Fischer Jason (Orcid ID: 0000-0001-7226-6500)

A Structured Approach to Remediation Site Assessment: Lessons from 15 Years of Fish Spawning Habitat Creation in the St. Clair-Detroit River System

Running Head: Structured Remediation Site Assessment

Jason L. Fischer[1,2]*, Edward F. Roseman[3], Christine Mayer[2], Todd Wills[4], Lynn Vaccaro[5], Jennifer Read[5], Bruce Manny[3], Greg Kennedy[3], Rose Ellison[6], Richard Drouin[7], Robin L. DeBruyne[2], Aline Cotel[8], Justin Chiotti[1], James Boase[1], David Bennion[3]

[1]U.S. Fish and Wildlife Service Alpena Fish and Wildlife Conservation Office, Detroit Sub-station, John D. Dingell Jr. Visitor Center, 5437 West Jefferson Ave., Trenton, MI, U.S.A 48183

[2]University of Toledo, Department of Environmental Sciences, Lake Erie Center, 6200 Bay Shore Rd, Oregon, OH, U.S.A 43616

[3]U.S. Geological Survey Great Lakes Science Center, 1451 Green Road, Ann Arbor, MI, U.S.A 48105

[4]Michigan Department of Natural Resources, Lake St. Clair Fisheries Research Station, 33135 South River Road, Harrison Twp., MI, U.S.A 48045

[5]University of Michigan, Graham Sustainability Institute, 625 E. Liberty Street, Suite 300. Ann Arbor, MI, U.S.A 48104

[6]U.S. Environmental Protection Agency, Great Lakes National Program Office, 2565 Plymouth Road, Ann Arbor, MI, U.S.A

[7]Ontario Ministry of Natural Resources, Exeter Road Complex, 659 Exeter Rd, London, ON N6E 1L3

[8]University of Michigan, Department of Civil and Environmental Engineering, 1351 Beal Avenue, 119 EWRE Ann Arbor, Michigan 48109

*Corresponding author. Email address: Jason_Fischer@fws.gov

Author contributions: JLF, EFR, CM conceived and carried out case study; JLF, EFR, TW, LV, JR, BM, GK, RE, RD, RLD, AC, JC, JB developed projects and conducted assessment; JLF, EFR, CM drafted the manuscript and all authors edited the manuscript.

Abstract

Ideally, restoration re-establishes natural processes in degraded habitats (e.g., flow and sediment regimes). However, in altered systems where process-based restoration is not feasible, habitat construction is another approach to mitigate degradation. Because habitat construction does not directly focus on restoring processes that build and maintain desired habitats, projects must be developed and placed within the contemporary regulatory, ecological, and hydrogeomorphic context of a system, to maximize effectiveness. Here, we develop a framework for evaluating the regulatory, ecological, and hydrogeomorphic components using 15 years of fish spawning habitat construction in the St. Clair-Detroit River System. The process began by identifying regulatory requirements at a coarse resolution to quickly focus on locations where ecological potential and hydrogeomorphic constraints could be assessed at finer resolutions. Next, ecological potential was assessed using a lithophilic fish spawning habitat suitability index. The suitability index identified five sites for habitat construction and Lake sturgeon spawning was documented at each site following construction. However, qualitative monitoring showed fine sediments accumulated at older sites. Thus, geomorphic assessments were incorporated to identify sediment sources and model flow within targeted areas. Since geomorphic assessments required the finest resolution and had the most uncertainty, they were conducted after broad-scale regulatory considerations and ecological assessments narrowed focus to a few candidate sites. The order of operations identified in this case study evolved from the iterative approach of the restoration team, but in retrospect, it helped develop a framework that directed project development resources to aspects with more uncertainty, where learning is most critical.

Key Words: Large River, Restoration Design, Project Placement, Adaptive Management

Implications for Practice

- Effective remediation projects account for regulatory, ecological, and geomorphological components during site selection.
- Assessing these components in a logical order could allow for effective use of resources.
- Assessing large-scale components with low uncertainty before directing assessment efforts towards components with greater uncertainty may improve the cost-effectiveness of developing and siting remediation of projects.

