The importance of open science for biological assessment

Marcus W. Beck ([marcusb@sccwrp.org](mailto:marcusb@sccwrp.org)), Raphael D. Mazor ([raphaelm@sccwrp.org](mailto:raphaelm@sccwrp.org)), Susanna T. Theroux ([susannat@sccwrp.org](mailto:susannat@sccwrp.org))

Version Date: Thu Sep 13 12:00:49 2018 -0700

# Abstract

Open science principles that seek to democratize science can effectively bridge the gap between researchers and environmental managers, yet widespread adoption has yet to gain traction for the development and appplication of bioassessment methods. At the core of this philosophy is the concept that research should be reproducible and transparent, in addition to having long-term provenance through effective modes of data preservation and sharing. We discuss core open science concepts that have been advocated more generally in the ecological sciences and will emphasize how adoption can benefit bioassessment for both prescriptive condition assessments and proactive applications that inform planning activities. Examples from the state of California will be used to demonstrate effective adoption of open science principles through data stewardship, reproducible research, and engagement of stakeholders with multimedia applications. Technical, sociocultural, and institutional challenges for adopting open science will also be discussed, including practical approaches for overcoming these hurdles in bioassessment applications.

# Introduction

Bioassessment is an essential element of aquatic monitoring programs that establishes a foundation of decisions for managing the ecological integrity of environmental resources. Legal mandates to assess biological condition have set a precedent for developing bioassessment methods in the United States (Clean Water Act, CWA), Canada (Canada Waters Act), and Europe (Water Framework Directive). Decades of research to meet these mandates have supported the development of methods for multiple assemblages with regional applications in streams, rivers, lakes, and marine environments (Karr et al. [1986](#ref-Karr86); Kerans and Karr [1994](#ref-Kerans94); Fore and Grafe [2002](#ref-Fore02); Beck and Hatch [2009](#ref-Beck09); Borja, Ranasinghe, and Weisberg [2009](#ref-Borja09)). This body of applied tools represents substantial progress in understanding how biological organisms can be used as accurate and interpretable sentinels of environmental condition. Monitoring programs in the United States and internationally have collected millions of records of biological data spanning decades and hundreds of assessment methods have been developed from these data. The explicit link to environmental management distinguishes bioassessment from basic ecological research. Although bioassessment can and has been used to inform basic research, the intended use of these tools is to inform the protection and restoration of ecological integrity.

Bioassessment products will have limited use if they do not meet the needs of management and regulatory communities (Bain et al. [2000](#ref-Bain00); Stein et al. [2009](#ref-Stein09); Kuehne et al. [2017](#ref-Kuehne17)). In the United States, the CWA gives power to states, tribes, and territories for method development, which in turn requires federal approval to be implemented in a regulatory framework(e.g., Total Maximum Daily Load reporting, stormwater permitting). An imbalance exists between the developed methods and those that are approved for regulatory use. A recent review of assessment methods for ecological integrity in the US showed that few were explicitly connected to freshwater policy (Kuehne et al. [2017](#ref-Kuehne17)). Of those methods that are actively used, a more problematic issue is the manner of application within standard regulatory frameworks. Biological indices are typically used to develop post-hoc diagnoses to trigger remediative or restoration actions, or serve as early warning indicators of environmental change (Niemi and McDonald [2004](#ref-Niemi04)). A critical concern is that these tools, although technically sound, are implicitly being used to document the long-term demise of environmental health. A much broader use for bioassessment to guide planning activities, such as identifying conservation priorities (Linke, Turak, and Nel [2011](#ref-Linke11); Howard et al. [2018](#ref-Howard18)), could extend the reach of bioassessment products beyond regulatory applications.

