, interviews and survey, we asked scientists what they thought about a "holistic approach", which we described as:

- bringing together human and natural systems;
- being cross-disciplinary, both within and across the biophysical and social sciences;
- connecting landscapes and riverscapes; and
- recognizing the connections between multiple issues of concern – water quality, water quantity, species and habitat.

There was overwhelming support for a holistic approach, with all of our interviewees expressing support, and over 90% of survey respondents agreeing that management that integrates across issues and scientific disciplines is "important" or "very important". There was also widespread agreement (over 92% of respondents) that a holistic approach that moves beyond water quality (which has been the focus of much of the work in the Basin) is needed in order to better engage stakeholders.

> **"A holistic approach in the Mississippi River Basin will not only enhance ecological health but also provide long-term economic and social benefits, ensuring the sustainability of this vital resource for generations to come."**
> **Scientist from the Survey**

We do not presume to present even a straw proposal for an institutional structure that would support such a holistic approach, beyond noting that it must allow for coordination and collaboration across existing institutions, while at the same time providing support for science activities that connect across water quality, water quantity, habitat and species, and for science activities critical to management of the Basin as a whole. We do, however, note that in the large-scale ecosystem restoration programs which we reviewed, the critical elements of the science component of such programs (the tools, processes and scientific infrastructure described above) were housed in a centralized location.

Lay the groundwork for a shared approach to monitoring

As noted earlier, there has already been a significant investment in monitoring within the MARB. The challenge at present is that, seen at the scale of the whole Basin, these programs are not consistent in what environmental outcomes they monitor, the protocols they use to monitor these outcomes, or the way they analyze and report data. This makes it difficult to tell a coherent story about the health of the Basin and how it is changing with time, or to identify hotspots of particular concern. Scientists attempting to synthesize monitoring data at scale are hindered by the need to reconcile dissimilar datasets, many of which are difficult to access for scientists outside of the sponsoring institution. Scientists told us they were frustrated by this situation, and 86% of survey respondents rated an integrated database of monitoring data as “useful” or “very useful”.

The Nature Conservancy is currently convening scientists from across the Basin to develop a sentinel monitoring system to aid efforts to address water quality, water quantity, habitat and navigation challenges within the Basin. This work should serve as a foundation for additional work by the MRST to develop guidelines for standardization of the indicators to be monitored, the monitoring protocols to be used, and methods for data reporting that include pathways to broader data accessibility. A critical question to be addressed upfront is where a Basin-wide data repository could be housed. Given the potential threat to government datasets under different administrations, it will be advisable to build in redundancy so that critical data remains accessible to the full range of scientists.

In advocating for Basin-wide standardization of monitoring data, we do not mean to imply that more locally focused monitoring programs should be discontinued or forced to align with more regionally oriented programs. Whether at sub-basin, state or watershed scale, there will often be issues of interest that are supplemental to those that are the focus of Basin-wide monitoring. These programs provide valuable information to local managers and stakeholders, and in some cases, they may be the first to identify emerging issues of concern that will impact the Basin as a whole in the future.

Publish a “State of the Basin” report

We recommend that an early activity of the MRST be the compilation and publication of a “State of the Basin” report for policymakers. We stress policymakers as an audience because of lessons learned from the Chesapeake Bay Program and Great Lakes Restoration Initiative: a report that clearly and concisely identifies the challenges in the Basin, with a particular emphasis on environmental conditions and the impacts of a degraded environment on communities, can be the key to unlock public funding. An articulation of the challenges to the Basin as a whole enables policymakers and funders to understand the scale of the problem and can prompt policymakers and funders to support solutions at an appropriately large scale.

The report should clearly identify the priority problems that must be addressed if the Basin and its dependent communities are to thrive in the coming decades. It should also explain – in non-technical language – the causes of those problems. To be most useful to a policy audience, it should include economic valuation of the ecosystem services – the benefits to human communities - that will be lost if action is not taken.