Introduction

Ideal ecosystem restoration re-establishes physical, chemical, and biological processes that build and maintain desired habitats, allowing restored ecosystems to be self-sustaining (Beechie et al. 2010; Hobbs & Norton 1996; SER 2004). The specific processes in need of restoration vary by restoration objectives and history of alteration in a system. However, many large rivers are so degraded that restoration of altered processes is not feasible within realistic timelines or budgets (Słowik 2015). Moreover, governance and competing uses (i.e., regulatory requirements) may limit opportunities for ecological restoration (Decamps 2005; Pedroli 2005). In systems that are irreparably altered, habitat construction (hereafter remediation) can provide desired habitat function (Słowik 2015; Wohl, Bledsoe, et al. 2015). Unfortunately, in highly degraded rivers, hydrogeomorphic processes, which drive channel form (Benda et al. 2002; Wohl, Bledsoe, et al. 2015), are often disturbed. Therefore, remediation site selection that accounts for these processes is crucial to remediation success in highly degraded rivers (Beechie et al. 2010).

Standard restoration and adaptive management guidelines (Kondolf 2000; Palmer et al. 2005; Pastorok et al. 1997; Williams et al. 2009; SER 2004) often lack guidance on how to allocate limited funding to assess remediation design and placement (Wohl et al. 2005). Larger rivers necessitate an explicit process for identifying constraints and opportunities for siting remediation projects. Project development that begins with large-scale constraints with little measurement uncertainty could quickly eliminate areas where remediation is not feasible or necessary. Assessment can then proceed towards constraints with greater uncertainties, finer scales, or higher resolution requirements, such as modeling ecological response or fostering stakeholder participation (Piazza et al. 2015; Roni et al. 2018). Thus, restoration teams can benefit from an ordered process to allocate resources for assessing design and placement constraints to effectively use project funds.

We present a 15-year lithophilic fish spawning habitat remediation program targeting Lake sturgeon (*Acipenser fulvescens*) in the St. Clair-Detroit River System (SCDRS) as a case study for prioritizing design and placement assessments. The program began by following established adaptive management and habitat restoration guidelines (Manny et al. 2015) to identify ecological impairments and remediation needs prior to the site assessment and design phase (Fig. 1a boxes i - iii). However, an ordered process for prioritizing location and design assessment was lacking when the program began in 2004. Building on lessons learned through the 15 years of remediation, we propose a generalized ordered approach to project development and site assessment (Fig. 1a boxes iv a – iv c). Through this case study, we describe how the order of operations for reef remediation developed and identify generalities that can streamline resource allocation during project development in other remediation programs.

Framework for Project Development

Our framework developed through the adaptive management approach to reef remediation in the SCDRS and integrates into the adaptive management paradigm by expanding the project development phase into three sub-components: regulatory, ecological, and hydrogeomorphic constraints (Fig.1). Assessing regulatory requirements ensures projects fit within governance, social, and commerce requirements. Whereas evaluation of ecological and hydrogeomorphic constraints ensures that projects could be used by target species over a long enough time period to be considered successful. Although, our case study in the SCDRS focuses on constructing habitat that could be maintained given contemporary hydrogeomorphic conditions, these considerations would also apply to process-based remediation projects (Beechie et al. 2010). Evaluation of each component follows a logical order during project development, beginning with information that is easiest and least expensive to acquire, to quickly eliminate areas unlikely to support remediation efforts and focus resources towards components with more uncertainty (Fig. 1b). In the case study below, we describe how the framework developed alongside a fish spawning habitat remediation program, allowing the program to become more efficient with each new remediation project.

Case History

Study System

The SCDRS is a 145-km connecting channel between Lakes Huron and Erie encompassing the St. Clair River, Lake St. Clair, and Detroit River (Fig. 2). It remains barrier-free and maintains a relatively stable discharge of approximately 5,300-m^3/s, which is naturally regulated by water level differences between Lakes Huron and Erie (Anderson et al. 2010). However, construction of over 97-km of navigational channels removed spawning substrates used by Lake sturgeon, Lake whitefish (*Coregonus clupeaformis*), Walleye (*Sander vitreus*), and other lithophilic spawning fishes (Bennion & Manny 2011; Roseman et al. 2012). Removal of spawning substrates was one of the most substantial alterations in the SCDRS and identified as limiting the recovery of Lake sturgeon and other lithophilic spawning fishes, prompting consideration of reef remediation to increase population sizes (Bennion & Manny 2011; Manny et al. 2015). The approach to identifying the resource at risk, goals, actions, and project evaluation (Fig. 1a boxes i - iii) was previously documented (Manny et al. 2015; Vaccaro et al. 2016), therefore we focus on the ordered process used to identify constraints and remediation locations.

Identify Constraints

Regulatory Requirements: Governance, Social and Competing Uses

From 2004 to 2018, nine 0.1–1.6-hectare fish spawning reefs were constructed in seven locations (Fig. 2; Manny et al. 2015; Vaccaro et al. 2016). Historic accounts of Lake sturgeon spawning locations and proximity to contemporary staging areas guided the location of the first spawning reefs constructed in 2004 at Belle Isle (Manny et al. 2015). However, the need to incorporate additional considerations into site selection was quickly identified.

