A lake management framework for global application: monitoring, restoring, and protecting lakes through community engagement

Jacob A. Cianci-Gaskill[1*], Jennifer L. Klug[2], Kellie C. Merrell[3], Edward E. Millar[4], Danielle J. Wain[5], Lilith Kramer[6,7,8], Dianneke van Wijk[6,7,9], Ma Cristina A. Paule-Mercado[10], Kerri Finlay[11], Max R. Glines[12], Elias M. Munthali[13], Sven Teurlincx[6], Lisa Borre[14], Norman D. Yan[15,16]

[1]Old Woman Creek National Estuarine Research Reserve, Ohio Department of Natural Resources, 2514 Cleveland Rd E, Huron, OH, USA

[2]Biology Department, Fairfield University, 1073 N Benson Rd, Fairfield, CT, USA

[3]Vermont Department of Environmental Conservation, State of Vermont, 1 National Life Dr, Davis 3, Montpelier, VT, USA

[4]Environmental Applied Science and Management Department, Toronto Metropolitan University, 250 Victoria St, Toronto, ON, Canada

[5]7 Lakes Alliance, Belgrade Lakes, ME, USA

[6]Department of Aquatic Ecology, Netherlands Institute of Ecology (NIOO-KNAW), Droevendaalsesteeg 10, 6708 PB, Wageningen, The Netherlands

[7]Aquatic Ecology and Water Quality Management Group, Wageningen University & Research, Droevendaalsesteeg 4, 6708 PB, Wageningen, The Netherlands

[8]Department of Freshwater Ecology and Water Quality, Deltares, Delft, The Netherlands

[9]Water Systems and Global Change Group, Wageningen University & Research, Droevendaalsesteeg 4, 6708 PB, Wageningen, The Netherlands

[10]Biology Centre of the Czech Academy of Sciences, Institute of Hydrobiology, Na Sádkách 7, České Budějovice 370 05, Czech Republic

[11]Biology Department, University of Regina, 3737 Wascana Parkway, Regina, SK, Canada

[12]Department of Biological Sciences, Rensselaer Polytechnic Institute, 110 8th St, Troy, NY, USA

[13]*Operations Department, Northern Region Water Board, Bloemwater St, Mzuzu, Malawi*
[14]*Cary Institute of Ecosystem Studies, 2801 Sharon Turnpike, Millbrook, NY, USA*
[15]*Friends of the Muskoka Watershed, 126 Kimberley Ave, Box 416, Bracebridge, ON, Canada*
[16]*Department of Biology, York University, 2275 Bayview Ave, Toronto, ON, Canada*

*Corresponding author: jacob.cianci-gaskill@dnr.ohio.gov

Abstract

Despite decades of management and regulation, global freshwater resources remain imperiled. Management has had mixed success in restoring degraded lakes and has few mechanisms for stopping the decline of high-quality systems. Too often, lake managers play "catch-up" by addressing stressors only after damage occurs or has become entrenched, or make decisions without acquiring sufficient information about how a lake might respond to proposed management actions. As a tool to address these management challenges, we propose the MoReCo (**Mo**nitoring, **Re**storing/Protecting, **Co**mmunity Engagement) lake management framework. The framework centers around community engagement, and we outline engagement mechanisms in the context of lake management. The framework includes two loops: a Monitoring Loop to detect emerging stressors; and a Restoring/Protecting Loop to address stressors that are causing or may cause lake degradation. The MoReCo framework builds on the strengths of existing natural resource management frameworks and was developed to address the unique challenges associated with lake management and protection, as well as those resulting from climate change. Specifically, it can address multiple stressors concurrently, which makes it simultaneously suitable for ameliorating stressors while also protecting lake ecosystems. The MoReCo framework is an interactive and multi-directional process in which management occurs even when no stressor is apparent, and it incorporates explicit benchmarks for evaluating management actions and determining whether additional measures should be taken. This novel lake management framework is suitable to address any stressors that may threaten a lake ecosystem, and we present it here as a resource for those who manage freshwater resources.

Key words: Climate Preparedness, Ecosystem Protection, Ecosystem Restoration, Lake Management Framework, Monitoring, Natural Resource Management, Community Engagement

Introduction

Globally, lake condition has been declining due to a rapidly changing climate (Williamson et al. 2009, Woolway and Merchant 2019, Sharma et al. 2021) and growing human populations near lakes and reservoirs (hereafter "lakes"), which increases pressure on diminishing freshwater resources (Vörösmarty et al. 2013, Settele et al. 2014). Regulatory policies have been developed around the world to restore degraded lakes and management plans have been used to implement these regulatory policies. However, lake condition continues to deteriorate across the globe (UNEP 2016, Ho et al. 2019, Jenny et al. 2020, Albert et al. 2021, USEPA 2022). An overarching decline in lake condition is partially because the implementation of many laws and regulations, like the US Clean Water Act, focus attention and limited resources on restoring heavily degraded lake ecosystems at the expense of protecting high-quality lakes and restoring those which are minimally degraded (Zellmer and Glicksman 2013, Spears et al. 2022). Another reason for the deterioration of aquatic resources may be because of exemption clauses, regulatory "flexibility," and the unwillingness or inability of regulators to hold "bad actors" accountable (Andreen 2007, Andreen 2013, Green et al. 2013, Starke and Van Rijswick 2021). Management plans may also fail when they attempt to use a "one-size-fits-all" approach that does not consider how a stressor may respond to different management actions. Technical expertise is essential because it informs the evidence-based decision making necessary for restoration to succeed (Williams and Brown 2016). The fact that many of today's lake management challenges are complex problems without simple solutions means that we need a new approach to protect high quality, and restore degraded, aquatic ecosystems and the wealth of ecological services they provide (Rittel and Webber 1973, Sterner et al. 2020).

Here, we introduce the MoReCo (**Mo**nitoring, **Re**storing/Protecting, **Co**mmunity Engagement) framework (Figure 1). This framework builds on existing management frameworks and is designed to be holistic and broadly applicable to any stressor that occurs in a lake or watershed anywhere in the world. The MoReCo framework addresses multiple stressors simultaneously, provides mechanisms for community engagement, evaluates success using pre-determined thresholds, and is designed to be a continuous loop so that users of the framework can begin at any step and continue management after a stressor is addressed. While the MoReCo framework is presented as unidirectional (Figure 1), managers may go back and forth between steps and incorporate aspects from one step into others. For example, while mechanisms for community engagement are described in the community axis, there are many instances where community engagement may also be appropriate in other steps (e.g., community science in water quality monitoring; community invasive species removal efforts for restoration). We are not aware of any other lake management framework with similar characteristics. The MoReCo framework is composed of three main sections: (a) "Community Engagement Axis," which outlines community engagement, public participation, and prioritization of management issues; (b) "Monitoring Ecosystem State Loop" which establishes baseline conditions and sets targets; and (c) "Restoring or Protecting Ecosystem State Loop" which describes the steps required to develop and implement a successful management plan. To illustrate how these steps might be implemented, we provide a fictitious example of a common stressor to lake condition, in this case an invasive plant (Boxes 1–3). This paper focuses on improving lake condition by addressing environmental stressors, however, the framework would also be suitable for human-centered issues (e.g., lake access and recreation). The MoReCo framework is intended for lake managers, defined as anyone involved in lake ecosystem restoration and protection, and we believe it will be a useful tool for preparing for and adapting to a rapidly changing climate.

The MoReCo Framework

Community Axis (C1–C4)

The central axis of the MoReCo framework identifies the importance of community engagement for successful natural resource management (Chidammodzi and Muhandiki 2015) and outlines different levels of interaction. We acknowledge that there is no "one size fits all" approach to community engagement and aim to provide a tool that works across the range of what community engagement might look like in lake management. Community engagement has several recognized benefits such as obtaining public support for management objectives and actions, and fostering public involvement in the implementation of management plans beyond the tenure of individual managers or government officials (Fitchett et al. 2020). We use the term "community engagement" to refer to interactions between traditional managers or decision makers and actors who will be impacted by management decisions.

We define "community engagement" as a broad category which includes communication (informing the public via unidirectional transfer of information from managers to communities, or via public science education efforts), consultation (public feedback and bi-directional communication between community members and managers), and participation (Rowe and Frewer 2005). We further subcategorize community participation, differentiating between mechanisms to facilitate co-management and direct public participation in agenda-setting, decision-making, and policy formation (Rowe and Frewer 2000); and mechanisms for involving community members in the other stages of the MoReCo framework (e.g., community science methods to assist in monitoring, volunteer actions to restore or protect the desired ecosystem condition, public participation in adaptive management experiments; Aceves-Bueno et al. 2015, Creed et al. 2018). While these categories are not mutually exclusive and can each be adopted throughout the various stages of our framework, differentiating between them can help managers select from a range of engagement pathways and mechanisms best suited to their local contexts (Table 1). We consider our framing of community engagement to be consistent with similar concepts such as translational ecology (Lawson et al. 2017), public participation in scientific research (Dickinson et al. 2012), and community-based monitoring for common pool resource management (Conrad and Daoust 2008, Slough et al. 2021).

Our framework proposes four steps to operationalize engagement in the Community Axis. To start, community members must be identified (C1). Then, appropriate channels, pathways, and engagement mechanisms should be selected (C2). Through these engagement mechanisms, managers will seek community input and then prioritize goals if multiple or conflicting issues or concerns arise (C3). Once the goals and priorities for the lake are clear, these can be combined with knowledge of ecosystem state to evaluate whether current ecosystem conditions align with the prioritized goals (C4). The result of the evaluation directs the process towards either the Monitoring Loop or the Restoring/Protecting Loop, which are described in the Monitoring Ecosystem State Loop (M1–M5) and Restoring or Protecting Ecosystem State Loop (RP1–RP5) sections, respectively. After these loops, the framework can be used iteratively by reinitiating the Community Axis stages and the subsequent loops again.

C1) Identify Community Partners

Extensive and comprehensive engagement is crucial in successful lake management to ensure decision-making is well-informed (Reed 2008, Fitchett et al. 2020, Smyth et al. 2021). Effective engagement requires the identification of community partners who will be contacted and included in discussions about management objectives, approaches, and priorities. Partners are sometimes identified based on managers' tacit intuition through key informants, previous experience working with community members in similar areas or on similar issues, or the use of media (e.g., traditional news media, social media, online searching). Community partners can also be self-selected, whereby groups or members of the public present themselves to managers as relevant actors who should be engaged with and looped into the decision-making process (Colvin et al. 2016). Following upon the "rights of nature" movement (Ryan et al. 2021), some countries have attempted to expand the definition of who counts as a "stakeholder" beyond individuals, groups, and networks by considering lakes themselves as possessing distinct rights and interests that can be defended (O'Donnell and Talbot-Jones 2018). Potential community partners can be identified through methods of "stakeholder analysis" (Vogler et al. 2017, Bendsten et al. 2021) based on a range of criteria, including geographical scope (e.g., anyone located within a predefined area can be engaged with; Colvin et al. 2016), interests (e.g., those who have a financial, moral, lifestyle, or place-based interest in the management issue, which can include non-resident visitors and lake users), or influence (e.g., those who have the power to influence management).

"Stakeholder mapping" is an approach to identify potential community partners that can be plotted on a power/interest matrix (Newcombe 2003). In a lake management context, this could involve identifying the intensity of a group's impact on the lake and determining how much the lake impacts them. Social network analysis (SNA) is another recognized method for identifying and communicating with community members and groups, using sociograms to represent relationships within networks (Sharpe et al. 2021).

C2) Engage with Communities on the State of the Lake Ecosystem and Potential Threats

During this step, managers identify and implement appropriate mechanisms for engaging communities or gathering public input (Table 1). The engagement mechanisms chosen will depend on the nature of the specific issue, the number of expected participants, the diversity of community participants, the nature of their relationship to the lake, the resources available for participation, and the circumstances under which public input is useful for setting agendas, informing decisions, or setting policy (Rowe and Frewer 2000, Rowe and Frewer 2005, Bucchi 2009). Not every engagement mechanism will be appropriate in all situations, but we present four types of mechanisms (Table 1) that could be used across the range of community engagement that is required. In some circumstances, the urgency of the issue may require a rapid response from managers, which may make it challenging to engage with communities and rights-holders in all stages of the Community Engagement Axis. In these cases, managers may emphasize the "communication" dimensions of public engagement, particularly those strategies identified in Table 1 which emphasize the rapid dissemination of communication over more extended and open dialog. If the problem faced by the lake could justifiably be better served by unidirectional approaches to communication, then managers may skip C3 and C4 of the engagement process and initiate the Monitoring or Restoring/Protecting loops, and then reinitiate the loop cycle after the most urgent and timely problem has been addressed. Even in those select cases where the urgency of the issue leads managers to decide to adopt unidirectional communication strategies at earlier stages, managers may still decide to adopt more active forms of community engagement during the rest of the Community Engagement loop, as well as during the Monitoring and Restoring/Protecting stages (e.g., community science methods for water quality monitoring; community events for restoration actions).