An effective bioassessment product must jointly address the technical challenges of developing a diagnostic index and the implementation challenges of using an index to address the needs of environmental managers and regulators (Jackson and Davis [1994](#ref-Jackson94); Dale and Beyeler [2001](#ref-Dale01)). For decades, research in the bioassessment community has focused on addressing the former. Substantial technical advances have been made in predicting biological responses to environmental change, how these responses can be distinguished from natural environmental variation, and determining the impacts of these changes. Standardized protocols have also been developed (McDonald et al. [2004](#ref-McDonald04); Stoddard et al. [2008](#ref-Stoddard08)). Many bioassessment indices are characterized as either multimetric, such as an index of biotic integrity (Karr et al. [1986](#ref-Karr86)), or multivariate where condition is based on predictive methods that evaluate similarity of taxonomic composition to reference expectations. The reference-condition approach establishes the foundation for many bioassessment methods whereby a set of reference sites are identified and used to evaluate levels of biological deviation to define potential impacts (Reynoldson et al. [1997](#ref-Reynoldson97); Stoddard et al. [2006](#ref-Stoddard06)). Most indices can be broadly categorized in the context of these well-established technical methods.

Implementation challenges have severely limited the use of bioassessment products in management and regulatory applications relative to the availability of developed methods. Characterizing how an index could be used in practice to inform decisions and prioritize management actions is often opaque relative to why an index may have been originally developed. Hundreds of assessment methods have been developed for specific regional applcations (Birk et al. [2012](#ref-Birk12)) and concerns about redundancy, comparability, duplicated effort, and lack of coordinated monitoring have recently been discussed within the research community (Cao and Hawkins [2011](#ref-Cao11); Poikane et al. [2014](#ref-Poikane14); Kelly et al. [2016](#ref-Kelly16); Nichols et al. [2016](#ref-Nichols16)). Moreover, existing methods may not be discoverable beyond immediate research applications (Hering et al. [2010](#ref-Hering10); Nichols et al. [2016](#ref-Nichols16)) or may be incorrectly applied based on differences between goals for developing an index and the needs of management programs (Dale and Beyeler [2001](#ref-Dale01); Stein et al. [2009](#ref-Stein09)). The abundance of available methods can be a point of frustration for managers given a lack of guidance for choosing an appropriate method among alternatives, particularly as to how a method may relate to specific management, monitoring, or policy objectives (Dale and Beyeler [2001](#ref-Dale01); Stein et al. [2009](#ref-Stein09)).

Environmental managers require additional tools that transform bioassessment data and methods into actionable information. A new mode of operation is needed where method development is open and transparent, developed products are discoverable and reproducible, and most importantly, implementation in the management community is intuitive and purposeful. Open science principles that can democratize all aspects of the scientific method can meet these needs, yet bioassessment research and its application to better serve the environment has not fully embraced these principles. Others have advocated more broadly for inclusion of open science principles in the ecological sciences (Hampton et al. [2015](#ref-Hampton15), [2016](#ref-Hampton16); Lowndes et al. [2017](#ref-Lowndes17)) and a growing wave of momentum has influenced how scientists conceptualize research in other disciplines (e.g., archeaology, Marwick et al. ([2016](#ref-Marwick16)); behavioral ecology, Ihle et al. ([2017](#ref-Ihle17)); vegetation sciences, Collins ([2016](#ref-Collins16))). Adopting an open science paradigm in biaossessment is particularly relevant compared to other fields given the explicit need to develop tools that are open and accessible to the management community. Legal and ethical precedents in bioassessment may also necessitate the open sharing of data given that environmental monitoring programs are often publicly funded.

This review will demonstrate tools and approaches for open science, which will empower the research and management community to embrace a new mode of thinking for bioassessment applications. These approaches are expected to benefit the research community by augmenting existing workflows for developing assessment tools, but more importantly, improve the ability of these methods to address environmental issues by bridging the gap between the scientific, management, and regulatory communities. An overview of the general principles of open science is provided, followed by a discussion of specific benefits and how these principles can be applied to bioassessment. We use examples from the state of California to demonstrate how existing tools can be tailored to address legislative mandates for free and open sharing of data, especially by directly engaging stakeholders that require practical approaches for using bioassessment tools in planning activities. We conclude with a discussion of technical, sociocultural, and instutional hurdles that have, thus far, prevented widespread adoption of open science and provide recommendations for the bioassessment community to address these challenges.