State and federal regulations required joint permits for each project. Michigan landowners along the Detroit and St. Clair Rivers own the bottomland to the middle of the channel and the state permitting agency required the team to seek landowner approval for each project. The team discovered that the terms of the 1909 U.S.-Canada Boundary Waters Treaty required a consultation with the International Joint Commission to ensure that river levels and flows were not materially affected by the projects. Recognizing that construction noise and dirt can be disruptive, the team also learned to engage adjacent landowners to ensure that no one along the river opposed the projects during the permit commenting period.

Finally, commercial shipping proved to be a primary constraint in the SCDRS. The shipping industry expressed concerns that reef construction could interfere with navigation and that propeller wash might damage nearby reefs. In response, the restoration team and shipping industry collaboratively identified areas where reef construction would not disrupt navigation. These efforts resulted in a spatial model identifying locations of shipping channels where reef construction was not feasible (Bennion & Manny 2014).

The reef remediation team initially used a “downstream” approach to public involvement, where public input was garnered after project development and later transitioned to an “upstream” approach where stakeholder input was incorporated into project development (Wohl, Lane, et al. 2015). The team began sharing reef locations over the program’s website, participating in angler stakeholder meetings, and utilizing creel survey to assess angler-satisfaction (Castle 2018; Vaccaro et al. 2016). Moreover, the team worked with navigation-industry representatives on project development to relax some initial constraints imposed by navigation, allowing reef construction in deeper navigation routes (e.g., the Hart’s Light Reef and Fort Wayne Reef). Incorporating stakeholders early in the site-assessment process eliminated sites where regulatory requirements precluded construction and targeted sites where these requirements were more flexible. Thus, the “upstream” assessment approach helped to garner stakeholder support, to ensure resources were not expended on unacceptable locations, and to expand opportunities for remediation.

Ecological Constraints

After identifying areas where navigational and ownership requirements precluded reef construction, the team identified potential remediation sites and what substrates were most effective. Identification of sites with high ecological potential evolved with subsequent projects, transitioning from placement based on proximity to historic spawning locations and habitat use (i.e., the 2004 Belle Isle Reefs and Fighting Island Reef; Caswell et al. 2004) to using a habitat suitability index, that was later refined to a habitat suitability model, to target areas with water depths and velocities most suitable for Lake sturgeon spawning (Bennion & Manny 2014; Fischer et al. 2018). The team also considered impacts to threatened and endangered species. Burial of freshwater mussel beds was a primary concern and mussel surveys were conducted prior to reef construction to ensure proposed reef sites did not overlap with mussel beds. Additionally, the team worked to minimize benefits towards two invasive species, sea lamprey (*Petromyzon marinus*) and round goby (*Neogobius melanostomus*). Sea lamprey require 5–13 cm diameter gravel for reproduction (Applegate et al. 1950) and round goby were thought to benefit from large reef substrates (>25 cm; Vaccaro et al. 2016). Thus, constraints imposed by invasive species limited the substrate sizes used for reef construction. Lake sturgeon egg deposition over the experimental reef units within the Fighting Island Reef (12 sub-reefs constructed with four rock types, three reefs per rock type) indicated Lake sturgeon would spawn over a variety of rock types and sizes (Roseman et al. 2011). Therefore, reefs constructed after 2013 used cost-effective 10–20 cm broken limestone to avoid favoring invasive species. To evaluate use of spawning reefs, the team used a before-after-control-impact monitoring protocol to assess egg deposition and adult fish relative abundance at reef sites and adjacent control sites for at least two years prior and two years after reef construction. Using an adaptive management approach ensured that evaluations informed future projects. For example, Lake sturgeon did not spawn on the 2004 Belle Isle Reefs, likely because the individual reefs were smaller than the 0.07 ha recommended for spawning habitat (Bruch & Binkowski 2002), whereas larger projects were used by Lake sturgeon (Fischer et al. 2018). Thus, confidence in project size and placement criteria increased with each successive project. Because spawning habitat assessments required more resources and were more difficult to assess than navigational constraints, we identified ecological assessments as the second step in project development (Fig. 1a box iv b).

Hydrogeomorphic Constraints

To continue providing Lake sturgeon spawning habitat, constructed reefs must remain free of fine sediments (e.g., sands and silts). The reef team documented sediment infiltration on the Middle Channel Reef and part of the Fighting Island Reef in 2013 and consequently reconsidered the reef design and placement criteria. Although hydrogeomorphic processes within the SCDRS remained largely unaltered (Anderson et al. 2010; IUGLS 2009), they still influenced the effectiveness of reef remediation projects. Therefore, project development began to focus on how to optimize project design and location, given the hydrogeomorphology at a site.

