EMERGING METHODS AND TOPICS

Section Introduction: Exploring the Exciting New Landscape of Inland Waters Research

Kendra Spence Cheruvelil[a] **and Herbert Kasozi**[b], [a]Department of Fisheries and Wildlife, Lyman Briggs College, and Ecology, Evolution, and Behavior Program, Michigan State University, East Lansing, Michigan, United States; [b]Department of Fisheries and Wildlife, Michigan State University, East Lansing, Michigan, United States

Introduction

The study of inland waters has a robust and long history. However, what is most exciting to us (and many scientists), are the newest scientific questions that require us to develop different perspectives of freshwaters, engage with new areas of study, and develop or apply new approaches and methods. That's what this encyclopedia section *Emerging Methods and Topics*, is all about—the new frontiers that are advancing the understanding and management of inland waters.

Some of these new perspectives and questions are the result of emerging technologies opening new areas of research. Many of these questions come from our heightened understanding of the pressures facing our freshwater resources in the face of global changes, such as land use intensification, climate change, and the spread of exotic species. These global changes that are inextricably linked with humans, requiring us to interrogate the belief that science (and scientists) is objective and to embrace new ways of transforming knowledge and translating that new knowledge to those beyond academia. Therefore, many of these questions require limnologists to collaborate with experts in the social sciences, humanities, and communication sciences. The emerging approaches and methods required may be brand new, requiring algorithm or technology development and partnering with those in fields such as statistics, computer science, and engineering. Alternatively, these approaches and methods may already exist in those disciplines, but haven't yet been applied to understand inland waters.

This *Emerging Methods and Topics* section brings you chapters that highlight some of those exciting new questions being asked, perspectives being developed, and methods and approaches either being developed or applied to inland water research and management. These chapters are written by emerging leaders in limnology, mainly early-to-mid-career scientists who are pushing the boundaries of their specialties to answer important questions that are just now surfacing. The chapters are arranged to introduce you to a new perspective, research question, or area of research and then to share some of the new approaches and methods being used by those taking such perspectives, asking those questions, and developing these new areas of research.

First, we bring you a chapter that shifts our perspective of inland waters. We like to use a medical analogy when thinking about this perspective change. In the past, many limnologists were like medical doctors, studying and managing individual bodies of water, watersheds, or water-rich regions. More recently, some limnologists have become more like epidemiologists, seeking to understand and manage entire populations of inland waters. In *Macrosystems Limnology and Beyond: Re-Envisioning the Scale of Limnology*, the authors describe the importance of this perspective. We then follow that chapter with a series of five chapters that share approaches, tools, and methods that help advance this broad-scale perspective (i.e., high-frequency sensors; remote sensing; machine learning; research teams, networks, and networks of networks; and citizen science, crowdsourcing, and social media).

Next, we bring you a series of three chapters introducing you to some interesting new areas of inland waters research: dust and fog effects, understanding the soundscape (i.e., ecoacoustics), and fungi in the Anthropocene. Finally, we end the section with three chapters that share exciting new approaches, tools, and methods to better understand and manage organisms in inland waters (i.e., environmental DNA or eDNA, electronic tagging and tracking, and fatty acid markers and foodweb tracers). Below, we provide a short summary of each chapter of the *Emerging Methods and Topics* section to pique your interest and prompt you to turn to each respective chapter to learn more about the future of inland waters research and management.

Macrosystems limnology and beyond: Re-envisioning the scale of limnology (McCullough et al., 2022)

This chapter discusses the emerging field of *macrosystems limnology*, which recognizes freshwater ecosystems as components of larger, integrated systems influenced by aquatic, terrestrial, and atmospheric components and processes at multiple scales of space and time. This field has its content roots in landscape limnology, biogeography, and systems science, and has been advanced with data from long-term monitoring networks, government monitoring programs, large compilation databases, coordinated snapshot surveys, remote sensing, and citizen science. The aim of macrosystems limnology is to uncover patterns that exist and the underlying processes operating at different levels of biological organization and across scales of space and time. A macrosystems perspective could be instrumental in predicting how freshwaters will respond to global changes and guide regional to continental (and even global) management efforts.