Different time frames and scales can impact the selection of appropriate engagement mechanisms. Each type of engagement can include a bi-directional educational component to ensure that community members are well informed and understand the ramifications associated with each decision, and that managers are educated about community concerns. The form this education may take will also vary by time frame and scale. Public opinion surveys or sending expert representatives to lake association meetings can be conducted in the short-term, while constructing forums for participatory decision-making or instituting community science programs for baseline monitoring are often only possible at longer time scales. Managers should avoid selecting by default either the “lowest” level of public engagement (based on the assumption that doing so will be the simplest or most cost-effective choice) or selecting by default the “highest” level of public engagement (based on the assumption that this will lead to greater public buy-in of remedial or regulatory options). More complex issues may require more extensive public engagement mechanisms, but granting the community more control over decision-making processes does not always lead to better ecological restoration outcomes and may delay remedial or regulatory actions that might otherwise have been taken sooner if the problem is perceived to be too costly to resolve (Few et al. 2011). At the same time, even in circumstances where the urgency of the problem could preclude managers from actively engaging communities at all stages of the decision-making and priority-setting processes, they must understand local values, priorities, and concerns, so that communication strategies can be effectively tailored to the specific social and cultural contexts of the various groups. In cases where community groups are comprised of marginalized populations who may face cultural constraints to engagement in environmental issues, and who may find that conventional discourse around water management lacks relevance to their community, it is especially important for managers to understand the varying goals and values of different community groups (Prahananga et al. 2019). Understanding these values, effectively engaging with them, and establishing trust with communities can be a lengthy and complex process that often necessitates more co-designed and participatory mechanisms at all stages of the community engagement process (Pateman et al. 2021).

C3) Assemble and Prioritize Community Concerns

Although joint decision-making and community consensus may be the desired outcome of the C2 engagement process, soliciting public input may result in a long list of contradictory or oppositional priorities. The MoReCo framework is designed to address a variety of environmental and human-centered stressors, but balancing or prioritizing public input is a challenge of engagement in environmental management that often involves negotiating overlapping or competing interests and values (Sharpe et al. 2021). Due to their complexity and political nature, some problems arising from competing values can be impossible to resolve, and potential solutions may be temporary and imperfect (Rittel and Webber 1973).

Sharpe et al. (2021) suggest adopting formal criteria for operationalizing prioritization of public concerns. Managers can prioritize community concerns based on the magnitude of impact, the probability of impact, urgency/temporal immediacy of impact, proximity to the issue, economic interest, rights, fairness, and interests of underrepresented/underserved populations. Public input can be scored according to criteria and analyzed using multi-criteria decision-making analysis software, which provides decision makers with a transparent and replicable method for considering and visualizing a range of metrics and criteria (Bourne 2022).

C4) Evaluate How the Current Ecosystem State Relates to the Values and Knowledge

Through the engagement processes outlined above, lake managers can gather and analyze information about the values of lakes that are relevant to local communities. Such values can, for instance, be mapped in the context of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) Nature Future's Framework, which identifies instrumental, intrinsic and relational values of nature, and especially how these values interact (Peirera 2020, Kuiper et al. 2022). The identified values may be conflicting or threatened in the current situation. Managers can then use knowledge gained through community engagement to determine whether immediate management action is needed to bring the lake's state into alignment with desired values, or whether more information is needed. In a situation where there is insufficient knowledge on the state and drivers of the lake due to data deficiency, managers will initiate the Monitoring Ecosystem State Loop (M1–M5). If managers already possess sufficient data about the condition of the lake, and decide that immediate action is warranted, management will proceed to the Restoring or Protecting Ecosystem State Loop (RP1–RP5).

The MoReCo framework is designed to consider multiple stressors simultaneously, so it is possible for managers to pursue various issues in each loop. Often, a scenario occurs where managers are working on different steps for different stressors. By compiling and prioritizing community concerns (C3), managers can draw on local knowledge and values to determine which issues require immediate attention and which should be monitored for future assessment. Public engagement also raises questions about who is in charge and the extent to which communities can actively influence or determine manager's decisions.

Under Type 1 and Type 2 scenarios (Communication and Consultation, Table 1), engagement is framed as mechanisms for soliciting information which inform decisions made by managers. Type 3 and Type 4 scenarios (Decision-making and Management Participation, Table 1) open the possibility of "delegated power," where community partners can become decision-makers. When deciding which mechanisms to adopt for community involvement, the various possibilities of public participation in decision-making should be considered. Although the framework differentiates "engagement," "monitoring," and "restoring" as three distinct stages, it is important to note that community engagement can also occur within the other loops. Managers, for instance, may coordinate community science programs or community-based water monitoring initiatives with community partners across the Monitoring Ecosystem State Loop. Communities can also be engaged in the Restoring or Protecting Ecosystem State Loop through community-based conservation initiatives including invasive species removal efforts, shoreline naturalization planting days, or community outreach to instigate collective action to reduce nutrient input or other stressors which may be contributing to a deviation from the desired ecosystem state.

Box 1: Lake Management Example – the Community Engagement Axis (C1–C4)

While boating, a local resident took a photo of an unfamiliar plant and sent it to the local lake association (LLA). The LLA then forwarded it to the regional management agency (RMA), who identified it as a noxious, invasive aquatic plant. In partnership with local town boards, business groups, recreational user groups, and lake associations, the RMA compiled a list of community members and sent them a press release about the discovery **(C1)**. The LLA called a public meeting at which an invasive plant specialist presented on the potential risks of uncontrolled growth and treatment options. A local government official moderated the discussion to identify community concerns. The RMA then sent surveys to the local tourism industry, local fishing organizations, lakefront property owners, and posted notices requesting public comment in the local newspaper and through social media (**C2**). Feedback indicated community concerns about unusable beaches, clogged propellers, native plant diversity, and tourism impacts. Some strongly opposed the use of herbicide, while others were concerned about treatments that would harm native plants or affect fish habitat. Concerns were also expressed about the local economy if the lake was closed to boats from outside to prevent spread. A few disputed the potential magnitude of the problem and favored no action **(C3)**. From this process, several competing values were identified: preserving fish habitat, protecting native plants to support biodiversity, high-quality boating/swimming, maintaining high property values, and tourism. Regional regulations mandate the preservation or restoration of aquatic life; thus, the RMA communicated to the public that fish habitat preservation and native plant protection should be the legal priorities. Community members agreed that maintaining high-quality boating/swimming was the next priority, which would also maintain tourism and property values. It was determined that the community did not have enough information to determine if the current state of ecosystem supported the priority values. Based on knowledge of the plant's impacts on other lakes, community members recognized that values were threatened and further action was needed **(C4)**.

Monitoring Ecosystem State Loop (M1–M5)

The loop moving clockwise from the bottom of the Community Engagement Axis outlines the process for assessing and monitoring lake condition to capture whether it meets management goals and local values. This loop may also be an entry-point into the framework if there are not enough existing data to begin the community engagement process. The process relies on the selection of specific lake condition parameters that will be monitored to assess whether the lake currently meets and is expected to continue to deliver the values identified during the engagement process. Depending on the selected values being managed, there are numerous lake condition parameters that can be used as indicators to assess lake condition (Seelen et al. 2021). Selecting correct indicators is critical for evidence-based decision making, so managers should not hesitate to revisit indicators with each iteration of the framework, as new information becomes available.

Our framework proposes to first identify reference conditions for the lake that reflect conditions before human disturbance (M1). These reference conditions are not a threshold but are instead the historical range for any given condition to better reflect environmental variability. Reference conditions do not necessarily reflect the ultimate goal for lake restoration, but they help mangers gain an understanding of what is possible and feasible in a system.

Once reference conditions are determined, managers select parameters that indicate compliance with acceptable conditions (compliance indicators) and parameters that indicate that conditions are at risk of falling outside the acceptable range (detection indicators, M2; Cairns et al. 1993; Table 2). Target values are set for each compliance indicator (M3). These target values should be used to objectively determine whether an indicator is in an acceptable condition, which often means that targets will be numeric thresholds. A key point here is that target conditions will not necessarily fall within the reference condition range if it is determined that delivery of desired values and services from the lake can be achieved without restoration to conditions before human disturbance. The next step in this loop requires development of a lake condition monitoring program that is specifically designed to quantify compliance and detection indicators (M4). Lastly, the state of the lake ecosystem is assessed using the quantified indicator values and information is provided to the community (see Community Engagement Axis). Once a sufficient dataset is established, monitoring, and the continuous interpretation of gathered data, also enables managers to identify emerging threats to the values and priorities identified by the communities. These threats can be addressed in the Restoring or Protecting Ecosystem State Loop before they affect those values.

M1) Define Reference Condition

The Monitoring Ecosystem State Loop begins by defining reference conditions for use in the lake management process. Knowing the historical range of conditions in a lake can help managers avoid setting targets (M3) that are unachievable (Dodds et al. 2006). When watersheds have been severely altered from historical conditions, maintenance of or restoration to reference conditions of minimal disturbance may not be possible. In such cases it may be possible to set targets to maintain or restore basic ecosystem processes in the lake in a manner that meets community values without restoring an ecosystem to reference conditions. Knowing whether it is possible to restore a lake back to reference conditions, rehabilitate it to acceptable conditions, or ensure its function as a healthy, resilient ecosystem will inform the next two steps (selecting detection and compliance indicators, and setting target conditions).

Many existing lake management programs rely on the concept of reference conditions to help set goals and recovery targets. For example, the European Water Framework Directive (WFD 2000) and the United States Clean Water Act require member states to establish reference conditions for a range of water quality parameters (Gibson et al. 2000). The reference condition generally refers to the variability of a parameter in a lake that is minimally disturbed by human activities, given the lake type and general physical, hydrological, and watershed characteristics (WFD 2003). Both the US Clean Water Act and EU Water Framework Directive have been criticized for their reliance on the reference-based approach (Adler 2010, Bouleau and Pont 2015) which, critics argue, does not consider the shifting nature of ecosystems nor the importance of achieving resilient systems that provide desired ecosystem services. We include reference conditions in our framework because of their pervasiveness throughout legislation but acknowledge criticism of the use of reference conditions and emphasize that their role in our framework is to provide a range of values that reflect pre-stressor conditions. Reference conditions do not necessarily represent the goal that restoration actions should try to achieve. Instead, the numerical value of the reference condition and/or ecosystem health will inform M3 to set achievable targets for ecosystem state.

Several methods have been used to establish reference conditions. In some cases, data from many lakes are pooled to determine the numerical values of a parameter in the least disturbed systems. For example, Dodds et al. (2006) used data from 220 lakes in Kansas, US, to establish reference conditions for total nitrogen (TN) and total phosphorus (TP) concentrations. In other cases, sediment core data within a lake can be used to establish historical reference conditions (e.g., Bennion et al. 2010). For some parameters, the reference condition may be the absence of a chemical or biological parameter. For example, the European Water Framework Directive states that the reference condition for certain synthetic pollutants should be set to near zero or below detection levels (WFD 2003). Similarly, the reference condition for an invasive species may be set at zero. Defining reference conditions for other biological indicators, such as percent native species or integrity of the food web, may be more data-intensive and require collection of substantial data on the diversity, abundance, and biomass of organisms across multiple levels of the food web.

M2) Select and Refine Detection and Compliance Indicators

Once reference conditions are established, managers will select indicator variables that will be monitored to assess whether the lake is within the range of acceptable conditions for the use or value being managed, as well as variables which will help detect potential threats to that use. What is deemed acceptable should relate to the community values and priorities identified in C3 and C4. While reference conditions are important to establish expected variations within the lake, they must be considered along with community values when determining indicators for detection and compliance. The definition and usage of the term “indicator” varies across the field of environmental management, which can lead to confusion and misunderstanding (Heink and Kowarik 2010). In this framework, we use the approach detailed by Cairns et al. 1993 (Table 2). In some cases, managers may select indicators that have already been developed (e.g., Nürnberg 1996); in other cases, indicator variables may need to be developed or adapted (e.g., Becker et al. 2018). Using established variables and standard protocols, when possible, will allow for comparison across lakes. If the use or value is based on a single measurable parameter, for example, cyanotoxins in drinking water or mercury in fish, the compliance indicator may be a direct measure of the parameter of interest. In other cases, such as in US states that have designated aquatic life uses, the compliance indicator may be an indirect measure of use (e.g., alkalinity; Table 3). In some cases, the same indicator variable can be used for monitoring multiple uses. For example, Secchi disk depth may be used as a compliance indicator for the value of clear water (aesthetic use) and habitat for aquatic life (biotic use) and as a detection indicator for the value of clean drinking water (water supply use).

Variables should be selected based on their ability to directly assess compliance with lake condition goals and detect future threats. The process of selecting indicators for compliance and detection may appear straightforward, but their selection requires careful consideration to ensure they meet the needs of current monitoring goals as well as long-term continuity and comparison with larger scale monitoring efforts (Niemi and McDonald 2004). Indicator selection may be constrained by factors such as cost, technical capabilities, regulatory requirements, and site access (Cairns et al. 1993, Larson et al. 2020). In addition, managers should consider using a range of detection indicators to capture potential threats not yet identified through the Community Engagement process. Niemi and McDonald (2004), and Larson et al. (2020) provide recommendations on factors to consider when selecting indicator variables.