In early 2014 (before the construction of the Pointe Aux Chenes and Hart's Light Reefs), the team added geomorphologists and hydrologists to assist with reef design and placement. The team refined project design from channel spanning-reefs to long, narrow reefs that allowed placement to be optimized within the channel cross-section (Manny et al. 2015). Reef designs were tested in hydraulic models and flume studies to determine which shapes minimized flow disturbance and sedimentation potential. Rectangular and wedge profiles had less sedimentation potential than more complex designs (e.g., airfoil) and the team decided to use the rectangular profile, which was more affordable to construct (Vaccaro et al. 2016).

The reef team expanded field surveys to make more substantial use of side-scan sonar, underwater video, SCUBA surveys, and water velocity mapping with acoustic Doppler current profilers to identify potential upstream sediment sources, mobile bedforms indicative of bedload transport, and areas where decreasing shear stresses could encourage sediment deposition (Fischer et al. 2018; Fischer, Roseman, et al. 2020; Fischer, Filip, et al. 2020; Vaccaro et al.

2016). Additionally, a two-dimensional flow model was developed for the system, to predict flow patterns and sediment transport potential at a 20 x 20 m resolution (Kinzel et al. 2016). Although the model was developed late in the program, it helped prioritize locations where sediment deposition was expected to be low compared to other areas in the system. Thus, the flow model directed field surveys to areas with the most potential for long-term success.

The hydrogeomorphic assessments required extensive field, lab, and computational efforts, hence we identified this as the last step in project development (Fig. 1a box iv c). Moreover, there was generally greater uncertainty in the hydrogeomorphic conditions at a site than was associated with regulatory considerations or ecological assessments. The role of long-term sediment dynamics remains a common uncertainty in river restoration in general (Benda et al. 2002; Wilcock 2012; Wohl, Bledsoe, et al. 2015) and is the case in the SCDRS. Although the SCDRS has a naturally low supply of fine sediments, episodic events, including ice jams and strong winds and storms producing large waves, can temporarily alter flows and mobilize pulses of sediment (IUGLS 2009; Liu et al. 2012). Sediment composition monitoring within the reefs began in 2015 and showed fine sediments in some of the reefs (Fischer, Roseman, et al. 2020). However, unlike egg deposition by Lake sturgeon, which began within a year of construction, the reefs may be slower to respond to sediment dynamics. Therefore, long-term monitoring will be needed to determine if the reefs continue to provide functional Lake sturgeon spawning habitat.

Identify Remediation Location and Implement Action

The reef team was able to narrow down potential reef locations relatively easily based on regulatory considerations and ecological components. However, finalizing a reef site based on hydrogeomorphic assessments often required extensive discussion and acceptance of some risk.

Additional modeling and assessment may reduce uncertainty, but eventually, a point of diminishing returns will be reached where the cost of new information exceeds its value for decision making. The appropriate level of information required to move forward with a decision will be project and team specific. The SCDRS team discussed the placement and design options candidly and worked to develop consensus. The team recognized that risk of sedimentation remained and therefore, contingency plans were discussed, leading to a decision to research maintenance options for sedimented reefs (Baetz et al. 2020). Thus, the ordered process to identify constraints and remediation locations (Fig. 1) in the SCDRS was viewed as a means to reduce, but not eliminate potential future maintenance costs.

Discussion

The process followed by the SCDRS team evolved with each reef constructed and the order of operations for selecting remediation sites emerged through the iterative approach of the adaptive management cycle. As projects were completed and learning occurred, new criteria were added to improve project placement. Later projects benefited by beginning placement decisions with components with the most accessible knowledgebase and fewest uncertainties (i.e., regulatory considerations), followed by more difficult decisions based on components where more uncertainties exist. Strategically narrowing focus away from data-rich metrics allows remediation teams to direct valuable resources towards metrics that need to be addressed at finer scales, where less information is available. Early placement decisions function as a coarse filter, guiding assessments to areas where project feasibility is higher by removing unsuitable areas from further consideration. The ordered process to assess site constraints, can be integrated into the adaptive management framework to improve project development. Although multiple habitat restoration frameworks consider cost of project implementation (Clewell et al. 2005; Failing et al. 2013; Hobbs et al. 2014; Pastorok et al. 1997), this case study indicates that cost-effectiveness of projects can be further improved through a strategic approach to the development and assessment phase.