Organize a Mississippi River Research Forum

We noted earlier that many scientists in the MARB have at best limited interactions with other scientists. One way to foster these interactions is through a regular in-person and/or online convening, perhaps on the lines of the current Mississippi River Research Consortium. In our survey, 74% of respondents rated a regular forum for scientists to identify common interests, share research and connect with potential collaborators from other scientific disciplines as "useful" or "very useful".

In addition to an ongoing convening role, a Mississippi River Research Forum could also make the case for additional investment in the MARB. We say this because we anticipate that the process of compiling a "State of the Basin" report will reveal a number of research questions that need to be addressed if ecosystem restoration is to be successful. The Mississippi River Research Forum could compile these questions into a targeted research agenda that would identify critical research gaps, as well as areas of scientific conflict and uncertainty. Such an agenda, by clearly demonstrating how the answers to scientific questions will move management efforts forward, could potentially attract funding in advance of a larger implementation-focused funding initiative.

Work with stakeholders in a formal process to develop goals for the Basin as a whole and for sub-basins

As with environmental monitoring, a number of initiatives have already sought to identify goals for Basin restoration. Not surprisingly, these goals have in common a focus on the key environmental challenges facing the Basin: impaired water quality (at both local and regional scales); a mismatch between the amount and timing of flows of water (surface and groundwater) and the needs of the ecosystem and communities (e.g., flows needed to sustain aquatic habitat, the social and economic challenges of both floods and droughts); loss and degradation of habitats; and threats to overall biodiversity and to specific species. Some initiatives have identified other goals, related more to socio-economic outcomes in the Basin, such as the maintenance of the inland navigation system and redress of historic inequities borne by disadvantaged communities. In publicly funded ecosystem restoration programs, the public must play a large role in deciding on goals. These goals may be quite high-level and ambitious, e.g. “”. It can, however, be difficult to assess progress towards meeting such goals, and this is where scientists can provide value, by working with stakeholders to translate high-level goals into specific, measurable targets. These goals and targets can then be incorporated into the science program and management processes of the larger program; from them flow indicators which can be modeled and monitored to evaluate possible solutions and measure the impacts of management actions.

To advance this effort, the MRST should compile a list of the Basin-wide goals already developed within the MARB and work with the stakeholder-driven organization that represents the most diverse array of stakeholders – perhaps the MRWP – to review these goals and translate them into the more specific and measurable targets that will be needed to ground a Basin-wide ecosystem restoration program.

As with environmental monitoring, a limited suite of Basin-wide goals will not fully capture the interests of stakeholders in all parts of the MARB. Regional (sub-basin) and more local goals are just as important as Basin-wide goals, so long as they are not in conflict with them, and scientists have a role to play here, too, in helping translate high-level narrative goals into measurable targets. However, given the Basin-wide perspective of the MRST we recommend that it focus on Basin-wide goals while encouraging scientists working within sub-basins to develop sub-basin goals.

Looking further ahead: Building a stronger scientific foundation for Basin management

As we listened to scientists across the Basin, some challenges were called out repeatedly. Some of these challenges are unique to the MARB, while some reflect a growing societal and scientific understanding of how complex systems work and what interventions are possible. None can be addressed by scientists alone. Solutions will require ongoing dialog between scientists, stakeholders and managers, and we note them here in hopes of inspiring such dialog.

Seeing the system as a whole, while respecting local differences

A challenge unique to the MARB is the sheer size of the system. The five major sub-basins differ in climate and physiography; these differences have driven development patterns and therefore the dominant stressors – and resulting impacts on ecosystem health – vary from sub-basin to sub-basin. Stakeholder priorities also vary from sub-basin to sub-basin, which will affect the relative prioritization of goals at smaller scales.

As indicated in previous sections, to make progress at the scale of the Basin will require setting Basin-wide goals and using a Basin-wide monitoring system to track progress towards those goals. Evaluating the potential impact of management actions will also require a Basin-scale model, to avoid the risk that actions taken in one sub-basin simply export problems elsewhere. At the same time, it will be important to recognize that the desired directionality of goals may need to vary from sub-basin to sub-basin (e.g. some suffer from excess water while others suffer from not enough).