M3) Set Target Conditions

Numerical targets, or target conditions, will be set for each of the compliance indicators defined in M2. In addition to the values identified through community engagement (C4), target conditions should consider what is technically feasible to achieve given land use in the watershed, historical reference conditions, and degree of anticipated compliance and implementation. Setting target conditions translates desired values into a shared image, and quantifies the restoration required to achieve that image. In some cases, desired values and benefits may reflect historical reference conditions, although they may also demand a different ecological quality than that of the past (Bouleau and Pont 2015). Numerical targets are often thought of in the context of pollution control, but they are also used to measure ecosystem integrity, such as a measure of the biological community. The details of how each indicator is quantitatively assessed to determine compliance may vary based on the nature of the indicator. Some indicators may be relatively simple to evaluate based on a numerical range of acceptable values, while other indicators may require more complex processes for assessment, such as multivariate analysis of community structure compared to reference sites with similar natural/desired characteristics or historical conditions.

Indicator variables for lake state, like chlorophyll *a* concentration (chl-*a*), Secchi disk depth, or nutrient concentrations are commonly used because they are relatively simple and can be easily monitored using established methods (Stefan et al. 1996, Rose et al. 2009, Markogianni et al. 2022). These variables are also less resource intensive than collecting detailed data on the biological community, such as phytoplankton community structure. Often, targets are set by laws or regulations that are reassessed periodically as monitoring continues and ecosystem conditions change. The European Water Framework Directive and Total Maximum Daily Loads (TMDLs), which are part of the US Clean Water Act, are examples that include mechanisms allowing for target condition to change as more data are collected and variability within the system is better understood.

M4) Collect Data and Monitor Detection and Compliance Indicators

Monitoring programs should be designed to specifically address the information needs of resource managers by tracking key indicator variables (M2) at representative sites. The definition of representative indicators and the scope of the monitoring program may vary greatly in terms of spatial and temporal resolution, depending on the nature and scale of the stressor in each lake. A monitoring program designed to evaluate ecosystem conditions for a relatively small-scale, site specific, and/or short-term restoration project will be different from a program designed to track average conditions over the long-term. Furthermore, monitoring different zones within a lake (e.g., nearshore vs. offshore) will require different sampling frequencies to assess indicator variables, depending on how much conditions vary in that zone. Once a thorough understanding of the inter-annual variation in monitoring parameters has been acquired, these data may also help managers identify emerging stressors.

Monitoring programs can be established according to a wide variety of sampling designs, depending on the goal and scope of the monitoring needs. For example, to routinely monitor the

Laurentian Great Lakes, both the US Environmental Protection Agency (EPA) Great Lakes National Program Office (GLNPO) and Environment and Climate Change Canada (ECCC) have established standardized long-term monitoring stations that are revisited at the same time(s) each year to monitor interannual variation and assess long-term trends in the offshore waters of the lakes. In these large water bodies, the agencies aim to track changes based on representative sites, rather than targeted monitoring of an area undergoing restoration. Good design, including considerations of statistical tests, is crucial to effective monitoring (Lindenmayer and Likens 2009). Random site selection may be most appropriate in instances where spatial autocorrelation for the indicator has been untested or expected to be low. In other cases where sampling sites are expected to have strong spatial relationships with each other, such as when monitoring a new invasive plant, spatially intensive field surveys that cover most areas of a lake may be required (Box 2). Understanding ecosystem function at an invaded site throughout the growing season may require sampling at greater temporal frequency than at a non-invaded site. Similarly, to monitor the ecosystem for specific parameters that occur over short and sometimes variable time periods (e.g., summer cyanobacteria blooms, storm runoff, or larval fish growth), the monitoring plan may need to provide greater flexibility to allow relatively short-term deployments and adaptation of sampling to local conditions, or *in situ* technologies may be useful to continuously monitor conditions at a small number of locations (e.g., in-stream monitoring).

M5) Assess the State of the Ecosystem

Once sufficient data have been collected for the detection and compliance indicators through monitoring activities, they will be analyzed to determine if lake conditions meet defined target conditions (M3), and ultimately fulfill the values identified through community engagement (C4). To help determine the state of the ecosystem, a quantitative assessment of whether key compliance indicators fall within the range defined for target conditions (M3) should be performed, and a synthesis of multiple indicator variables should be conducted. Once the monitoring plan is established, this step should also include an assessment of changes or trends since previous monitoring. Even if indicator variables are within target conditions, trends over time may indicate an early warning that variables are moving in an undesirable direction due to new or changing ecosystem stressors. Assessment of lake ecosystem state should be conducted periodically when sufficient new data are available to evaluate previously defined compliance and detection indicators (M2). This state of the ecosystem assessment is based on indicator thresholds combined with management objectives, as defined by community values and goals.

Assessment of ecosystem state based on detection and compliance indicators can be a complex process and it is common for some indicators to meet compliance criteria while others trend in the opposite direction. The State of the Great Lakes (SOGL) reporting process executed under the Great Lakes Water Quality Agreement (ECCC and USEPA 2022) accounts for these challenges partly by assessing general state (poor, fair, good) for many indicators based on targets set and direction of change for each indicator (deteriorating, unchanging, improving). In the SOGL reporting, a relatively large number of sub-indicators (40 for the 2022 report, ECCC and USEPA 2022) are combined to summarize data at the level of fewer (9) high-level indicators. These results are then used to inform managers and the public on the state of the lake ecosystem, both on a fine scale for specific indicators and on a coarser scale that considers a wide variety of ecosystem stressors. Inland lakes also can have state of the ecosystem reports, such as the Vermont, US, Lake Score Card, the US EPA’s National Lake Assessment Report (USEPA 2022), or watershed report cards.

Effective communication of the state of the lake ecosystem is a crucial step in the framework and requires accurate conveyance of the science while making it accessible and understandable to non-scientists in the public and policy making arenas. Reaching out directly to journalists can be a great way to reach a broader audience and make sure the assessment is communicated correctly (Likens 2010). Sometimes, a lag exists between when scientists find concerning trends and when it becomes feasible to implement remedial action. This lag can be caused by the time delay between scientific findings and public awareness, or by lobbying from private interest groups results in a lack of political support for remediation. A classic example is the lag between the discovery of acid rain in the US and the passage of the amendments to the US Clean Air Act (Grennfelt et al. 2020).

Box 2: Lake Management Example – the Monitoring Loop (M1–M5)

Previously defined reference conditions for aquatic plant communities in regional lakes indicated that the reference conditions for native plants in this lake would be 30% coverage in the littoral zone. Because the invasive plant was not previously present, the reference condition for this species is 0% cover **(M1)**. After reviewing indicators used in other lakes and best practices, community members decided on these detection and compliance indicators: % native and % invasive plant cover, presence/absence of the invasive plant, and TN and TP concentrations. The plant indicators are directly linked to the priority values defined in C4. The nutrient indicators were selected because changing concentrations were identified as a possible mechanism for an increase in the invasive plant **(M2)**. Based on the experience of recreational users in other lakes, community members agreed on a target range for the invasive plant of <1% cover. Because a priority value (C4) was to maintain fish habitat and protect native plants, the target range for native plants was set to 25–40% cover of the littoral zone. The target range for nutrient concentrations was set at +/- 10% of current concentrations **(M3)**. The RMA and LLA established a monitoring program. The RMA conducted annual transects to detect presence/absence of invasive plants, and quadrats along these transects to determine the % cover of all plants. The LLA organized training materials for distribution to angling and paddling groups, who were asked to monitor the presence/absence of invasive plants on an ad hoc basis. If invasive plants were detected, a photo was sent to the RMA for confirmation **(M4)**. Initial sampling determined that native plants covered an average 45% across all transects, TP and TN concentrations were 25 $\mu g\ L^{-1}$ and 600 $\mu g\ L^{-1}$, respectively, and the invasive plant was present in 4 of 10 transects and covered an average of 5% of the littoral zone. Additionally, recreational users detected the invasive plant at 5 locations outside of the sampling transects. The % cover of the invasive plant was outside the target range, so the community moved to the Restoring or Protecting Loop **(M5)**.

Restoring or Protecting Ecosystem State Loop (RP1–RP5)

If ecosystem state does not meet the values and priorities of community members (C4) or if potential threats have been identified during routine monitoring (M5), the Restoring or Protecting Ecosystem State Loop should be followed. The objectives of this loop are tri-fold: (1) identify stressors causing degradation, (2) remediate stressors that negatively impact community goals and priorities, and (3) prevent emerging stressors from progressing to the point where they impact the values and priorities identified through community engagement. We discuss prevention and restoration together because they require the same sequence of steps. Prevention is preferable to restoration because it is more cost effective, maintains continuity of ecosystem services, and reduces the impact of a threat before the damage is done (Spears et al. 2022).

A crucial part of the Restoring or Protecting Ecosystem State Loop is identifying the stressors that act on the lake condition variable of interest and to understand how those stressors will respond to management actions. The inability to do so will likely result in failed restoration. Stressors are first identified using diagnostic indicators (RP1), then modeled to determine their impacts on the lake (RP2). An effective management plan identifies remedial actions that will have the greatest impact on improving the lake condition and have the greatest chance for successful implementation (RP3). Maintaining strong community engagement during RP3 is an important way for managers to balance both factors (Osmond et al. 2019). After implementation of the preferred restoration option (RP4), re-evaluation is needed to determine whether the plan's actions are producing the intended outcomes (RP5). Newly acquired data and insights are important to verify that remedial actions are affecting the stressor as originally predicted, and to inform modifications to the plan if actions are not having the planned effects (Olsson and Folke 2001, Failing et al. 2013).

RP1) Identify Stressors with Diagnostic Indicators

If it is determined that the objectives and values identified during the community engagement process are not being met or are at risk of not being met soon (C4 or M5), the stressors causing this unacceptable or threatened ecosystem state must be identified. Stressors are identified using *diagnostic indicators* (Table 2), which are specific, measurable variables that represent the underlying causes of the degraded condition. Diagnostic indicators are characteristics of the environment that can be quantified to inform the cause and degree of an issue and are strategically selected by experts. Successful identification of the cause is important to ensure that restoration or prevention measures are well-targeted to areas that provide the greatest benefit to community values, while misidentifying the underlying stressor will cost time and resources and could erode public trust in the management process.

A detailed description of the selection of appropriate and effective diagnostic indicators can be found in Cairns et al. (1993). Aquatic ecosystems are complex and there are numerous factors that can contribute to ecosystem stress. A key part of selecting effective diagnostic indicators is ensuring that they describe why compliance and detection indicators are occurring outside the acceptable range identified in M3. It is important to set clear objectives about what the indicator is trying to identify (Niemi and McDonald 2004), and to select diagnostic indicators that reflect the spatial and temporal scales of the stressor (Boulton 1999). It is also important to select unbiased indicators. For example, when selecting a diagnostic indicator to determine the cause of declining water clarity as measured by Secchi disk depth, it is common to rely on the diagnostic indicators of chl-*a* or total suspended solids, whereas water color would be a more appropriate indicator if terrestrial derived sources of dissolved organic matter are the cause of the decline in water clarity

RP2) Model Stressor Action

A thorough understanding of the factors causing the undesirable ecosystem state is necessary to develop a successful management plan. Research into the identity and mode of action of the stressor causing the lake’s condition, as well as a list of potential sources of the stressor are required. Many threats to lake condition originate outside the lake, so it is important to consider how actions within the watershed, as well as its characteristics, influence the stressor being modeled. Modeling the stressor provides a quantitative tool for comparing different management plans and helps identify which measures may have the greatest effect on addressing the stressor. Managers must understand the mechanisms that influence the stressor and the magnitude of that impact. Creating or modifying existing models is a common method to achieve this understanding (Haith and Shoemaker 1987, Schneiderman et al. 2007). For example, the Generalized Watershed Loading Functions model used to estimate nitrogen and phosphorus inputs to streams (Haith et al. 1992) is often modified to provide estimates of nutrient loading in individual watersheds or regions (Schneiderman et al. 2007). If not enough technical capacity to create a new model or to modify an existing one exists, this step may be completed by a partnering organization or contracted out to paid consultants.

Failures in lake management are sometimes attributed to an incomplete understanding of the system (Sharpley et al. 2013, Osgood 2017). Ecosystem impacts can arise from co-occurring stressors (Craig et al. 2017), and it is important to quantify how the different stressors are likely to respond to restoration actions. The implementation of management practices can have unintended consequences if their impacts on stressors have not been modeled (Jarvie et al. 2017). Managers need to consider how multiple factors, particularly those within the watershed, influence the stressor and incorporate these into their models. Many model inputs may be acquired from monitoring activities in the lake (M4), but it can be difficult to acquire data for model inputs if sufficient monitoring data do not yet exist, or if they must be acquired from the terrestrial landscape. Publicly available datasets could fill some of these data gaps. For example, Gémesi et al. (2011) used LANDSAT imagery to link land cover and water quality, Woolway and Merchant (2019) used previously developed climate models to assess the impacts of climate change on lake mixing, and Rood et al. (2017) compared regulated and unregulated flow regimes using publicly available stream discharge data. Weather data, too, is widely available at high spatial and temporal resolutions. In other instances, modeling may require additional data collection. Robust datasets reduce model uncertainty and serve to test whether the causes of the stressor have been adequately captured (Williams and Brown 2016). Once the problem is thoroughly understood, management approaches can be developed to reduce the impact of the stressor (R3).