# Principles of open science and what they mean for bioassessment

Conventional modes of creating scientific products and more contemporary approaches that align with open science principles share the same goals. Both are motivated by the same guiding principles of the scientific method that seek to make the process of discovery transparent and repeatable. Where the conventional and open science approaches diverge is the extent to which technological advances in communication are leveraged as instrumental tools that are used during every step of the research process. The distinction in thinking between the two approaches can be conceptualized as the “paper as the only and final product” for the conventional approach, whereas the open science approach is inherently linked to advances in communication and documentation that have been facilitated by the Internet and computer sciences. As a result, the open science approach enhances all aspects of the scientific process from initial conception of a research idea to the delivery and longevity of a research product.

The paradigm of the scientific paper as the final research product can inhibit forward progress for several reasons, particularly so in the applied sciences. Traditionally, the research paper was viewed as a communication tool to report and share results among peers in the scientific community. Researchers access periodicals to stay informed of advances in the field and use the information to replicate methods for follow-up analysis. Although the primary literature continues to provide these fundamental services, this workflow can stifle progress when scientific products are developed to serve interests outside of the research community. The paper as an endpoint for environmental managers fails to deliver tools that are easily accessible from the practitioners perspective, both in application and interpretation. A research paper is rarely sufficient to affect environmental change because it does not provide a mechanism for engaging those that require scientific guidance as the foundation for decision-making. Numerous studies have documented implementation failures as a result of siloing among research communities where the flow of information rarely or insufficiently extends beyond institutional walls. The loss of information over time that intimately describes a research product is another well-known flaw associated with the paradigm of research paper as final product (Michener et al. [1997](#ref-Michener97)).

The open science approach can be conceptualized by placing the researcher in the role of data steward rather than data owner. This mode of thinking treats the data as a living product with a history, rather than proprietary and serving only the needs of an immediate research goal. Data can be generically described as any component of the research process that is used to address a research goal and could include literal tabular data, a laboratory notebook, a research report, data visualizations or maps, analysis code or software, or even presentation materials. Open science principles can be applied to any and all of these data with the end goal of facilitating communication for researchers and those for which the research was developed. These tools also benefit the individual researcher by providing information for the “future-self” to recreate a past working environment. In all cases, the data are openly accessible and documented for reproducibility and discovery using technologies that facilitate communication and sharing.

Open data can benefit research by contributing to an increase in novel products created through collaborative efforts. An increasing trend in collaborative publications has been observed in the environmental sciences as researchers leverage open data from different contexts to create synthesis products as the sum of individual datasets. Quantitative meta-analyses and systematic reviews are increasingly used to extract information from the primary literature to identify commonalities across independent research efforts and datasets (Lortie [2014](#ref-Lortie14)). In addition, open data products can increase efficiency of the individual researcher and a collective research team by encouraging collaborators to adopt an open science workflow that improves reproducibility and transparency. Many tools developed within the software and computer science community are now easily accessible to environmental scientists that can be used to create open data. Version control software (e.g, Git, GitHub), open source programming languagues (e.g, R), and integrated development environments (IDE, e.g., RStudio) can all be leveraged by applied ecologists to dynamically create and share open data products that support instutional memory. These tools promote deliberate and shared workflows among researchers that can lead to better science in less time (Lowndes et al. [2017](#ref-Lowndes17)).