As we have alluded to elsewhere, the need for Basin-wide tools (e.g. models), processes and a scientific infrastructure will require a coordinated science program to support Basin-wide efforts. Again, this is not intended to disenfranchise or devalue existing science programs that operate at sub-basin scale (e.g. the Army Corps' Upper Mississippi River Restoration Program). These programs are well-adapted to achieving restoration objectives at sub-region scale, and there should be at least one well-funded science program focused on ecosystem restoration in each sub-basin with ongoing lines of communication to coordinate the efforts within the Basin.

People and Nature: the MARB as a socio-ecological system

Historically, most large-scale ecosystem restoration programs have focused primarily on the health of the system as measured in terms of ecological outcomes (e.g., water quality, species populations). Today, scientists increasingly recognize that ecological and human outcomes are closely interconnected, and we will be more successful in improving both types of outcome if we manage places as socio-ecological systems. This means that, in addition to the biophysical scientists traditionally engaged in ecosystem restoration, it will be important to accord equal value to insights from the social sciences, including sociology and economics.

There is not, as yet, a template for managing ecosystem restoration in the context of socio-ecological systems, but there are promising innovations[18]. Perhaps the most important implications of looking through a socio-ecological lens are an increased focus on complexity, awareness of the inevitability of change, and recognition of the importance of adaptive capacity. We recommend the work done by the Upper Midwest Sciences Center on the Upper Mississippi River mainstem[19] as an example of the types of approaches likely to be useful in the future.

Altered landscapes: the future will not look like the past

Together with the reframing of ecosystem restoration in the socio-ecological context, the past decade has seen a growing recognition of the fact that restoration *per se* - in the sense of a return to historic conditions - is not possible. Increasingly the focus of restoration efforts has shifted from creating specific ecosystem conditions (e.g. habitat types and populations of specific species) to sustaining ecosystem processes (e.g., nutrient cycling). This change in focus risks creating a disconnect with stakeholders, who commonly envision healthy ecosystems in terms of specific conditions. Again, we call for dialog between scientists, managers and stakeholders to jointly re-imagine possible future landscapes and riverscapes.

However, no matter what we imagine today, the possible future will always be constrained by threats that we may not yet fully comprehend. In addition to climate change, the impacts of which we are only just beginning to grasp, future threats include novel contaminants, continuing invasions by exotic species, and new pests and diseases. Perhaps the only thing we can be certain of is that change is constant, and that we will increasingly have to make decisions in the face of growing uncertainty. This serves to emphasize the importance of adaptive management as illustrated in Figure 2.

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[18] See, e.g., https://www.sciencedirect.com/science/article/pii/S0169534720302482

[19] Bouska, K.L., Houser, J.N., De Jager, N.R. and Hendrickson, J., 2018. Developing a shared understanding of the Upper Mississippi River. *Ecology and Society*, *23*(2). Also: Bouska, K.L., Houser, J.N., De Jager, N.R., Van Appledorn, M. and Rogala, J.T., 2019. Applying concepts of general resilience to large river ecosystems: a case study from the Upper Mississippi and Illinois rivers. *Ecological Indicators*, *101*, pp.1094-1110.

Closing Thoughts

We look forward to the day when the scale of public and private investment in the MARB reflects the Basin's importance to the nation. Stewarding that investment to ensure the best possible outcome for Basin communities and the nation at large will require that decisions are based on the best available science. The ideas presented in this paper are intended to provide guidance on best practices for integrating science with management decision-making, based on our understanding of "what works" in existing large-scale ecosystem restoration programs, coupled with insights from scientists working in the Basin.

While we recognize that implementing all of the ideas presented here will require an infusion of funds, there is value in moving forward today to align and strengthen existing science efforts in the Basin in anticipation of subsequent funding. These steps – creating a Mississippi River Science Team, aligning monitoring efforts, publishing a "State of the Basin" report, and working with stakeholders to develop Basin and sub-basin goals – will be of value in both the near- and long-term.