RP3) Assess or Develop Remedial or Regulatory Options

Restoration is enacted by public agencies using incentives and regulations, the private sector, and/or through collective action, and lake managers can come from any of these groups. RP3 requires engagement with participants from many different sectors, both to develop the list of potential options and to evaluate the magnitude of impact and probability of restoration success. At this step, the sustainability of proposed plans is an important consideration to ensure that environmental impacts are minimal and that the need for future action is low, which will help maximize the cost-effectiveness of the project (Tammeorg et al. 2023). The most successful plan may not always include the management actions that provide the greatest benefit if those actions are unlikely to be implemented. It is the responsibility of lake managers to pursue a strategy that has the greatest likelihood of addressing the problem, while also considering the likelihood of implementation by the various groups who impact and who are impacted by management decisions and regulations. For example, if modeling (R2) shows that reducing nutrient loading from agricultural runoff is a primary management goal, reducing fertilization on fields in the surrounding watershed may be the most effective solution. However, asking farmers to voluntarily reduce their rates of fertilization, and thus their yields and incomes, may not receive widespread adoption. Established relationships with local communities (C1–C4) are critical during this step.

There are numerous ways to evaluate which management actions will have the greatest remedial benefits. “Stakeholder surveys and workshops” in the Maumee River watershed, Ohio, US, helped managers better understand which best management practices would likely be accepted by farmers (Kalcic et al. 2016). Based on what they learned from these surveys and workshops, managers were able to refine their models and create a management plan for nutrient loading in the western basin of Lake Erie (Kalcic et al. 2016). Another way to implement the most effective remedial or regulatory options is to focus efforts on areas that will have the greatest impact. Management efforts may fail when they are not implemented at the watershed scale (Jarvie et al. 2017, Osmond et al. 2019), but by strategically targeting areas of high impact, restoration efforts can still have a greater net impact than if they were spread across a larger area. Land acquisitions (MILCC 1996), targeted restoration projects (Almendinger 1998), and addressing point source pollution (Cavalcanti et al. 1997) are all ways in which managers can focus management efforts in high impact areas. In some cases, collective action may be the most effective method of implementing remedial actions. Collective action is particularly promising in situations when traditional government regulation or private sector tools are not achieving desired outcomes (Ostrom 1992), or where government regulations are incompletely applied to lakes or watersheds that span political boundaries (Swallow et al. 2001). For example, the shift to a collective action model for fisheries management in Cambodia’s Tolne Sap Lake resulted in a more community driven fishery harvest in a lake located across numerous provincial jurisdictions (Ratner et al. 2014).

RP4) Implement Preferred Option

Once the preferred option(s) for restoration are assessed or developed, they need to be implemented. This process includes mechanisms for monitoring effectiveness (RP5) and identifying key restoration targets within a well-defined timeline. The targets will depend on the restoration plan established in RP3 and will help managers evaluate whether restoration is on track as time goes on. Depending on the lake stressor and the chosen plan, implementation may need to be planned for time scales ranging from less than a year to several decades. Implementation over longer time scales may be challenging because of changes in climate, land use, population, and politics. Therefore, an effective implementation plan will include both short- and long-term targets to ensure that the plan remains adaptable if necessary. It will also be necessary to determine who will implement the plan. Plan implementation will differ for every situation, but clearly defined objectives and roles should be established to ensure that all aspects of the plan are implemented. After implementation begins, it will be important to regularly assess the extent to which community members are following through on the plan so that adjustments can be made if implementation is below expectations.

To reduce the uncertainty and complexity of long-term plans, it may be helpful to periodically create a series of short-term plans to complement long-term goals (CRWD 2019). Short-term plans allow the long-term plan to adjust to potentially changing conditions or low effectiveness through rigorous monitoring and reporting. It is also important to prioritize the most important and achievable target objectives (MILCC 1996). For example, managers for Lake Shaokatan in Minnesota, US, identified a swine operation as a major source of nutrient pollution, determined that removal of the swine operation was achievable, and then prioritized its removal (MILCC 1996). In many cases, successful implementation depends on active and sustained community participation in the lake's watershed, and it is important to raise awareness of the issues, recruit local participants from a variety of groups, support relationship-building and integration among these different groups (Holifield and Williams 2019), and gage social acceptance of chosen measures (Heldt et al. 2016). As many community members may not have experience in lake management, promoting and sustaining recruitment is highly dependent on clearly outlining goals, expectations, and timelines early and often throughout the implementation process (Reed 2008).

RP5) Monitor Lake Response

Regular, ongoing monitoring of lake response to the implemented actions is necessary to ensure that the restoration or prevention target is attained and ultimately that values laid out in C3–C4 are achieved. Effectiveness can be assessed using data from monitoring conducted in M4, but additional parameters may be needed to specifically monitor the mechanism of action by the stressor and the restoration action. It is also important to compare the actual lake response to implemented actions with the predicted response (RP2) to verify that the stressor mechanisms have been correctly identified and modeled. The results obtained here should be summarized into a new state of the ecosystem report, which can be compared against the desired state. If the restoration actions were successful, management can return to the Monitoring Ecosystem State Loop. If the actions were unsuccessful or only partially successful, management will return to RP1 to evaluate additional restoration and prevention options.

Without regular monitoring, it is difficult to determine whether implemented strategies are having the desired effect on the lake. Instituting ongoing monitoring and reporting allows lake managers to evaluate restoration effectiveness, and ultimately determine whether management plans need to be adapted. While monitoring options in RP5 may be similar to those in M4, RP5 monitoring should be specific to the restoration and/or protection goals and the stressor. It is important for monitoring in this stage to evaluate both short-term (e.g., seasonal) and long-term trends to fully understand lake responses (Chapman 1996). Towards this goal, monitoring methods frequently used in lakes include the use of high-frequency sensors (Rose et al. 2016), satellite remote sensing (Palmer et al. 2015), and the establishment of community science monitoring programs (Thornhill et al. 2016). Considering multiple temporal and spatial scales enables managers to understand how lake processes and the stressor are responding to restoration measures. In addition to monitoring the lake's response, it is also important to assess public participation in the implementation process. Chidammodzi and Muhandiki (2015) used a combination of interviews, surveys, document reviews, and on-site observations to determine the level of awareness and involvement of key demographic groups in an ongoing management project in the Lake Malawi watershed. Understanding community participation in the management plan, and how it might be improved, is key to ensuring successful implementation.

Box 3: Lake Management Example – the Restoring and Protecting Loop (RP1–RP5)

Nutrient concentrations and boat traffic at the public launch were chosen as diagnostic indicators because of the invasive plant's biology and the likelihood that it was being introduced by boat fouling (**RP1**). The watershed characteristics indicated that plant growth in the lake was likely phosphorus limited. Regional managers modified an existing model to predict that decreasing phosphorus inputs would decrease growth of the invasive but not the native plants. Existing models of invasive plant spread suggested that increased boat traffic from other lakes would increase the likelihood of reinvasion (**RP2**). The community discussed several control options and proposed this plan based on feedback from C3 and subsequent meetings: for high-quality swimming and boating, locals agreed to manage the invasive plant in their swimming areas and around docks using benthic barriers or vacuum suctioning. The local chamber of commerce agreed to fund benthic barriers at the public boat launch. A local scuba club was recruited to hand-pull the invasive where native plant growth dominated. Because tourism was a priority value, community members decided not to restrict boat movement or implement a washdown station. The plan called for a reassessment after 3 years (**RP3**). The LLA agreed to help implement the plan as the contact for locals who wanted to hire contractors to apply benthic barriers or do vacuum suctioning. The group also held a yearly hand pulling "party" where participants were trained to identify the invasive and then go to designated areas to remove it. This social and educational event drew dozens of participants every year (**RP4**). The RMA continued the monitoring in M4. After 3 years, the % native cover had declined by 10% and the % invasive cover had increased by 10%, indicating that efforts were not sufficient to abate invasive plant growth to a level where community values were met. While the control methods in swimming areas and around docks were maintaining high-quality swimming and boating, the values of maintaining fish habitat and preserving native plants were threatened. Based on modeling done in **RP2**, a 20% phosphorus reduction was predicted to restrict the invasive growth and release the native plants from competition. A regional partnership applied for a grant to develop a watershed plan to reduce phosphorus. After the grant was funded, the group returned to the Community Engagement Axis to start the process again (**RP5)**.

Discussion

Lake condition across the globe remains poor and continues to deteriorate. In some instances, continued management has failed to restore degraded systems to desired thresholds (Osgood 2017), while in others, emerging contaminants (Reid et al. 2019) and/or increasing anthropogenic pressures (Vörösmarty et al. 2013, Settele et al. 2014) have caused the degradation of once high-quality systems. Sometimes, management and restoration can fail due to a lack of understanding of how actions will affect the ecosystem (Jonsson and Setzer 2014). Despite some management successes (Lettenmaier et al. 1991, Moore and Christensen 2009), the overall trend of lake condition has been worsening over past decades (UNEP 2016, Ho et al.

2019, Albert et al. 2021, USEPA 2022). One reason why lake management may be unsuccessful is that many regulations are reactionary, and restoration is not pursued until predetermined thresholds are exceeded, demarcating the lake as "impaired" (Zellmer and Glicksman 2013). Another reason may be that restoration efforts sometimes lack data and models crucial to understanding how the system will respond to restoration. For example, pools of unaccounted legacy phosphorus in agricultural soils are often the reason why efforts to curtail negative effects associated with eutrophication are unsuccessful (Sharpley et al. 2013). Furthermore, while restoration can result in short-term gains, long-term improvements are not always achieved if the underlying cause of impairment is not addressed (Mackay et al. 2014). The framework we propose is designed to improve lake management outcomes by including steps to maintain high quality resources, and to promote evidence-driven restoration. It relies on technical expertise to establish informative indicators, set realistic targets, and predict how management actions will impact lake stressors. Many lake management projects include members with technical expertise in one or more project areas. However, this expertise may not always extend to all aspects of a project, and managers must recognize these cases and seek out external partners to ensure that each step in the framework is completed from an informed standpoint. Consultants frequently have experience working in a wide range of conditions and can act as external partners to fill any knowledge gaps that may exist on the project team.

A critical tenant of the MoReCo framework is that effective community engagement is crucial to successful management outcomes. Since the 1990s, interest in "stakeholder engagement" in environmental management has grown, as part of a wider shift away from top-down management styles and toward collaborative approaches to governance and knowledge production that recognize the value of lay expertise and joint decision-making (Irwin 1995, Nowotny et al. 2003, Jasanoff 2003, Fitchett et al. 2020). Although the term "stakeholder engagement" has conventionally been used to refer to formal and informal collaboration with actors or groups who either impact or are impacted by lake management decisions, we recognize there are other groups who have relationships with management agencies that are more complex and nuanced than can be captured by the term "stakeholder." Several objections have been made to the term "stakeholder," based on its colonialist linguistic origins and underlying assumptions that all actors involved are on a level playing field, which may obscure the underlying power dynamics involved in environmental management strategies that rely on public participation mechanisms (Cooke and Kothari 2001, Sharfstein 2016). Furthermore, these assumptions may ignore the power imbalances which can exist when multiple types of actors and social groups are lumped together under one term or in one type of engagement process, even if they do not have the same degree of potential influence on management outcomes (CDC 2022).

For instance, in countries with Indigenous peoples who have constitutionally protected rights and are distinct legal relationship with the state, the term "stakeholder" has particularly negative connotations (Government of British Columbia 2023), because Indigenous peoples are more accurately considered to be "rights-holders" (Darling et al. 2023). When working with Indigenous communities on environmental management issues, managers will need to go beyond the general community engagement mechanisms that we describe in our framework, and familiarize themselves with the specific requirements and best practices for engagement and consultation with the groups and nations that exist in or near their regions, as well as the cultures and ways of reading the environment which are specific to the communities in question (McGregor 2008, Wilson and Inkster 2018, McGregor et al 2020). The problems that arise related to public participation in environmental management cannot be solved by an adjustment to terminology alone, since they point to deeper challenges that arise when engaging diverse publics in management decisions. Nevertheless, terminology is important, because terms like "stakeholder" have connotations which may contribute to fostering distrust (University of British Columbia 2023).

Potential Challenges of the MoReCo Framework

Our framework is designed for anyone practicing lake management and we regard it as an egalitarian tool for users such as government agencies, lake associations, private consultants, and grassroots advocates. While we believe the participatory nature of the framework is largely a strength (Reed et al. 2018), community engagement can be time consuming, expensive, and difficult to operationalize, potentially generating new sources of conflict that lead to delays in action or dissatisfaction among participants (Reed 2008, Luyet et al. 2012). One potential source of frustration is "consultation fatigue," which occurs when community members feel that their involvement is not yielding desired outcome and become tired of the ongoing requests to engage in participatory processes (Reed 2008). In addition, participants may face barriers to engagement, including a lack of time, awareness, interest, and funding, while sustained participation may wax and wane over time based on the perceived urgency of the issue (Holifield and Williams 2019).

We anticipate potential challenges emerging over the lack of leadership structure within the MoReCo framework. Participatory forums and engagement mechanisms can subvert existing decision-making processes, especially when some participants have veto power, and may overrule decisions that have been made through participatory mechanisms (Reed 2008), or when community-identified priorities conflict with regulatory mandates. Levels of engagement and opportunities for community members to influence decision-making vary depending on the context, design, power, and scale of each management issue, making it important to create transparency about how decisions are made, how responsibilities are delegated, and how power is distributed. Additionally, although this framework provides a general structure to lake management, each step includes flexibility about which models and monitoring options to pursue. Therefore, it is imperative that leadership possess sufficient knowledge to either make these decisions themselves, or to ensure that proper parties are consulted at each step. Strong partnerships with knowledgeable groups and individuals, such as consultants, are one way of helping to ensure that expertise is present during the decision-making process.