The contemporary state of large waterways is often the product of complex interactions among governance, competing uses, ecological components, and hydrogeomorphic factors (Benda et al. 2002; Kondolf 2000; Pedroli 2005). Thus, accounting for each component during the development phase of a remediation project may occur simultaneously. For instance, ecohydraulic models are frequently used to simultaneously assess habitat suitability and geomorphic dynamics of remediation designs in gravel-bedded rivers (Wheaton et al. 2004). Moreover, previous assessments can be revisited if new information becomes available or constraints change. In the SCDRS, a habitat suitability index identified several locations with high potential to provide spawning habitat (Bennion & Manny 2014), including areas initially thought to conflict with navigation. However, by working with the navigation industry, the remediation team was able to receive authorization and expand opportunities for reef remediation, resulting in the construction of the Fort Wayne Reef in an area deep enough to allow remediation within a navigation route. Therefore, previous steps can be revisited if later assessments indicate a strong potential for a successful project.

Although the approach to reef remediation in the SCDRS is not unique, the iterative nature and long program duration (15 years) allowed efficiencies to be identified. Lessons learned improved subsequent projects, leading to program-level adaptive management. Similarly, in the Upper Mississippi River (not shown; 90.1507°W, N41.9217°N), program-level adaptive management allowed a structured approach to emerge, guiding the design and placement of low velocity-shallow water habitat remediation projects (Rohweder et al. 2008; Theiling et al. 2015).

Their approach also accounted for regulatory, hydrogeomorphic, and ecological factors, although later projects relied more heavily on ecohydraulic models to identify designs that altered local hydrogeomorphical factors to produce conditions favorable to target species. Since remediation goals were to create conditions that developed shallow water habitat, ecological and hydrogeomorphic components were assessed together, after identifying navigational and other regulatory requirements. Conversely, if remediation goals are to improve habitat and stewardship of privately-owned lands, beginning with broad assessments of ecological potential can help identify which landowners to target for conservation efforts, an approach used to direct conservation within the Atchafalaya River Floodway (not shown; 91.2123°W, 29.6877°N; Piazza et al. 2015). The most efficient processes for project development will vary by program and system, depending on remediation goals and pre-existing knowledge within the system. However, an ordered approach can direct project resources towards designs and locations where success is more likely to be realized.

Generalizing the ordered approach of the reef design and placement begins to answer the call for guidelines for allocating resources during project development (Wohl et al. 2005). The SCDRS reef remediation case study provided the opportunity to identify assessment components that were best addressed first and those more logical to address at later stages. The process fits within the planning and design phase of the adaptive management framework, allowing allocation of resources to be considered as part of the framework. In other irreparably damaged systems where habitat construction is preferred and habitat restoration is not practical, the basic approach of assessing components where knowledge is clear before directing assessment efforts towards components with greater uncertainty may improve the cost-effectiveness of developing and siting remediation projects.

Acknowledgements

This work was made possible the many individuals who served on and consulted the reef remediation team, including Laura Alford, Jeff Braunscheidel, Mary Bohling, Grzegorz Filip, Jim Francis, Hal Harrington, Paul Kinzel, Jon Nelson, Sara Thomas, Mike Thomas, and Smith Group JJR. We also thank Taaja Tucker for assistance with figure preparation and Stephen Murphy and an anonymous reviewer for input on previous versions of the manuscript. The findings and conclusions of this article are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service. Funding for this work and the reef remediation program was provided by the Great Lakes Restoration Initiative, Great Lakes Fishery Trust, Detroit Edison Energy, and the Michigan Wildlife Council.

References

Anderson EJ, Schwab DJ, Lang GA (2010) Real-Time Hydraulic and Hydrodynamic Model of the St. Clair River, Lake St. Clair, Detroit River System. Journal of Hydraulic Engineering-Asce 136:507–518

Applegate VC, Fish US, Wildlife S (1950) Natural history of the sea lamprey, Petromyzon marinus, in Michigan.

Baetz A et al. (2020) Review of Methods to Repair and Maintain Lithophilic Fish Spawning Habitat. Water 12:2501

Beechie TJ et al. (2010) Process-based Principles for Restoring River Ecosystems. Bioscience 60:209–222

Benda LE et al. (2002) How to avoid train wrecks when using science in environmental problem solving. Bioscience 52:1127–1136

Bennion DH, Manny BA (2014) A model to locate potential areas for lake sturgeon spawning habitat construction in the St. Clair–Detroit River System. Journal of Great Lakes Research 40:43–51

Bennion DH, Manny BA (2011) Construction of shipping channels in the Detroit River history and environmental consequences. U.S. Dept. of the Interior, U.S. Geological Survey, Reston, Va.