Creating and managing data from high-frequency environmental sensors (Rose et al., 2022)

This chapter discusses the relevance and applications of high frequency sensors for advancing limnological research. High frequency sensors facilitate fast and repeated sampling of ecological phenomena, even where it is impossible to make manual measurements (such as in sites that are not easily accessible), which has resulted in many insights into ecosystem dynamics. The chapter describes a range of sensors and outlines practical considerations for their use in data collection. In addition, the authors discuss key sampling concepts and their ecological implications and challenges, as well as some disadvantages of fast sampling rates such as increased dataset complexity, power consumption, and storage requirements. The chapter outlines practical considerations in sensor choice and management, including sensor type, system design, cost, and measurement variables. Rose et al. also explain the challenges associated with these methods, such as harsh environmental conditions, and explore considerations for ensuring data quality and adequate data management.

Remote sensing of inland waters (Tyler et al., 2022)

This chapter provides an overview of the principles and applications of earth observation (EO) technologies (e.g., satellite or airborne remote sensing) for monitoring water quality. The chapter describes ways to characterize water color and how light propagation, optical complexity, and water typology affect EO estimation of water color. Additionally, the chapter explores the evolution of remote sensing platforms and defines the criteria for selecting sensor and platform developments. Platforms discussed are spaceborne, airborne, drone, in situ above-water, and in situ subsurface sensors. The criteria discussed include size of distinguished objects, range, number and width of spectral bands, number of digital levels used to express collected data, and the interval between the different resolutions. The authors also discuss additional applications such as estimating chlorophyll *a*, phycocyanin, turbidity, and total suspended matter. Monitoring algal blooms, brownification, and primary production at both national and global scales using remote sensing can provide critical information for lake management.

Machine learning for understanding inland water quantity, quality, and ecology (Appling et al., 2022)

This chapter provides an overview of machine learning (ML) models and their applications to the science of inland waters. ML is the development and application of models that adapt and can analyze and draw inferences from patterns in large amounts of data. The authors describe many aspects of ML models, including their characteristics and how they compare with process-based and empirical models, ways to determine model trustworthiness, ways to choose among model classes, and ways to understand and interpret model results. They focus on four classes of ML approaches that are gaining in popularity when studying inland waters - neural networks, classification and regression trees, clustering and dimensionality reduction methods, and model interpretation techniques. The authors provide examples of ML model applications for predicting and understanding inland waters, including the prediction of water quality, quantity, and ecology across space or time.

Teams, networks, and networks of networks advancing our understanding and conservation of inland waters (Read et al., 2022)

This chapter discusses the important role of people working together to advance inland water science and management and provides case studies demonstrating the importance of teamwork for advancing knowledge. Teams, networks, and networks of networks lie at the forefront of inland water research, management, and conservation. This is largely due to the multi- and interdisciplinary and complex nature of inland water research and management. The chapter examines the role of teams, networks, and networks of networks in the research and management of inland water resources, discusses aspects of team building and maintenance and their respective roles in propagating successful research and management, and methods for successful social connections within teams, networks, and networks of networks. The authors explain that teams, networks, and networks of networks may include individuals within the same or different organizations, but that they are bound together by a common goal, and that trust is the foundational tenet for success. Effective team and network dynamics are critical for effective flow of information, allocation of resources, coordination of logistics, knowledge generation and sharing, as well as building and engaging in collective action.

Citizen science, crowdsourcing, and social media advance our understanding and conservation of inland waters (Latimore and Lowry, 2022)

This chapter discusses how increasingly important it is for inland waters scientists and managers to engage with diverse audiences. The chapter focuses on three rapidly expanding methods for public engagement: citizen science, crowdsourcing, and the use of social media. These methods produce large amounts of reliable data; often represent cost-effective approaches to increase research scale, public relevance, participant knowledge of content and the scientific process; and empower participants to engage in stewardship and decision-making processes. The authors point to the recent growth of these approaches and provide case studies highlighting the use of these methods in both scholarship and application. Participation of non-scientists can result in more relevant research questions, can produce a richer set of data and knowledge, generate innovative solutions to complex conservation problems, and increase scientific literacy and public support for research and conservation work.

Dust and fog effects on inland waters (Brahney et al., 2022)

This chapter describes a new research area, that of the roles of fog and dust in the transportation of atmospheric nutrients to inland waters. Human activity (such as construction) is a major agent of dust generation and fog is critical in the deposition of dust into aquatic ecosystems. Nutrients carried by dust may alter the chemistry of the affected aquatic systems with negative effects on the ecology and behavior of microbial, phytoplankton, and zooplankton communities within. Fog is likely to have indirect impacts on inland waters through scattering and absorption of incoming light, and hydrologic and biogeochemical impacts on adjacent catchments. The authors discuss the process of dust and fog formation, controls on dust and fog composition, nutrient bioavailability, common measurement techniques of dust and fog, and provide case studies that exemplify the effects of dust and fog on water chemistry and the ecology of inland waters.