Although not unique to our framework, community engagement processes have been criticized for failing to integrate diverse or marginalized social groups. In short, public engagement is shaped by social power and may therefore reproduce social inequalities (Lewenstein 2022). Community science, a common mechanism to operationalize public engagement in lake management, has been characterized by participation inequality (Haklay 2013), and diverse communities are not always engaged with or represented in participatory environmental monitoring programs (Pandya 2012, Pateman et al. 2021). For instance, community-based lake monitoring programs may disproportionally attract more white, affluent, and highly educated demographics (Blake et al. 2020), or may be spatially biased towards geographic regions that are outside urban areas but within a reasonable driving distance from major cities (Millar et al. 2019).

Marginalized communities may face additional barriers to engagement, including language barriers, communication styles, cultural integration, inattentiveness to community needs, differences in recreational priorities related to water resources, lack of decision-making power, and the complex and often uncoordinated nature of water management and authorities (Pradhananga et al. 2019). Strategies for overcoming barriers to participation include building relationships with participants, designing support structures for participants, accounting for participant access to time and technology, and empowering communities to define problems (Davis et al. 2020). While our framework for “community engagement” is intended to be broadly inclusive of many forms of collaborative relationships between the public and environmental managers, we also recognize that there is no “one size fits all” approach to community engagement. Engaging with different types of groups and community members will involve varying degrees of attention and effort, and building trusting relationships with marginalized communities will involve more significant investments in time and resources (Davis and Ramirez-Andreotta 2021). Doing so involves the cultivation of strong partnerships with communities, and in cases where lake managers are working with marginalized communities, it can be beneficial to hire community members as engagement staff and to create data reports for community members which are ‘translated’ into community-oriented language and learning, as well as information on opportunities for further involvement by community members (Davis and Ramirez-Andreotta 2021).

Funding can also be a challenge, as our framework does not contain a formal step for resource acquisition. Engagement mechanisms require funding, expertise, and facilitator skill (Reed 2008, Holifield and Williams 2018, Eaton et al. 2021). Environmental monitoring (M4 and RP5) is expensive and can fail without continued financial support (Lindenmayer and Likens 2009). Data analysis (RP2) and report preparation (M5) require time and personnel. Restoration activities (RP3–RP4) can be expensive and highly variable depending on type of restoration, project size, and restoration area. Long-term plans to restore entire lakes can take years to decades (Søndergaard et al. 2007, Nikraftar et al. 2021) and cost billions of US dollars (He et al. 2015), although smaller, individual projects can cost in the order of hundreds of thousands of US dollars (Huser et al. 2016). Funding and support are necessary for lake management and must be considered despite not being explicitly addressed in the MoReCo framework.

Strengths of the MoReCo Framework

The MoReCo framework builds on existing management frameworks by incorporating elements that have proven effective in the past (Table 4). We see five important strengths that make the MoReCo framework useful for almost any type of lake management. First, the framework is designed specifically for lentic systems and the unique management challenges associated with them. Some existing natural resource management frameworks have been applied to lakes, such as the DPSIR framework (Svarstad et al. 2008) and adaptive management (Table 4), but broadly applicable frameworks risk oversimplifying complex interactions that may be unique to aquatic systems (Gari et al. 2015).

Second, community engagement is a major tenant of the MoReCo framework. Community goals and values are identified early and informed by the best available scientific knowledge. The emphasis placed on community input is consistent with the global trend of considering nature's values from numerous and diverse perspectives (Pereira et al. 2020), and these values are then considered throughout each subsequent step. Community engagement can support public buy-in for management decisions by reducing conflict, fostering trust, building community capacity, and facilitating learning (Reed et al. 2018, Millar et al. 2023). Ultimately, community buy-in can lead to better preservation of ecological integrity, and improved delivery of ecosystem services (Eaton et al. 2021).

While many discussions of “stakeholder engagement” in lake management focus on passive engagement through questionnaires (Shackleton et al. 2019), our framework identifies opportunities and mechanisms for active participation and multi-directional knowledge flows. Furthermore, our framework builds on existing “stakeholder engagement” theory to move beyond a “one size fits all” approach to co-designing and co-implementing management plans, and instead proposes choosing modes of community engagement best suited to the local contexts, issues, and scales (Table 1; Reed et al. 2018). While other management frameworks often acknowledge the importance of engaging with the public, they typically lack details on the range of approaches and mechanisms for operationalizing engagement. Our goal is to provide lake managers with a knowledge base and additional resources to effectively incorporate community engagement as they work through the MoReCo framework.

A third strength is the focus on setting explicit benchmarks for guiding management actions and defining success. These benchmarks are established in M3 based on prioritized values identified during the community engagement process. They are explicitly quantified through detection and compliance indicators and informed by data collected from both the system being managed as well as reference ecosystems (M Loop). Benchmarks are not static but can be updated as the understanding of stressor response grows, and as managers determine which actions are most feasible to implement (RP Loop). Target benchmarks help determine when restoration should begin and when restoration and protection should be considered successful. Furthermore, targets can be used to determine pathways towards success, based on narrative or quantitative scenario analysis (e.g., Haasnoot et al. 2013). Furthermore, the process for setting benchmarks is well-defined and transparent, reducing ambiguity about which party gets to define success. Explicit benchmarks are sometimes missing from existing frameworks

(Table 4), despite their usefulness in establishing baseline conditions, identifying trends, and evaluating whether management strategies are working (Hawkins et al. 2010).

A fourth strength of the MoReCo framework is the ability to manage multiple stressors simultaneously. The existence of emerging stressors (Reid et al. 2019) and the fact that lakes concentrate pollutants from the landscape (Williamson et al. 2009) mean that it is often necessary to address multiple stressors at once to restore degraded systems and maintain lake condition. However, frameworks and management plans that address multiple stressors remain uncommon (Table 4; Spears et al. 2021). The MoReCo framework includes several elements that can lead to more effective management of multiple stressors. For example, the focus on community engagement means all concerns about water quality can be identified during the application of the framework. Similarly, the robust Monitoring Loop provides data that can support restoration efforts for different stressors simultaneously.

Finally, the MoReCo framework recognizes that lake management is a continuous process and must occur even without an identified stressor. As such, the framework is not unidirectional, unlike other management plans that emphasize sequential steps (Table 4; Berkes 2000, Ansell and Gash 2008, Vaes et al. 2009). Instead, concurrent loops mean that managers can begin at any step, which provides mechanisms to constantly re-evaluate priority values, identify stressors early, and address them before they become unmanageable. In some instances, it may be appropriate for managers to move back and forth between steps. The iterative nature incorporates some elements of adaptive management (Williams and Brown 2016). Its holistic approach and flexibility set the MoReCo framework apart and make it suitable for addressing both current stressors and emerging threats, such as those brought on by climate change, that have not yet been identified.

Vision for Future Application of the MoReCo Framework

We envision the MoReCo framework as a tool for those involved in lake management and intend for it to be relevant for all lakes across the globe, regardless of characteristic or condition. A rapidly changing climate and emerging stressors continue to threaten lakes, and we believe this framework can aid in the preparation for and adaptation to these changes. While lake management often falls to the government, agencies are unable to comprehensively manage every lake under their jurisdiction. Therefore, in addition to government agencies, we see lake associations and consultants as common end users of this framework. Collective action has also been identified as an effective means of managing natural resources (Ostrom 1992), and we believe the MoReCo framework can be used by anyone who sees that a lake ecosystem is under threat. At its core, the MoReCo framework is an egalitarian tool designed to empower concerned community members interested in promoting healthy lake ecosystems. An important next step will be to evaluate the MoReCo framework's implementation to real-world lake management examples. This is true for upcoming projects as the framework begins to be used, but future work should also focus on how application of the MoReCo framework could have benefited past lake management case studies.

Acknowledgements

Work presented here benefited from participation in the Global Lake Ecological Observatory Network (GLEON). This manuscript came about from discussions in the Lake and Reservoir Management working group at the GLEON 21 meeting in Huntsville, Ontario, CA, and grew legs at the GLEON 21.5 virtual meeting. Thanks to all who participated in discussions related to this framework at those meetings, especially A. Scofield and J. Hejzlar. Your thoughts and ideas were instrumental in shaping the MoReCo framework and this manuscript. A special thank you also goes to K.M. Somers, G. Mierle, and P.J. Dillon who, along with N. Yan, originally developed the predecessor of the MoReCo framework in 1995 for the Ontario Ministry of Environment and Energy. This project would not exist without your original idea and we are incredibly grateful to your willingness to share it with us. We also thank Gunn (1995), Dodson (2005), and Myers and Bazely (2003) who, many years ago, saw the promise of the original framework and liked it enough to include it in their books. Finally, we would like to thank the associate editor and three reviewers whose questions, comments, and suggestions led to a much-improved final manuscript.

EEM received funding support from the Geoffrey F. Bruce Fellowship in Canadian Freshwater Policy. LK is funded by the Dutch Research Council (NWO) under grant number 645.002.002. DvW was supported by the Wageningen Institute for Environment and Climate Research (WIMEK) [Grant number 5160957732]; and the WGS Graduate Programme of Wageningen University & Research [Grant number 5100000470]. M. Paule-Mercado's funding is from Czech Science Foundation project (23-07152S), Norway Grants and the Technology Agency of the Czech Republic within the KAPPA Programme (TO01000202) and ERDF/ESF Project Biomanipulation (CZ.02.1.01/0.0/0.0/16_025/0007417). ST was funded through the 2020-2021 Biodiversa and Water JPI joint call for research proposals, under the BiodivRestore ERA-Net COFUND programme, and with the funding organisations: German Federal Ministry of Education and Research; Agencia Estatal de Investigación; Ministry of Agriculture, Nature and Food Quality of the Netherlands.

Author Contribution Statement

The original idea for this framework was by NDY. The manuscript was developed from discussions about the ideas and concepts of the framework that occurred between all co-authors. JCG, JLK, KCM, EEM, LK, MCAPM, and KF developed the manuscript's structure and organization, and JCG, JLK, KCM, EEM, DJW, MCAPM, KF, and MRG wrote the manuscript. JCG, JLK, KCM, EEM, DvW, MCAPM, MRG, and EMM contributed to literature review. JCG, JLK, KCM, EEM, DJW, LK, and DvW contributed to the creation of figures and tables. All authors provided edits and comments to drafts of the manuscript and approved the submitted version.

Disclosure Statement

The authors report there are no competing interests to declare.

References

Aceves-Bueno E, Adeleye AS, Bradley D, Brandt WT, Callery P, Feraud M, Garner KL, Gentry R, Huang Y, McCullough I, Pearlman I, Sutherland SA, Wilkinson W, Yang Y, Zink T, Anderson SE, Tague C. 2015. Citizen science as an approach for overcoming insufficient monitoring and inadequate stakeholder buy-in in adaptive management: criteria and evidence. Ecosystems. 18:493–506.

Adler RW. 2010. Resilience, restoration, and sustainability: revisiting the fundamental principals of the Clean Water Act. Wash Univ J Law Pol. 32:139–173.

Albert JS, Destouni G, Duke-Sylvester SM, Magurran AE, Oberdorff T, Reis RE, Winemiller KO, Ripple WJ. 2021. Scientists' warning to humanity on the freshwater biodiversity crisis. Ambio. 50:85–94.

Almendinger JE. 1998. A method to prioritize and monitor wetland restoration for water-quality improvement. Wetl Ecol and Manag. 6:241–251.

[AWWA] American Water Works Association. 2016. Cyanotoxins in US drinking water: occurrence, case studies and state approaches to regulation. Denver (CO).

Andreen, WL. 2007. Motivating enforcement: institutional culture and the Clean Water Act. Pace Environ Law Rev. 24:67–98.

Andreen WL. 2013. Success and backlash: the remarkable (continuing) story of the Clean Water Act J Energ Environ Law. 25:25–37.

Ansell C, Gash A. 2008. Collaborative governance in theory and practice. J Pub Adm Res Theory. 18:543–571.

Arhonditsis GB, Neumann A, Shimoda Y, Kim DK, Dong F, Onandia G, Yang C, Javed A, Brady M, Visha A, Ni F, Cheng V. 2019. Castles built on sand or predictive limnology in action? Part A: evaluation of an integrated modeling framework to guide adaptive management implementation in Lake Erie. Ecol Inform. 53:100968.

Armstrong M, Kramer L, de Senerpont Domis LN, van Wijk D, Gsell AS, Mooij WM, Teurlincx S. 2021. Flipping lakes: explaining concepts of catchment-scale water management through a serious game. Limnol Oceanogr-Meth. 19:443–456.

Bacigalupi J, Staples DF, Treml MT, Bahr DL. 2021. Development of fish-based indices of biological integrity for Minnesota lakes. Ecol Indic. 125:107512.

Barnhart BL, Golden HE, Kasprzyk JR, Pauer JJ, Jones CE, Sawicz KA, Hoghooghi N, Simon M, McKane RB, Mayer PM, Piscopo AN, Ficklin DL, Halama JJ, Pettus PB, Rashleigh B. 2018. Embedding co-production and addressing uncertainty in watershed modeling decision-support tools: successes and challenges. Environ Monit Assess. 109:368–379.

Becker ME, Becker TJ, Bellucci CJ. 2018. Diatom tolerance metrics to identify total phosphorus as candidate cause of aquatic life impairment in Connecticut, USA freshwater streams. Ecol Indic. 93:638–646.