Open and unfettered access to data can also benefit management and regulatory communities. Most bioassessment products are applied in regional contexts, as for indices developed at the state-level to satisfy federal requirements. By necessity, the development of indices that cover large spatial areas require datasets that sufficiently describe the natural varation of a biological assemblage and relevant stressor gradients to evaluate biological response. These datasets are commonly provided by coordinated monitoring programs that are supported through public funds given the required scale of assessment. Many management and regulatory agencies include monitoring programs developed specifically for these purposes and the availability of these data beyond institutional walls is critical for research efforts in developing bioassessment products. While many monitoring sets are publicly available, the data quality, level of documention, and ease of use varies widely. This can create research and implementation challenges as datasets may be difficult to locate, contexts for data may be misunderstood, and data from different sources require synthesis for comparison. Many open science tools can improve the accessibility of data from monitoring programs by establishing workflows for data synthesis and discovery, often through the adoption of a common metadata structure (e.g., Ecological Metadata Language Standard) and integration of data within federated data networks (e.g., DataONE). Open data maintained by management or regulatory communities benefits the research community, which in turn benefits the data maintainers that require scientific products to inform decisions.

Use Bond-Lamberty as example, more than just the paper as final product Fox and Hendler about data viz - similar paradigm where the static plot as not the final product

Ecology and bioassessment by extension have not adopted these tools because modes of communication that are intrinsically linked to subjet matter in other fields, such as computer science, are not common.

* Overview of the open science process – follow Hampton paradigm, distinguish between benefits for the researcher vs research institution vs stakeholder/managers
  + Use the report/manuscript as final product paradigm as old way of thinking
  + Nielsen def of open science cited in hampton
  + A philosophy and set of tools that can democratize scientific analysis by making data and analyses more accessible
  + Emphasis on reproducibility, transparency, communication, and longevity, researchers as data stewards not owners
  + Embraces all aspects of a project from idea conception to delivery of final products, implications for bioassessment
  + Overall, encourages collaboration and access to/sharing of data
* Why is open science particularly relevant for bioassessment?
  + Overall, management of water quality requires science that has been publicly funded and the application of the science is a public service that should be inherently open - but it typically is not.
  + data are publicly funded, typically, so legal/moral mandates necessitate open analysis, see Molloy 2011 for UK example
  + Multiple methods have been developed, an important component of open science is data discovery. Making methods open and transparent can facilitate synthesis and meta-analysis
  + Data used for bioassessment methods are typically not the “long-tail” of the ecological sciences, i.e., the carefully collected observational data meant to address specific research questions. Scientists in the long-tail are potentially more relucant to adopt open-science because of the perception of less benefit to making the data open. This suggests that bioassessment datasets and associated methods are inherently more likely to benefit from openness because more widespread appeal. Conversely, the long-tail datasets individually may not have broad relevance but collectively could serve larger purposes, some countries have abandonated national-scale coordinated monitoring efforts in favor localized sampling (Nichols et al. 2016)
* Aspects of the process that can benefit bioassessment
  + Data provenance and open data
  + Method development – existing software packages to facilitate
  + Method delivery –
    - portable packages and data visualization, emphasis on interactive online tools: Zastrow 2015 describes power of interactive mapping, Kelling et al. 2009 describe data-intensive approaches for biodiveristy to identify patterns born from the data and data viz is one approach, Fox and Hendler 2011 emphasize viz as part of analysis process not as end-product, the case for open computer programs described by Ince et al. 2012 emphasizes the type of problem present in bioassessment - all methods should be complementary with a software packgae as supplement to the primary document
    - Communication within collaborative teadm and management community, Kelling et al. 2009
* Why is open science particularly important for bioassessment? Vs. general ecological research? Vs. other kinds of environmental monitoring? Vs. other publicly funded data collection?

# California examples

* Example approach
  + What is the legal/policy framework for supporting/impeding open science in CA? Are we living up to our aspirations?
    - On July 10, 2018 the The State Water Resources Control Board “adopted a resolution on open data principles committing it and the Regional Water Boards to providing broader access to the data used to make local, regional and statewide water management and regulatory decisions in California.” [press release](https://www.waterboards.ca.gov/press_room/press_releases/2018/pr_water_data_071018.pdf), [resolution](https://www.waterboards.ca.gov/board_info/agendas/2018/jul/071018_5_drft_reso.pdf)
  + AB 1755, Dodd. The Open and Transparent Water Data Act. Passed in 2016, requires state water quality institutions to “create, operate, and maintain a statewide integrated water data platform that, among other things, would integrate existing water and ecological data information from multiple databases and provide data on completed water transfers and exchanges” and “develop protocols for data sharing, documentation, quality control, public access, and promotion of open-source platforms and decision support tools related to water data”
  + The California vision – describe legal/policy demands for bioassessment, current methods developed, developing tools to link technical products with management
  + Existing applications – assessment methods packaged as standalone applications complete with documentation, vignettes, versioning
  + Bioassessment as proactive vs reactive – SCAPE for regulatory applications, SCAPE for conservation, other examples