Bruch RM, Binkowski FP (2002) Spawning behavior of lake sturgeon (Acipenser fulvescens). Journal of Applied Ichthyology 18:570–579

Castle D (2018) Fishing for Answers: Restoration in the St. Clair-Detroit River System Improves Angling Opportunities. Central Michigan University

Caswell NM et al. (2004) Spawning by lake sturgeon (Acipenser fulvescens) in the Detroit River. Journal of Applied Ichthyology 20:1–6

Clewell A, Rieger J, Munro J (2005) Guidelines for Developing and Managing Ecological Restoration Projects, 2nd Edition. Tucson: Society for Ecological Restoration International

Decamps H (2005) The ‘why?’ and the ‘so what?’ of riverine landscapes. In: Issues and Perspectives in Landscape Ecology. Wiens, JA & Moss, M, editors. Cambridge University Press, Edinburgh Building, Cambridge, UK pp. 248–256.

Failing L, Gregory R, Higgins P (2013) Science, Uncertainty, and Values in Ecological Restoration: A Case Study in Structured Decision-Making and Adaptive Management. Restoration Ecology 21:422–430

Fischer JL et al. (2018) Lake Sturgeon, Lake Whitefish, and Walleye Egg Deposition Patterns with Response to Fish Spawning Substrate Restoration in the St. Clair–Detroit River System. Transactions of the American Fisheries Society 147:79–93

Fischer JL, Filip GP, et al. (2020) Supporting aquatic habitat remediation in the Detroit River through numerical simulation. Geomorphology 353:107001

Fischer JL, Roseman EF, et al. (2020) If you build it and they come, will they stay? Maturation of constructed fish spawning reefs in the St. Clair-Detroit River System. Ecological Engineering 150

Hobbs RJ et al. (2014) Managing the whole landscape: Historical, hybrid, and novel ecosystems. Frontiers in Ecology and the Environment 12:557–564

Hobbs RJ, Norton DA (1996) Towards a conceptual framework for restoration ecology. Restoration Ecology 4:93–110

IUGLS (2009) Impacts on Upper Great Lakes Water Levels: St. Clair River: Final Report to the International Joint Commission, December 2009.

Kinzel P et al. (2016) Use of repeat surveys and flow and sediment transport modeling to support fish spawning reef placement in the Detroit River, MI. River Flow - Proceedings of the International Conference on Fluvial Hydraulics, RIVER FLOW 2016 2047–2054

Kondolf GM (2000) Some suggested guidelines for geomorphic aspects of anadromous salmonid habitat restoration proposals. Restoration Ecology 8:48–56

Liu X et al. (2012) Sediment mobility and bed armoring in the St Clair River: Insights from hydrodynamic modeling. Earth Surface Processes and Landforms 37:957–970

Manny BA et al. (2015) A scientific basis for restoring fish spawning habitat in the st. clair and detroit rivers of the laurentian great lakes. Restoration Ecology 23:149–156

Palmer MA et al. (2005) Standards for ecologically successful river restoration. Journal of Applied Ecology 42:208–217

Pastorok RA et al. (1997) An ecological decision framework for environmental restoration projects. Ecological Engineering 9:89–107

Pedroli B (2005) The nature of lowland rivers: a search for river identity. In: Issues and Perspectives in Landscape Ecology. Wiens, JA & Moss, M, editors. Cambridge University Press, Edinburgh Building, Cambridge, UK pp. 259–273.

Piazza BP et al. (2015) Floodplain conservation in the Mississippi River Valley: combining spatial analysis, landowner outreach, and market assessment to enhance land protection for the Atchafalaya River Basin, Louisiana, U.S.A. Restoration Ecology 23:65–74

Rohweder J et al. (2008) Application of Wind Fetch and Wave Models for Habitat Rehabilitation and Enhancement Projects.