Bendtsen EB, Clausen LPW, Hansen SF. 2021. A review of the state-of-the-art for stakeholder analysis with regard to environmental management and regulation. J Environ Manage. 279:111773.

Bennion H, Battarbee RW, Sayer CD, Simpson GL, Davidson TA. 2010. Defining reference conditions and restoration targets for lake ecosystems using palaeolimnology: a synthesis. J Paleolimnol. 45:533–544.

Bennion H, Kelly MG, Juggins S, Yallop ML, Burgess A, Jamieson J, and Krokowski, J. 2014. Assessment of ecological status in UK lakes using benthic diatoms. Freshw Sci. 33:639–654.

Berkes F, Colding J, Folke C. 2000. Rediscovery of traditional ecological knowledge as adaptive management. Ecol Appl. 10:1251–1262.

Blake C, Rhanor A, Pajic C. 2020. The demographics of citizen science participation and its implications for data quality and environmental justice. Citiz Sci Theory Pract. 5:21.

Blocksom KA, Kurtenbach JP, Klemm DJ, Fulk FA, Cormier SM. 2002. Development and evaluation of the lake macroinvertebrate integrity index (LMII) for New Jersey lakes and reservoirs. Environ Monit Assess. 77:311–333.

Bouleau G, Pont D. 2015. Did you say reference conditions? Ecological and socio-economic perspectives on the European Water Framework Directive. Environ Sci Policy. 47:32–41.

Boulton AJ. 1999. An overview of river health assessment: philosophies, practice, problems and prognosis. Freshwater Biol. 41:469–479.

Bourne L. 2022. The stakeholder circle; [cited 22 July 2022]. Available from http://www.stakeholdermapping.com/stakeholder-circle-methodology/

Bucchi M. 2009. Beyond technocracy: science, politics and citizens. New York (NY): Springer.

Cairns J, McCormick PV, Niederlehner BR. 1993. A proposed framework for developing indicators of ecosystem health. Hydrobiologia. 263:1–44.

[CRWD] Capitol Region Watershed District. 2019. Como Lake management plan. St. Paul (MN): prepared by LimnoTech.

Carpenter SR, Stanley EH, Vander Zanden J. 2011. State of the world's freshwater ecosystems: physical, chemical, and biological changes. Annu Rev Env Resour. 36:75–99.

Cavalcanti CGB, Pinto MT, de Freitas HJ, Moreira RCA. 1997. Paranoá Lake restoration: impact of tertiary treatment of sewage in the watershed. Int Ver The. 26:689–693.

[CDC] Center for Disease Control and Prevention. 2022. Inclusive communication principals; [cited 11 Jan 2023]. Available from https://www.cdc.gov/healthcommunication/Health_Equity.html

Chapman D. 1996. Water quality assessments: a guide to the use of biota, sediments and water in environmental monitoring. 2nd ed. London (UK): CRC Press.

Chidammodzi CL, Muhandiki VS. 2015. Development of indicators for assessment of Lake Malawi Basin in an Integrated Lake Basin Management (ILBM) framework. Int J Commons. 9:209–236.

Colvin RM, Witt GB, Lacey J. 2016. Approaches to identifying stakeholders in environmental management: insights from practitioners to go beyond the ‘usual suspects’. Land Use Policy. 52:266–276.

Conrad CT, Daoust T. 2008. Community-based monitoring frameworks: increasing the effectiveness of environmental stewardship. Environ Manage. 41:358–366.

Cooke B, Kothari U, editors. 2001. Participation: The new tyranny? 5th ed. New York, NY: Zed Books.

Creed R, Baily B, Potts J, Bray M, Austin R. 2018. Moving towards sustainable coasts: a critical evaluation of a stakeholder engagement group successfully delivering the mechanism of adaptive management. Mar Policy. 90:184–193.

Craig LS, Olden JD, Arthington AH, Entrekin S, Hawkins CP, Kelly JJ, Kennedy TA, Maitland BM, Rosi EJ, Roy AH, Strayer DL, Tank JL, West AO, Wooten MS. 2017. Meeting the challenge of interacting threats in freshwater ecosystems: a call to scientists and managers. Elem Sci Anth. 5:72.

Darling S, Harvey B, Hickey GM. 2023. From ‘stakeholders’ to rights holders: How approaches to impact assessment affect indigenous participation in the Yukon Territory, Canada. Environ Impact Assess. 99:107025.

Davis LF, Ramírez-Andreotta MD, Buxner SR. 2020. Engaging diverse citizen scientists for environmental health: recommendations from participants and *promotoras*. Citiz Sci Theory Pract. 5:1–27.

Davis LF, Ramírez-Andreotta MD. 2021. Participatory research for environmental justice: a critical interpretive synthesis. Environ Health Persp. 129:026001-1–026001-20.

Dickinson JL, Shirk J, Bonter D, Bonney R, Crain RL, Martin J, Phillips T, Purcell K. 2012. The current state of citizen science as a tool for ecological research and public engagement. Front Ecol Environ. 10:291–297.

Dodds WK, Carney E, Angelo RT. 2006. Determining ecoregional reference conditions for nutrients, Secchi depth and chlorophyll *a* in Kansas lakes and reservoirs. Lake Reserv Manage. 22:151–159.

Dodson S. 2005. Introduction to limnology. New York (NY): McGraw-Hill.

Eaton WM, Brasier KJ, Burbach ME, Whitmer W, Engle EW, Burnham M, Quimby B, Chaudhary AK, Whitley H, Delozier J, Fowler LB, Wutich A, Bausch JC, Beresford M, Hinrichs CC, Burkhart-Kriesel C, Preisendanz HE, Williams C, Watson J, Weigle J. 2021. A conceptual framework for social, behavioral, and environmental change through stakeholder engagement. Soc Natur Resour. 34:1111–1132.

[ECCC and USEPA] Environment and Climate Change Canada and the US Environmental Protection Agency. 2022. State of the Great Lakes 2022 report: an overview of the status and trends of the Great Lakes ecosystem. EPA 905-R-22-004.

Environment Canada. 1972. Guidelines for water quality objectives and standards. Ottawa (CA): Technical Bulletin No. 67.

Failing L, Gregory R, Higgins P. 2013. Science, uncertainty, and values in ecological restoration: a case study in structured decision-making and adaptive management. Restor Ecol. 21:422–430.

Few R, Brown K, Tompkins EL. 2011. Public participation and climate change adaptation: avoiding the illusion of inclusion. Clim Policy. 7:46–59.

Fitchett LL, Sorice MG, Cobourn KM, Boyle KJ, Klug JL, Weathers KC. 2020. Pathways to enhanced lake integrity: a framework to assess the effectiveness of local lake associations. Lakes Reservoirs. 25:258–268.

Gari SR, Newton A, Icely JD. 2015. A review of the application and evolution of the DPSIR framework with an emphasis on coastal social-ecological systems. Ocean Coast Manage. 103:63–77.

Gémesi Z, Downing JA, Cruse RM, Anderson PF. 2011. Effects of watershed configuration and composition on downstream lake water quality. J Environ Qual. 40:517–527.

Gibson GR, Bowman ML, Gerritsen J, Snyder BD. 2000. Estuarine and coastal marine waters: bioassessment and biocriteria technical guidance. Washington (DC): EPA 822-B-00-024.

Government of British Columbia (2023) *Terminology in Indigenous context.* Available at: https://www2.gov.bc.ca/gov/content/governments/services-for-government/service-experience-digital-delivery/web-content-development-guides/web-style-guide/writing-guide-for-indigenous-content/terminology (Accessed 5 Sep 2023)

Green OO, Gamestani AS, Van Rijswick HFMW, Keessen AM. 2013. EU water governance: striking the right balance between regulatory flexibility and enforcement? Ecol Soc. 18:10.

Grennfelt P, Engleryd A, Forsius M, Hov Ø, Rodhe H, Cowling E. 2020. Acid rain and air pollution: 50 years of progress in environmental science and policy. Ambio. 49:849–864.

Gunn JM. 1995. Restoration and recovery of an industrial region: progress in restoring the smelter-damaged landscape near Sudbury, Canada. New York (NY): Springer-Verlag.

Haasnoot M, Kwakkel JH, Walker WE, ter Maat J. 2013. Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. Global Environ Chang. 23:485–498.

Haklay M. 2013. Citizen science and volunteered geographic information: overview and typology of participation. In: Sui D, Elwood S, Goodchild M, editors. Crowdsourcing geographic knowledge. London (UK): Springer, Dordrecht. p. 105–122.

Haith DA, Shoemaker LL. 1987. Generalized watershed loading functions for stream flow nutrients. J Am Water Resour As. 23:471–478.

Haith DA, Mandel R, Wu RS. 1992. GWLF: generalized watershed loading functions. Version 2.0, User's Manual. Department of Agricultural and Biological Engineering, Cornell University, Ithaca (NY).

Hawkins CP, Olson JR, Hill RA. 2010. The reference conditions: predicting benchmarks for ecological and water-quality assessments. J N Am Benthol Soc. 29:312–343.

He J, Sun X, He J. 2015. Spatial disparities of the willingness of the residents to pay for the wetland restoration of Taihu Lake and its integration into decision making: a case study on Wuxi, China. Environ Monit Assess. 187:492.

Hecker S, Haklay ME, Bowser A, Makuch Z, Vogel J, Bonn A. 2018. Citizen science. London (UK): UCL Press.

Heink U, Kowarik I. 2010. What are indicators? On the definition of indicators in ecology and environmental planning. Ecol Indic. 10:584–593.

Heldt S, Budryte P, Ingensiep HW, Techgräber B, Schneider U, Denecke M. 2016. Social pitfalls for river restoration: how public participation uncovers problems with public acceptance. Environ Earth Sci. 75:1053.

Huser BJ, Futter M, Lee JT, Perniel M. 2016. In-lake measures for phosphorus control: the most feasible and cost-effective solutions for long-term management of water quality in urban lakes. Water Res. 97:142–152.

Ho JC, Michalak AM, Pahlevan N. 2019. Widespread global increase in intense lake phytoplankton blooms since the 1980s. Nature. 574.7780:667–670.

Holifield R, Williams KC. 2019. Recruiting, integrating, and sustaining stakeholder participation in environmental management: a case study from the Great Lakes Areas of Concern. J Environ Manage. 230:422–433.

[ILEC] International Lake Environment Committee Foundation. 2005. Managing lakes and their basins for sustainable use: a report for lake basin managers and stakeholders. Kusatsu (Japan).

Irwin A. 1995. Citizen science: a study of people, expertise and sustainable development. London (UK): Routledge.

Jarvie HP, Johnson LT, Sharpley AN, Smith DR, Baker DB, Bruulsema TW, Confesor R. 2017. Increased soluble phosphorus loads to Lake Erie: unintended consequences of conversation practices? J Environ Qual. 46:123–132.

Jasanoff S. 2003. Technologies of humility: citizen participation in governing science. Minerva. 41:223–244.

Jenny J-P, Anneville O, Arnaud F, Baulaz Y, Bouffard D, Domaizon I, Bocaniov SA, Chèvre N, Dittrich M, Dorioz J-M, Dunlop ES, Dur G, Guillard J, Guinaldo T, Jacquet S, Jamoneau A, Jawed Z, Jeppesen E, Krantzberg G, Lenters J, Leoni B, Meybeck M, Nava V, Nõges P, Patelli M, Pebbles V, Perga M-E, Rasconi S, Ruetz III CR, Rudstam L, Salmaso N, Sapna S, Straile D, Tammeorg O, Twiss MR, Uzarski DG, Ventelä, Vincent WF, Wilhelm SW, Wängberg S-Å, Weyhenmeyer GA. Scientists' warning to humanity: rapid degredation of the world's largest lakes. J Great Lakes Res. 46:686–702.

Jonsson T, Setzer M. 2014. A freshwater predator hit twice by the effects of warming accross trophic levels. Nat Commun. 6:5992.

Kalcic MM, Kirchhoff C, Bosch N, Muenich RL, Murray M, Gardner JG, Scavia D. 2016. Engaging stakeholders to define feasible and desirable agricultural conservation in Western Lake Erie watersheds. Environ Sci Technol. 50:8135–8145.

Kuiper JJ, van Wijk D, Mooij WM, Remme RP, Peterson GD, Karlsson-Vinkhuyzen S, Mooij CJ, Leltz GM, Pereira LM. 2022. Exploring desirable nature futures for National Park Hollandse Duinen. Ecosyst People. 18:329–347.

Larson DC, Helstab M, Docker MF, Bangs B, Clemens BJ. 2020. Landlocked Pacific lamprey *Entosphenus tridentatus* in the Middle Fork Willamette River, Oregon. Environ Biol Fish. 103:291–298.

Lawson DM, Hall KR, Yung L, Enquist CAF. 2017. Building translational ecology communities of practice: insights from the field. Front Ecol Environ. 15:569–577.

Lettenmaier DP, Hooper ER, Wagoner C, Faris KB. 1991. Trends in stream quality in the continental United States, 1978–1987. Water Resour Res. 27:327–339.

Lewenstein BV. 2022. Is citizen science a remedy for inequality? Ann Am Acad Polit SS. 700:183–194.

Likens, G. 2010. The role of science in decision making: does evidence-based science drive environmental policy? Front Ecol Environ. 8:e1–e9.