# Challenges and recommendations for bioassessment

* Challenges for application
  + Technical hurdles – technical and constantly expanding skillset is required, immediate returns difficult to see (e.g., for data sharing Hampton et al. 2015, need to find citation for learnign tech skills)
  + Sociocultural hurdles – unwillingness to share hard-earned data (less so for bioassesssment than traditional ecology, but could be an issue), vulnerability to criticism (Lewandowsky and Bishop 2016 describe concerns of transparency leading to damage of scientific integrity)
  + Institutional barriers – entrenched modes of operation can discourage novelty and exploration, no incentive for adoption
* The way forward
  + The holy grail is widespread adoption of open science in bioassessment, but this will never be completely integrated, see challenges above
  + Teaching as an approach – let the trainee become the trainer, Hampton et al. 2017 describes training initiatives to close the skill-transfer gap, Touchon and McCoy 2016 describe mismatch between grad programs and tech skills used in contemporary ecological analysis
  + Who is likely to adopt? Cultivate adopters (researcher benefits, institution benefits, stakeholder benefits), work with non-adopters (institution benefits, stakeholder benefits)
  + Roles for adopters, roles for non-adopters
  + Development as an approach – roles for adopters, develop specialized software packages (require vetting, Borregard et al. 2016, could link in to new but existing pathways for review such as ROpenSci or peer review journals like the R Journal), Touchon and McCoy 2016 advocate for a role of adopters as specialists to facilitate collaboration with “less quantitatively trained or interested students” rather than the latter analysizing their data in potentially suboptimal ways.
* Call to implement now - field is transitioning to molecular approaches where information acquisition will be orders of magnitude greater than traditional taxonomic-based approaches. Data acquisition and management will require systematic methods for documenting, cataloging, and sharing information - start now. Use of online eDNA archives have been established. Baird and Hajibabaei 2012 describe the bioassessment paradigm with molecular approaches

# References

Bain, M. B., A. L. Harig, D. P. Loucks, R. R. Goforth, and K. E. Mills. 2000. “Aquatic Ecosystem Protection and Restoration: Advances in Methods for Assessment and Evaluation.” *Environmental Science and Policy* 3 (1):89–98.

Beck, M. W., and L. K. Hatch. 2009. “A Review of Research on the Development of Lake Indices of Biotic Integrity.” *Environmental Reviews* 17:21–44. <https://doi.org/10.1139/A09-001>.

Birk, S., W. Bonne, A. Borja, S. Brucet, A. Courrat, S. Poikane, A. Solimini, W. van de Bund, N. Zampoukas, and D. Hering. 2012. “Three Hundred Ways to Assess Europe’s Surface Waters: An Almost Complete Overview of Biological Methods to Implement the Water Framework Directive.” *Ecological Indicators* 18 (1):31–41. <https://doi.org/10.1016/j.ecolind.2011.10.009>.

Borja, A., A. Ranasinghe, and S. B. Weisberg. 2009. “Assessing Ecological Integrity in Marine Waters, Using Multiple Indices and Ecosystem Components: Challenges for the Future.” *Marine Pollution Bulletin* 59 (1-3):1–4.

Cao, Y., and C. Hawkins. 2011. “The Comparability of Bioassessments: A Review of Conceptual and Methodological Issues.” *Journal of the North American Benthological Society* 30 (3):680–701. <https://doi.org/10.1899/10-067.1>.