Finally, we note that despite well-intentioned efforts and some localized successes, ecosystem health in the MARB continues to decline, with growing impacts on all who live, work and play in the Basin. A new approach is needed, one that builds on existing science in the Basin while creating better alignment between existing scientific entities and with Basin-scale goals, and that supplements existing entities with resources coordinated within a science program. We recognize the political and institutional obstacles to creating a unified ecosystem restoration program at the scale of the MARB, but evidence from existing programs in the Chesapeake Bay and elsewhere indicates that this approach is what is needed to address the challenges already in front of us and the greater challenges that the future will bring.

Appendix A. AWRA Panel / Scientists Interviewed

AWRA Panel

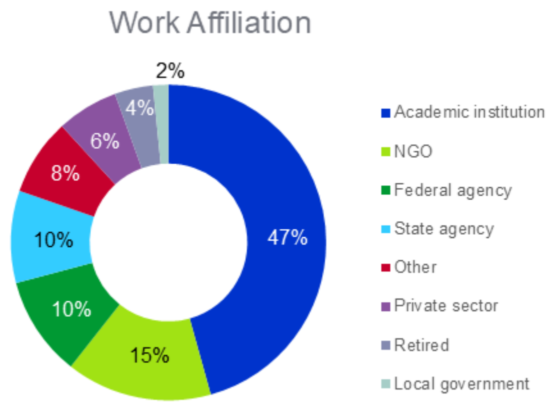
Don Boesch, Professor Emeritus, University of Maryland Center for Environmental Science

Jon Hortness, USGS Program Coordinator, Great Lakes Restoration Initiative

Buck Sutter, Deputy Executive Director, Gulf Coast Ecosystem Restoration Council

Denice Wardrop, Executive Director, Chesapeake Research Consortium

Appendix B. Scientists' responses to survey



Key areas of agreement

Question from the survey	**Response**
On a scale of 1 to 5, with 5 being "very important" and 1 being "not important", how important do you think it is that ecosystem management in the MRB be holistic, integrating across water quality, water quantity, habitat and species?	92% (116 out of 126) of scientists rated holistic management as important or very important.
On a scale of 1 – 5, with 5 being "very important" and 1 being "not at all important", how important is it to include adaptive management in a holistic approach to ecosystem management?	91% (115 out of 126) of scientists agreed that adaptive management is important or very important.
Do you agree that a holistic approach to ecosystem management would help foster collaboration toward specific outcomes in the MARB?	90% (113 out of 125) of scientists agree that a holistic approach would foster collaboration.
A holistic approach to ecosystem management could potentially coordinate ongoing and future research and scientific activities across federal and state agencies, academia, NGOs and private entities, to align efforts, avoid gaps, and avoid unnecessary duplication. On a scale of 1 – 5, with 5 being "very important" and 1 being "not important", how would you rate the importance of this possible role?	89% (111 out of 125) of scientists rated coordination as important or very important

Key challenges as shown by disagreement

Question from the survey	**Response**
If you think such a regular forum for scientists to identify common interests, share research and connect with potential collaborators from other scientific disciplines would be useful, what spatial scale would be most helpful?	a. At sub-basin scale (49) 39% b. At whole Basin scale (60) 48% c. Not sure (16) 13%
If you think that an integrated monitoring database would be useful, where should such a database be housed?	a. In an academic or non-profit institution (71) (57%) b. In the Council of Environmental Quality, to provide coordination across agencies (22) 18% c. In an individual Federal agency (15) 12%
If you agree that a set of guiding principles is important to a holistic approach, which of the following principles are important? (select all that apply)	a. Commitment to scientific integrity (30) 25% b. Recognition of historic inequities; commitment to avoiding new inequities and addressing existing (11) 9% c. Recognition of uncertainty in ecosystem response – adaptive management as way of reducing uncertainty (10) 8% d. Recognition that restoration to pre-colonial conditions is impossible; focus is on desired future conditions (6) 5% e. Recognition of climate change and other emerging stressors – adaptation needs to be ongoing (4) 3% f. Emphasis on doing science that is relevant to decision-making (4) 3% g. Commitment to communicating implications of science for management (3) 2.5% All of the above (50) 42%