Lindenmayer DB, Likens GE. 2009. Adaptive monitoring: a new paradigm for long-term research and monitoring. Trends Ecol Evol. 24:482–486.

Lopes FA, Davies-Colley R, Piazi J, Silveira JS, Leite AC, Lopes NIA. 2020. Challenges for contact recreation in a tropical urban lake: assessment by a water quality index. Environ Dev Sustain. *22*:5409–5423.

Luyet V, Schlaepfer R, Parlange MB, Buttler A. 2012. A framework to implement stakeholder participation in environmental projects. J Environ Manage. 111:213–219.

Mackay EB, Maberly SC, Pan G, Reitzel K, Bruere A, Corker N, Douglas G, Egemose S, Hamilton DP, Hatton-Ellis T, Huser BJ, Li W, Meis S, Moss B, Lürling M, Phillips G, Yasseri S, Spears BM. 2014. Geoengineering in lakes: welcome attraction or fatal distraction? Inland Waters. 4:349–356.

Markogianni V, Kalivas D, Petropoulos GP, Dimitriou E. 2022. Modeling of Greek lakes water quality using earth observation in the framework of the Water Framework Directive (WFD). Remote Sens-Basel. 14:739.

McGregor D, Whitaker S, Sritharan M. 2020. Indigenous environmental justice and sustainability. Curr Opin Env Sust. 43:35–40.

McGregor D. 2008. Anishnaabe-kwe, traditional knowledge and water protection. Canadian Woman Studies/les cahiers de la femme. 26:26–30.

Millar EE, Hazell EC, Melles SJ. 2019. The ‘cottage effect’ in citizen science? Spatial bias in aquatic monitoring programs. Int J Geogr Inf Sci. 33:1612–1632.

Millar EE, Melles S, Klug JL, Rees T. 2023. Stewarding relations of trust: citizen scientist perspectives on fostering community trust in science. Environ Sociol. 9:31–50.

[MILCC] Minnesota Interagency Lakes Coordinating Committee. 1996. Developing a lake management plan. St. Paul (MN).

Moore BC, Christensen D. 2009. Newman Lake restoration: a case study. Part 1. Chemical and biological responses to phosphorus control. Lake Reserv Manage. 25:337–350.

Moshi HA, Kimirei I, Shilla D, O'Reilly C, Wehrli B, Ehrenfels B, Loiselle S. 2022. Citizen scientist monitoring accurately reveals nutrient pollution dynamics in Lake Tanganyika coastal waters. Environ Monit Assess. 194:689.

Mikulyuk A, Barton M, Hauxell J, Hein C, Kujawa E, Minahan K, Nault M, Oele DL, Wagner KI. 2017. A macrophyte bioassessment approach linking taxon-specific tolerance and abundance in north temperate lakes. J Environ Manage. 199:172–180.

Muhandiki VS, Chidammodzi CL, Dumba N. 2014. The six pillars of integrated lake basin management: insights from Lakes Chivero and Malawi/Nyasa. J Hum Environ Syst. 25:63–71.

Myers JH, Bazely D. 2003. Ecology and control of introduced plants. Cambridge (UK): Cambridge University Press.

Nakatsuka N, Kosaka S, Taki K, Nakamura M, Nakagawa H. 2020. Better governance for integrated management of the Lake Biwa-Yodo River Basin. Lakes Reserv. 25:93–104.

Newcombe R. 2003. From client to project stakeholders: a stakeholder mapping approach. Constr Manag Econ. 21:841–848.

Niemi GJ, McDonald ME. 2004. Application of ecological indicators. Annu Rev Ecol Evol S. 35:89–111.

Nikraftar Z, Parizi E, Mossa Hosseini S, Ataie-Ashtiani B. 2021. Lake Urmia restoration success story: a natural trend or a planned remedy? J Great Lakes Res. 47:955–969.

Nowotny H, Scott P, Gibbons M. 2003. Introduction: 'Mode 2' revisited: the new production of knowledge. Minerva. 41:179–194.

Nürnberg, G. 1996. Trophic state of clear and colored, soft- and hardwater lakes with special consideration of nutrients, anoxia, phytoplankton and fish. Lake Reserv Manage. 12:432–447.

Nygrén NA. 2019. Scenario workshops as a tool for participatory planning in a case of lake management. Futures. 107:29–44.

O'Donnell EL, Talbot-Jones J. 2018. Creating legal rights for rivers: lessons from Australia, New Zealand, and India. Ecol Soc. 23:7.

Olsson P, Folke C. 2001. Local ecological knowledge and institutional dynamics for ecosystem management: a study of Lake Racken watershed, Sweden. Ecosystems. 4:85–104.

Osgood RA. 2017. Inadequacy of best management practices for restoring eutrophic lakes in the United States: guidance for policy and practice. Inland Waters. 7:401–407.

Osmond DL, Shober AL, Sharpley AN, Duncan EW, Hoag DLK. 2019. Increasing the effectiveness and adoption of agricultural phosphorus management strategies to minimize water quality impairment. J Environ Qual. 48:1204–1217.

Ostrom E. 1992. Governing the commons: the evolution of institutions for collective action. Cambridge (UK): Cambridge University Press.

Palmer SCJ, Kutser T, Hunter PD. 2015. Remote sensing of inland waters: challenges, progress and future directions. Remote Sens Environ. 157:1–8.

Pandya RE. 2012. A framework for engaging diverse communities in citizen science in the US. Front Ecol Environ. 10:314–317.

Pateman R, Dyke A, West S. 2021. The diversity of participants in environmental citizen science. Citiz Sci Theory Pract. 6:1–16.

Peeters ETHM, Gerritsen AAM, Seelen LMS, Begheyn M, Rienks F, Teurlincx S. 2022. Monitoring biological water quality by volunteers complements professional assessments. PlosOne. 17:e0263899.

Pereira LM, Davies KK, den Belder E, Ferrier S, Karlsson-Vinkhuyzen S, Kim H, Kuiper JJ, Okayasu S, Palomo MG, Pereira HM, Peterson G, Sathyapalan J, Schoolenberg M, Alkemade R, Carvalho Ribeiro S, Greenaway A, Hauck J, King N, Lazarova T, Ravera F, Chettri N, Cheung WWL, Hendriks RJJ, Kolomytsev G, Leadley P, Metzger J, Ninan KN, Pichs R, Popp A, Rondinini C, Rosa I, van Vuuren D, Lundquist CJ. 2020. Developing multiscale and integrative nature-people scenarios using the Nature Futures Framework. People Nat. 2:1172–1195.

Pradhananga A, Davenport M, Green E. 2019. Cultural narratives on constraints to community engagement in urban water restoration. J Contemp Water Res Educ. 166:79–94.

Ratner BD, Mam K, Halpern G. 2014. Collaborating for resilience: conflict, collective action, and transformation on Cambodia's Tonle Sap Lake. Ecol Soc. 19:31.

Reed MS. 2008. Stakeholder participation for environmental management: a literature review. Biol Conserv. 141:2417–2431.

Reed MS, Vella S, Challies E, de Vente J, Frewer L, Hohenwallner-Ries D, Huber T, Neumann RK, Oughton EA, Sidoli del Ceno J, van Delden H. 2018. A theory of participation: what makes stakeholder and public engagement in environmental management work? Restor Ecol. 26:S7–S17.

Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PTJ, Kidd KA, MacCormack TJ, Olden JD, Ormerod SJ, Smol JP, Taylor WW, Tockner K, Vermaire JC, Dudgeon D, Cooke SJ. 2019. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol Rev. 94:849–873.

Rittel HWJ, Webber MM. 1973. Dilemmas in a general theory of planning. Policy Sci. 4:155–169.

[RIVM] Rijksinstituut voor Volksgezondheid en Milieu. 2020. Blauwalgen protocol 2020 [Blue green algae protocol 2020]. RIVM-briefrapport 2020-0107. Dutch.

Rood SB, Kaluthota S, Philipsen LJ, Rood NJ, Zanewich KP. 2017. Increasing discharge from the Mackenzie River system to the Arctic Ocean. Hydrol Process 31:150–160.

Rose J, Hutcheson MS, West CR, Pancorbo O, Hulme K, Cooperman A, Decesare G, Issac R, Screpetis A. 2009. Fish mercury distribution in Massachusetts, USA lakes. Environ Toxicol Chem. 18:1370–1379.

Rose KC, Weathers KC, Hetherington AL, Hamilton DP. 2016. Insights from the Global Lake Ecological Observatory Network (GLEON). Inland Waters. 6:476–482.

Rowe G, Frewer LJ. 2000. Public participation methods: a framework for evaluation. Sci Technol Hum Val. 25:3–29.

Rowe G, Frewer LJ. 2005. A typology of public engagement mechanisms. Sci Technol Hum Val. 30:251–290.

Ryan E, Curry H, Rule H. 2020. Environmental rights for the 21st century: a comprehensive analysis of the public trust doctrine and rights of nature movement. Cardozo Law Rev. 42:2447–2576.

Safford TG, Carlson ML, Hart ZH. 2009. Stakeholder collaboration and organizational innovation in the planning of the Deschutes Estuary Feasibility Study. Coast Manage. 37:514–528.

Saunders BA, Rast W, Lopes V. 2014. Stakeholder evaluation of the feasibility of watershed management alternatives, using Integrated Lake Basin Management principals. Lakes Reservoirs. 19:255–268.

Schneiderman EM, Steenhuis TS, Thongs DJ, Easton ZM, Zion MS, Neal AL, Mendoza GF, Walter MT. 2007. Incorporating variable source area hydrology into a curve-number-based watershed model. Hydrol Process. 21:3420–3430.

Sharfstein JM. 2016. Banishing "stakeholders". Milbank Q. 94:476.

Sharma S, Richardson DC, Woolway RI, Imrit MA, Bouffard D, Blagrave K, Daly J, Filazzola A, Granin N, Korhonen J, Magnuson J, Marszelewski W, Matsuzaki SS, Perry W, Robertson DM, Rudstam LG, Weyhenmeyer GA, Yao H. 2021. Loss of ice cover, shifting phenology, and more extreme events in northern hemisphere lakes. J Geophys Res-Biogeo. 126:e2021JG006348.

Sharpe LM, Harwell MC, Jackson CA. 2021. Integrated stakeholder prioritization criteria for environmental management. J Environ Manage. 282:111719.

Sharpley A, Jarvie HP, Buda A, May L, Spears B, Kleinman P. 2013. Phosphorus legacy: overcoming the effects of past management practices to mitigate future water quality impairment. J Environ Qual. 42:1308–1326.

Smyth RL, Fatima U, Segarra M, Borre L, Zilio MI, Reid B, Pincetl S, Astorga A, Huamantinco Cisneros MA, Conde D, Harmon T, Hoyos N, Escobar J, Lozoya JP, Perillo GME, Cintia Piccolo M, Rusak JA, Velez MI. 2021. Engaging stakeholders across a socio-environmentally diverse network of water research sites in North and South America. Environ Dev. 38:100582.

Seelen LMS, Teurlincx S, Armstrong MR, Lürling M, van Donk E, de Senerpont Domis LN. 2021. Serving many masters at once: a framework for assessing ecosystem services delivered by quarry lakes. Inland Waters. 12:121–137.

Settele J, Scholes R, Betts R, Bunn S, Leadley P, Nepstad D, Overpeck JT, Taboada MA. 2014. Terrestrial and inland water systems. In: Field B, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL, editors. Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge (UK) and New York (NY): Cambridge University Press. p. 271–359.

Sharip Z, Zakaria S, Noh MNM, Nakamura M, Muhandiki V. 2021. A review of the importance, gaps and future directions of Integrated Lake Basin Management Planning in Malaysia. Lakes Reservoirs. 26:e12355.

Slough T, Rubenson D, Levy R, Alpizar Rodriguez F, Bernedo del Carpio M, Buntaine MT, Christensen D, Cooperman A, Eisenbarth S, Ferraro PJ, Graham L, Hartman AC, Kopas J, McLarty S, Rigterink AS, Samii C, Seim B, Urpelainen J, Zhang B. 2021. Adoption of community monitoring improves common pool resource management across contexts. Proc Natl Acad Sci U S A. 118:e2015367118.

Søndergaard M, Jeppesen E, Lauridsen TL, Skov C, Van Nes EH, Roijackers R, Lammens E, Portielje R. 2007. Lake restoration: successes, failures and long-term effects. J Appl Ecol. 44:1095–1105.

Spears BM, Chapman DS, Carvalho L, Feld CK, Gessner MO, Piggott JJ, Banin LF, Gutiérrez-Cánovas C, Lyche Solheim A, Richardson JA, Schinegger R, Segurado P, Thackeray SJ, Birk S. 2021. Making waves. Bridging theory and practice towards multiple stressor management in freshwater ecosystems. Water Res. 196:116981.

Spears BM, Hamilton DP, Pan Y, Zhaosheng C, May L. 2022. Lake management: is prevention better than cure? Inland Waters. 12:173–186.

Starke JR, Van Rijswick HFMW. 2021. Exemptions of the EU Water Framework Directive deterioration ban: comparing implementation approaches in Lower Saxony and The Netherlands. Sustainability. 13:930.

Stefan HG, Hondzo M, Fang X, Eaton JG, McCormick JH. 1996. Simulated long term temperature and dissolved oxygen characteristics of lakes in the north-central United States and associated fish habitat limits. Limnol Oceanogr. 41:1124–1135.