Collins, S. L. 2016. “Vegetation Science in the Age of Big Data.” *Journal of Vegetation Science* 27 (5):865–67. <https://doi.org/10.1111/jvs.12459>.

Dale, V. H., and S. C. Beyeler. 2001. “Challenges in the Development and Use of Ecological Indicators.” *Ecological Indicators* 1 (1):3–10. <https://doi.org/10.1016/S1470-160X(01)00003-6>.

Fore, L. S., and C. Grafe. 2002. “Using Diatoms to Assess the Biological Condition of Large Rivers in Idaho (U.S.A.).” *Freshwater Biology* 47 (10):2015–37. <https://doi.org/10.1046/j.1365-2427.2002.00948.x>.

Hampton, S. E., S. S. Anderson, S. C. Bagby, C. Gries, X. Han, E. M. Hart, M. B. Jones, et al. 2015. “The Tao of Open Science for Ecology.” *Ecosphere* 6 (7):1–13. <https://doi.org/10.1890/ES14-00402.1>.

Hampton, S. E., C. A. Strasser, J. J. Tewksbury, W. K. Gram, A. E. Budden, A. L. Batcheller, C. S. Duke, and J. H. Porter. 2016. “Big Data and the Future of Ecology.” *Frontiers in Ecology and the Environment* 11 (3):156–62. <https://doi.org/10.1890/120103>.

Hering, D., A. Borja, J. Carstensen, L. Carvalho, M. Elliott, C. K. Field, A. S. Heiskanen, et al. 2010. “The European Water Framework Directive at the Age of 10: A Critical Review of the Achievements with Recommendations for the Future.” *Science of the Total Environment* 408 (19):4007–19. <https://doi.org/10.1016/j.scitotenv.2010.05.031>.

Howard, J. K., K. A. Fesenmyer, T. E Grantham, J. H. Viers, P. R. Ode, P. B. Moyle, S. J. Kupferburg, et al. 2018. “A Freshwater Conservation Blueprint for California: Prioritizing Watersheds for Freshwater Biodiversity.” *Freshwater Science* 37 (2):417–31. <https://doi.org/10.1086/697996>.

Ihle, M., I. S. Winney, A. Krystalli, and M. Croucher. 2017. “Striving for Transparent and Credible Research: Practical Guidelines for Behavioral Ecologists.” *Behavioral Ecology* 28 (2):348–54. <https://doi.org/10.1093/beheco/arx003>.

Jackson, S., and W. Davis. 1994. “Meeting the Goal of Biological Integrity in Water-Resource Programs in the US Environmental Protection Agency.” *Journal of the North American Benthological Society* 13 (4):592–97. <https://doi.org/10.2307/1467854>.

Karr, J. R., K. D. Fausch, P. L. Angermeier, P. R. Yant, and I. J. Schlosser. 1986. “Assessing Biological Integrity in Running Waters: A Method and Its Rationale.” Special Publication 5. Champaign, Illinois: Illinois Natural History Survey.

Kelly, M. G., S. Birk, N. J. Willby, L. Denys, S.Drakare, M. Kahlert, S. M. Karjalainen, et al. 2016. “Redundancy in the Ecological Assessment of Lakes: Are Phytoplankton, Macrophytes and Phytobenthos All Necessary?” *Science of the Total Environment* 15 (568):594–602. <https://doi.org/10.1016/j.scitotenv.2016.02.024>.

Kerans, B. L., and J. R. Karr. 1994. “A Benthic Index of Biotic Integrity (B-IBI) for Rivers of the Tennessee Valley.” *Ecological Applications* 4 (4):768–85. <https://doi.org/10.2307/1942007>.

Kuehne, L. M., J. D. Olden, A. L. Strecker, J. J. Lawler, and D. M. Theobald. 2017. “Past, Present, and Future of Ecological Integrity Assessment for Fresh Waters.” *Frontiers in Ecology and the Environment* 15 (4):197–205. <https://doi.org/10.1002/fee.1483>.