Roni P et al. (2018) Review of Tools for Identifying, Planning, and Implementing Habitat Restoration for Pacific Salmon and Steelhead. North American Journal of Fisheries Management 38:355–376

Roseman EF et al. (2011) Lake sturgeon response to a spawning reef constructed in the Detroit river. Journal of Applied Ichthyology 27:66–76

Roseman EF et al. (2012) Life History Characteristics of a recovering lake whitefish coregonus clupeaformis stock in the detroit river, North America. Advances in Limnology 63:477–501

Słowik M (2015) Is history of rivers important in restoration projects? The example of human impact on a lowland river valley (the Obra River, Poland). Geomorphology 251:50–63

Society for Ecological Restoration International Science & Policy Working Group (2004) The SER International Primer on Ecological Restoration. Tucson: Society for Ecological Restoration International

Theiling CH, Janvrin JA, Hendrickson J (2015) Upper Mississippi River restoration: implementation, monitoring, and learning since 1986. Restoration Ecology 23:157–166

Vaccaro L et al. (2016) Science in Action: Lessons Learned from Fish Spawning Habitat Restoration in the St. Clair and Detroit Rivers. University of Michigan, Ann Arbor, MI

Wheaton JM, Pasternack GB, Merz JE (2004) Spawning habitat rehabilitation -I. Conceptual approach and methods. International Journal of River Basin Management 2:3–20

Wilcock PR (2012) Stream Restoration in Gravel-bed Rivers. In: Gravel-Bed Rivers: Processes, Tools, Environments. Church, M, Roy, AG, & Biron, PM, editors. John Wiley & Sons, Hoboken, NJ.

Williams BK, Szaro RC, Shapiro CD (2009) Adaptive Management: The U.S. Department of the Interior Technical Guide. U.S. Department of the Interior, Washington, DC

Wohl E et al. (2005) River restoration. Water Resources Research 41

Wohl E, Bledsoe BP, et al. (2015) The Natural Sediment Regime in Rivers: Broadening the Foundation for Ecosystem Management. Bioscience 65:358–371

Wohl E, Lane SN, Wilcox AC (2015) The science and practice of river restoration. Water Resources Research 51:5974–5997