Freshwater ecoacoustics (Linke et al., 2022)

This chapter discusses ecoacoustics, an emerging interdisciplinary field that investigates the ecological relevance of environmental sounds. It examines fundamental differences between bioacoustics and ecoacoustics and highlights applications of the latter in aquatic systems research. The chapter discusses biotic, abiotic, and anthropogenic sources of environmental sounds. Biotic sounds discussed commonly emanate from insects, fish, and plants; abiotic sounds include flow turbulence, sediment transport, and river flow; and anthropogenic sounds include water transport, recreational water parks, and mining and construction activities. After highlighting problems with traditional sampling methods, the chapter makes a strong case for the need of ecoacoustics to improve understanding of aquatic soundscapes. The chapter concludes by highlighting knowledge gaps, technical challenges, and relevance of ecoacoustics to society.

Inland water fungi in the Anthropocene: Current and future perspectives (Grossart et al., 2022)

This chapter examines the biological, chemical, and physical effects of pollution on inland water fungi. Fungi species have different mechanisms of assimilating and breaking down the pollutants. For example, some fungi have extracellular enzymes that break down pollutants from human environments. The ability to process and detoxify anthropogenic pollutants qualifies fungi as an indicator of ecosystem health. The authors explore the diversity and ecology of aquatic fungi and fungi-like organisms, and highlight the emerging topic of fungi-virus interactions. The authors also highlight the effects of micro plastic pollution on aquatic fungi and the roles of fungi in decomposition of micro plastics. Micro plastics are commonly generated from urban environments and washed into inland waters. However, some fungi assimilate micro plastic pollutants in aquatic environments. Understanding the ecological roles of aquatic fungi is critical in examining the negative feedback loops of human pollution to human health.

Environmental DNA advancing our understanding and conservation of inland waters (Seymour, 2022)

This chapter explores the application of environmental DNA (eDNA) for sampling freshwater animals. The use of eDNA is an emerging modern technique facilitated by recent advances in molecular techniques that is rapidly gaining popularity within freshwater ecological research. The method relies on extraction of free floating DNA samples in the environment without targeting a particular organism. The extracted samples are released by animals (e.g., as fecal material) into the environment and eDNA traces the source animal species. The chapter discusses concepts related to the accumulation of eDNA and its extraction from freshwater environments. The author discusses the use of eDNA for monitoring of organisms (including fish, macroinvertebrates, and diatoms), which would otherwise be laborious and invasive. He also highlights the importance of eDNA methods for detection of rare and invasive species and monitoring disease spread.

Electronic tagging and tracking of animals in inland waters (Cooke et al., 2022)

This chapter discusses the use of electronic tags to track inland water animals. This approach can be used to understand several aspects of aquatic animal ecology (such as habitat use and interspecific interactions), behavior (such as movement, migration, and dispersal patterns), and environmental conditions (many tags measure components such as depth and temperature). The authors describe biotelemetry and biologging as the major tools used to track inland water animals (e.g., radio and acoustic telemetry, Passive Integrated Transponders (PIT) tags), and provide example applications to study a diversity of animals ≥ 10 g body mass including invertebrates, amphibians, reptiles, waterbirds, fish, and some mammals. The authors discuss how information generated from animal tracking is used in the evaluation of conservation programs, including tracking animals reintroduced into the wild from captivity.

Fatty acid-markers as foodweb tracers in inland waters (Makhutova et al., 2022)

This chapter describes the use of fatty acid (FA) markers to trace the fluxes of matter and energy through foodwebs. The authors describe FAs and their use as foodweb markers in aquatic ecosystems, describe and compare the FA-marker analysis with other methods for studying aquatic animal diets, and describe the identifying characteristics of FAs in the main taxonomic groups of organisms inhabiting freshwater ecosystems (bacteria, algae and other photosynthetic eukaryotes, non-photosynthetic eukaryotes). The chapter also describes how FAs have been used to understand the feeding spectra of many aquatic consumers and have contributed to scientists successfully differentiating between external and internal sources of organic matter in inland waters (i.e., allochthonous versus autochthonous inputs). FA-marker analysis has facilitated discoveries such as selective feeding of filter-feeders, diet variability of detritovores, and adaptations of feeding behavior to changing environments.

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