Linke, S., E. Turak, and J. Nel. 2011. “Freshwater Conservation Planning: The Case for Systematic Approaches.” *Freshwater Biology* 56 (1):6–20. <https://doi.org/10.1111/j.1365-2427.2010.02456.x>.

Lortie, C. J. 2014. “Formalized Synthesis Opportunities for Ecology: Systematic Reviews and Meta-Analyses.” *OIKOS* 123 (8):897–902. <https://doi.org/10.1111/j.1600-0706.2013.00970.x>.

Lowndes, J. S. S., B. D. Best, C. Scarborough, J. C. Afflerbach, M. R. Frazier, C. C. O’Hara, N. Jiang, and B. S. Halpern. 2017. “Our Path to Better Science in Less Time Using Open Data Science Tools.” *Nature Ecology & Evolution* 1 (0160):1–7. <https://doi.org/10.1038/s41559-017-0160>.

Marwick, Ben, Jade d’Alpoim Guedes, C. Michael Barton, Lynsey A. Bates, Michael Baxter, Andrew Bevan, Elizabeth A. Bollwerk, et al. 2016. “Open Science in Archaeology.” *SAA Archaeological Record* 17 (4):8–14. <https://doi.org/10.17605/OSF.IO/3D6XX>.

McDonald, M., R. L. Blair, D. Bolgrien, B. S. Brown, J. J. Dlugosz, S. S. Hale, S. F. Hedtke, et al. 2004. “The US Environmental Protection Agency’s Environmental Monitoring and Assessment Program.” In *Environmental Monitoring*, edited by G. B. Wiersma, 649–68. Boca Raton, Florida, USA: CRC Press.

Michener, W. K., J. W. Brunt, J. J. Helly, T. B. Kirchner, and S. G. Stafford. 1997. “Nongeospatial Metadata for the Ecological Sciences.” *Ecological Applications* 7 (1):330–42.

Nichols, S. J., L. A. Barmuta, B. C. Chessman, P. E. Davies, F. J. Dyer, E. T. Harrison, C. P. Hawkins, et al. 2016. “The Imperative Need for Nationally Coordinated Bioassessment of Rivers and Streams.” *Marine and Freshwater Research* 68 (4):599–613. <https://doi.org/10.1071/MF15329>.

Niemi, G. J., and M. E. McDonald. 2004. “Application of Ecological Indicators.” *Annual Review of Ecology, Evolution, and Systematics* 35:89–111.

Poikane, S., N. Zampoukas, A. Borja, S. P. Davies, W. van de Bund, and S. Birk. 2014. “Intercalibration of Aquatic Ecological Assessment Methods in the European Union.” *Environmental Science & Policy* 44:237–46. <https://doi.org/10.1016/j.envsci.2014.08.006>.

Reynoldson, T. B., R. H. Norris, V. H. Resh, K. E. Day, and D. M. Rosenberg. 1997. “The Reference Condition: A Comparison of Multimetric and Multivariate Approaches to Assess Water-Quality Impairment Using Benthic Macroinvertebrates.” *Journal of the North American Benthological Society* 16 (4):833–52. <https://doi.org/10.2307/1468175>.

Stein, E. D., M. Brinson, M. C. Rains, W. Kleindl, and F. R. Hauer. 2009. “Wetland Assessment Alphabet Soup: How to Choose (or Not Choose) the Right Assessment Method.” *Society of Wetland Scientists Bulletin* 26:20–24.

Stoddard, J. L., A. T. Herlihy, D. V. Peck, R. M. Hughes, T. R. Whittier, and E. Tarquinio. 2008. “A Process for Creating Multimetric Indices for Large-Scale Aquatic Surveys.” *Journal of the North American Benthological Society* 27 (4):878–91. <https://doi.org/10.1899/08-053.1>.

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. “Setting Expectations for the Ecological Condition of Streams: The Concept of Reference Condition.” *Ecological Applications* 16 (4):1267–76. <https://doi.org/10.1890/1051-0761(2006)016[1267:SEFTEC]2.0.CO;2>.