Figures

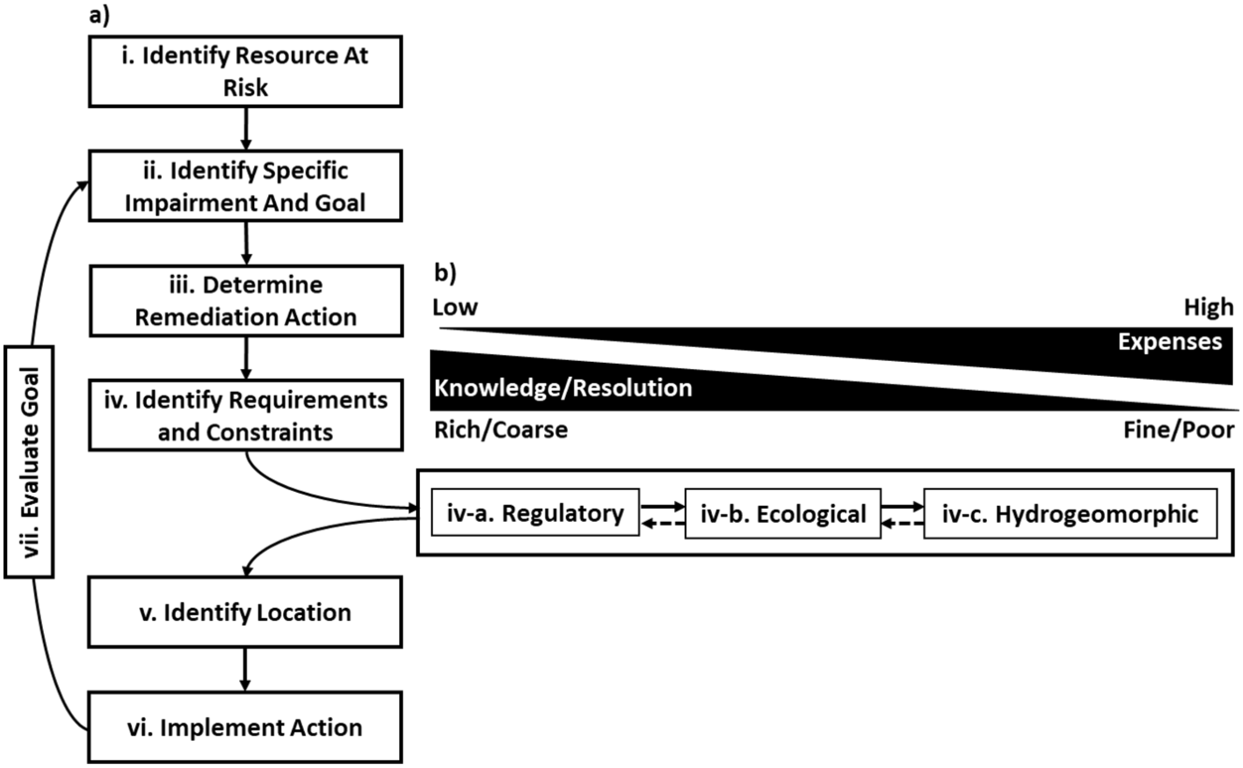

Figure 1: Flow chart of the decision-making process used to determine where to construct fish spawning reefs in the St. Clair-Detroit River System (a), where evaluation of remediation requirements and constraints is ordered by availability of data, resolution needed to inform decisions, and cost of assessment (b). The need for remediation and specific remediation actions were determined using the framework provided by the adaptive management paradigm and restoration guidelines (vertically stacked boxes). However, the ordered process for identifying requirements and constraints (horizontal boxes iv-a.c.) developed over the course of the reef remediation program. Once a remediation action was determined, the order of assessing factors constraining the placement of a project moved from components that could be quickly addressed at broad scales and coarse resolution to focus resources on components where less was known and required assessment at smaller spatial scales and finer resolution. The dashed arrows show

components that were occasionally reassessed if assessments at finer resolutions revealed sub-optimal conditions or locations more conducive to effective remediation.

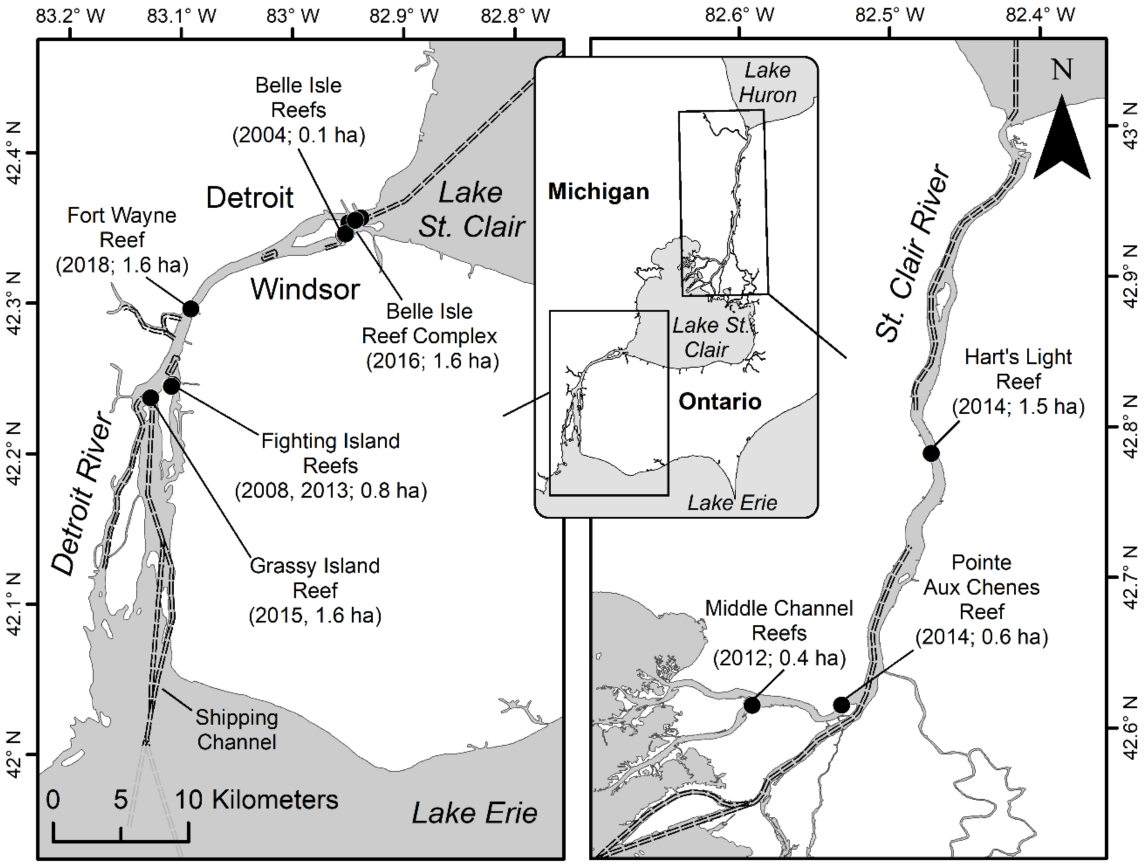

Figure 2: Locations of fish spawning reefs constructed in the St. Clair-Detroit River System (year of construction and area covered in parentheses). Shipping channels are also shown to highlight areas where navigation requirements prevented reef construction. Multiple years of physical habitat (e.g., sediment composition) monitoring beginning within a year of reef construction occurred at the Hart’s Light, Pointe Aux Chenes, Middle Channel, and Grassy Island Reefs.