Sterner RW, Keeler B, Polasky S, Poudel R, Rhude K, Rogers M. 2020. Ecosystem services of Earth’s largest freshwater lakes. Ecosyst Serv. 41:101046.

Stow CA, Glassner-Shwayder K, Lee D, Wang L, Arhonditsis G, DePinto JV, Twiss MR. 2020. Lake Erie phosphorus targets: an imperative for active adaptive management. J Great Lakes Res. 46:672–676.

Svarstad H, Kjerulf Petersen L, Rothman D, Siepel H, Wätzold F. 2008. Discursive biases of the environmental research framework DPSIR. Land Use Policy. 25:116–125.

Swallow BM, Garrity DP, van Noordwijk M. 2001. The effects of scales, flows and filters on property rights and collective action in watershed management. Water Policy. 3:457–474.

Tammeorg O, Chorus I, Spears B, Nõges P, Nürnberg, Tammeorg P, Søndergaard M, Jeppesen E, Paerl H, Huser B, Horppila J, Jilbert T, Budzyńska A, Dondajewska-Pielka R, Gołdyn

R, Haasler S, Hellsten S, Härkönen LH, Kiani M, Kozak A, Kotamäki N, Kowalczewska-Madura K, Newell S, Nurminen L, Nõges T, Reitzel K, Rosińska J, Ruuhijärvi J, Silvonen S, Skov C, Važić T, Ventelä A-M, Waajen G, Lürling M. 2023. Sustainable lake restoration: from challenges to solutions. WIRES Water. 2023:e1689.

Thornhill I, Loiselle S, Lind K, Ophof D. 2016. The citizen science opportunity for researchers and agencies. BioScience. 66:720–721.

[UNEP] United Nations Environmental Programme 2016. A snapshot of the world’s water quality: towards a global assessment. Nairobi (Kenya): DEW/1975/NA.

[USEPA] United States Environmental Protection Agency. 2019. Recommended human health recreational ambient water quality criteria or swimming advisories for microcystins and cylindrospermopsin. Washington (DC): EPA 822-P-16-002.

[USEPA] United States Environmental Protection Agency. 2022. National lakes assessment: the third collaborative survey of lakes in the United States. Washington (DC): EPA 841-R-22-002.

[USEPA] United States Environmental Protection Agency. 2023. Secondary Drinking Water Standards: Guidance for Nuisance Chemicals. Washington (DC).

Vaes G, Willems P, Swartenbroekx P, Kramer K, de Lange W, Kober K. 2009. Science-policy interfacing in support of the Water Framework Directive implementation. Water Sci Technol. 60:47–54.

Vogler D, Macey S, Sigouin A. 2017. Stakeholder analysis in environmental and conservation planning. Lessons Conserv. 7:5–16.

Vörösmarty CJ, Pahl-Wostl C, Bunn SE, Lawford R. 2013. Global water, the Anthropocene and the transformation of a science. Curr Opin Env Sust. 5:539–550.

[WFD] Water Framework Directive. 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy. Official Journal of the European Communities 22:2000.

[WFD] Water Framework Directive. 2003. Common implementation strategy for the Water Framework Directive (2000/60/EC). Guidance Document No 10: River and lakes - typology, reference conditions and classification systems. Luxembourg: Office for Official Publication of the Europeans Communities.

Whittier TR, Paulsen SG, Larsen DP, Peterson SA, Herlihy AT, Kaufman PR. 2002. Indicators of ecological stress and their extent in the population of Northeastern lakes: a regional-scale assessment. BioScience. 52:235–247.

[WHO] World Health Organization. 2021. Guidelines on recreational water quality. Volume 1: coastal and fresh waters. Geneva (Switzerland): Licence CC BY-NC-SA 3.0 IGO.

[WHO] World Health Organization. 2022. Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva (Switzerland): Licence CC BY-NC-SA 3.0 IGO.

Williams BK, Brown ED. 2016. Technical challenges in the application of adaptive management. Biol Conserv. 195:255–263.

Williamson CE, Dodds W, Kratz TK, Palmer MA. 2009. Lakes and streams as sentinels of environmental changes in terrestrial and atmospheric processes. Front Ecol Environ. 6:247–254.

Wilson NJ, Inkster J. 2018. Respecting water: Indigenous water governance, ontologies, and the politics of kinship on the ground. Environ Plann E.. 1:516–538.

Woolway RI, Merchant CJ. 2019. Worldwide alteration of lake mixing regimes in response to climate change. Nat Geosci. 12:271–276.

Zellmer SB, Glicksman RL. 2013. Improving water quality antidegradation policies. Geo Wash J Energ Environ Law. 4:1–24.

Zhu H, Hu XD, Wu PP, Chen WM, Wu SS, Li ZQ, Zhu L, Xi YL, Huang R. 2021. Development and testing of the phytoplankton biological integrity index (P-IBI) in dry and wet seasons for Lake Gehu. Ecol Indic. 129:107882.

Table Legends:

Table 1. Approaches to community engagement. The mechanisms behind each mode of communication are listed. Lake context, or situations in which each mode of communication might be most appropriate, is illustrated using the example of an invasive aquatic plant being discovered in a fictitious lake presented elsewhere in this manuscript (Boxes 1–3).

Table 2. Three types of indicators referred to in the MoReCo framework. The description of each indicator is modified from Cairns et al. (1993). We provide an example of each type of indicator, as it might apply to lake management.

Table 3: Example indicators used to assess and monitor lake condition based on values and goals.

Table 4: Existing natural resource management frameworks. We indicate whether each existing framework contains one of the five characteristics identified in this paper as important to effective lake management with an "x." Characteristics include whether the framework: (1) is capable of addressing multiple environmental stressors simultaneously; (2) includes explicit, quantitative benchmarks that can be used to evaluate success; (3) considers community engagement and provides guidance on how feedback from community members is incorporated; (4) is continuous and can restore existing stressors while concurrently preserving the resource from potential threats; and (5) is specifically designed to address issues specific to lakes and/or reservoirs. The "Examples of Use" column lists studies that either use the framework in management or mention it. For the Integrated Lake Basin Management Framework, the five

characteristics were evaluated based on the original source which is listed first and in bold. The additional examples may contain more or less of the characteristics based on their interpretation and usage of the original source.

Figure Legend:

Figure 1. MoReCo (Monitoring, Restoring/Protecting, Community Engagement) lake management framework diagram consisting of a Community Engagement Axis (S1–S4) surrounded by two loops, the Monitoring Ecosystem State Loop (M1–M5) and Restoring/Protecting Ecosystem State Loop (RP1–RP5). Although the steps of the framework are presented in a sequential fashion, there will be cases where the process will require revisiting earlier steps (e.g., during RP3 it may be necessary to move back to C2 and C3 to gather community input). For clarity, we have not included these instances in the diagram, rather, examples are discussed in the text.

Tables:

Table 1. Approaches to community engagement. The mechanisms behind each mode of communication are listed. Lake context, or situations in which each mode of communication might be most appropriate, is illustrated using the example of an invasive aquatic plant being discovered in a fictitious lake presented elsewhere in this manuscript (Boxes 1–3).

Mode	Mechanisms	Lake Context	References
Communication (Type 1)	Signage; Pamphlets and documents; News media; Social media; Presentations at regional meetings; Visiting experts at lake association meetings	An invasive plant has just been detected, prompting immediate communication campaigns with signage and social media related to clean, drain, dry boats to prevent further spread.	Rowe and Frewer (2000), Rowe and Frewer (2005)
Consultation (Type 2)	Electronic consultation; Consultation documents; Focus groups; Interviews; Town halls and public hearings; Scenario workshops; Public opinion surveys (e.g., opinion polls, multiple choice questionnaires, semi-structured surveys); Game-based education workshops	New lake management plans, bylaws, or policies are being considered at slightly longer timescales, or in regions located near heavily impacted areas, but which are not yet themselves heavily impacted. Invasive plant has just been detected in several nearby lakes, and lake managers want to develop a management plan to address plant if/when it arrives. Need knowledge from community members on the level of concern and whether they think management is needed.	Nygrén (2019), Armstrong et al. (2021)
Participation: Decision-making (Type 3)	Co-created lake management plans; Cooperatively led planning approaches; Study circles; Public representation on local watershed councils; Stakeholder research	New lake management plans, bylaws, or policies with somewhat longer time frame/scales, or in regions located near heavily impacted areas, but are not yet highly	Rowe and Frewer (2000), Rowe and Frewer (2005), Safford et al. (2009), Bucchi (2009)

	planning involvement; Stakeholder-led cooperative planning methods; Consensus conferences, citizens jury/panel; Negotiated rulemaking; Action planning workshop; Scenario workshops; Task force; Town/regional meeting with voting; Referenda	impacted themselves. In a situation where new regulations are appropriate for managing the invasive plant.	
Participation: Monitoring and management (Type 4)	Community science for baseline monitoring (e.g., sampling to evaluate lake condition, impact-oriented lake condition sampling, invasive species surveys); Public participation in ecological restoration or conservation (e.g., shoreline restoration, wetland restoration, habitat construction, and invasive species removal)	In an already heavily impacted condition, stakeholders remove the invasive plant. In a situation where the spread of the species is unknown, develop a monitoring program to survey the extent of the invasion. In a situation where the infestation is new and small, rapid eradication and spread prevention are implemented.	Early Detection and Distribution Mapping System (EDDMaps) for reporting invasive species EDDmaps.org Hecker et al. (2018), Fitchett et al. (2020), Peeters et al. (2022), Moshi et al. (2022)

Table 2. Three types of indicators referred to in the MoReCo framework. The description of each indicator is modified from Cairns et al. (1993). We provide an example of each type of indicator, as it might apply to lake management.

Indicator	Description	Example
Compliance	Compliance indicators are thresholds used to determine whether conditions are acceptable. If conditions are measured on one side of the threshold, they are considered acceptable, but if on the other side, a failure to meet management objectives is assumed.	Maintaining an average annual Secchi disk depth at a predetermined value appropriate for the study system may be used as an indicator of compliance with water clarity goals.
Diagnostic	Diagnostic indicators relate to the stressor and can provide insight into why the stressor exceeds established thresholds.	Chlorophyll *a* is one diagnostic indicator for Secchi disk depth. These parameters are often correlated, so increases in chlorophyll *a* concentration may suggest that water clarity goals are not being met because of high algal biomass.
Detection (called "early warning indicator" in Cairns et al. 1993)	Detection indicators identify when conditions begin to decline, but before they have deteriorated to where compliance indicators are affected.	Phosphorus concentrations above a threshold may be an early warning indicator of lake condition degradation, even if the average annual Secchi disk depth is above the compliance indicator.

Table 3: Example indicators used to assess and monitor lake condition based on values and goals.

Lake Condition Value/Goal	Example Indicators and Reference
Lake conditions support healthy aquatic life	Indices of biotic integrity for: Benthic macroinvertebrates (Blocksom et al. 2002), Fish (Bacigalupi et al. 2021), Phytoplankton (Zhu et al. 2021), Aquatic plants (Mikulyuk et al. 2017), Benthic diatoms (Bennion et al. 2014)
Clean drinking water	Microcystin concentration (AWWA 2016, USEPA 2019, WHO 2022); Chloride concentration (USEPA 2023)
Fish are safe to eat	Metal concentrations in fish tissue (Whittier et al. 2002)
Early detection or prevention of invasive species	Field surveys (Larson et al. 2020), eDNA (Larson et al. 2020)
Water is safe for swimming	*E. coli* concentration (WHO 2021), Index for contact recreation (Lopes et al. 2020), Microcystin and Chlorophyll *a* concentration (RIVM 2020, WHO 2021), Secchi disk depth (Environment Canada 1972)

Table 4: Existing natural resource management frameworks. We indicate whether each existing framework contains one of the five characteristics identified in this paper as important to effective lake management with an "x." Characteristics include whether the framework: (1) is capable of addressing multiple environmental stressors simultaneously; (2) includes explicit, quantitative benchmarks that can be used to evaluate success; (3) considers community engagement and provides guidance on how feedback from community members is incorporated; (4) is continuous and can restore existing stressors while concurrently preserving the resource from potential threats; and (5) is specifically designed to address issues specific to lakes and/or reservoirs. The "Examples of Use" column lists studies that either use the framework in management or mention it. For the Integrated Lake Basin Management Framework, the five characteristics were evaluated based on the original source which is listed first and in bold. The additional examples may contain more or less of the characteristics based on their interpretation and usage of the original source.

Framework	Addresses Multiple Stressors Simultaneously	Explicit Benchmarks for Defining Success	Community Engagement is Central	Framework is Continuous	Lake Specific	Examples of Use
Decision Support Tool Development Model		x	x	x		Barnhart et al. (2018)
Integrated Lake Basin Management	x	x	x	x		**ILEC (2005);** Lake Chivero (Muhandiki.et.al 2014); Rock and Marsh Creek watersheds (Saunders et al. 2014); Lake Biwa (Nakatsuka et al. 2020); Malaysia (Sharip et al. 2021)
Drivers-Pressures-State-Impacts-Responses (DPSIR)	x	x		x		EU Water Framework Directive (WFD 2000)
Adaptive Management	x			x		Arhonditsis et al. (2019); Stow et al. (2020)
MoReCo (this paper)	x	x	x	x	x	

Figure:

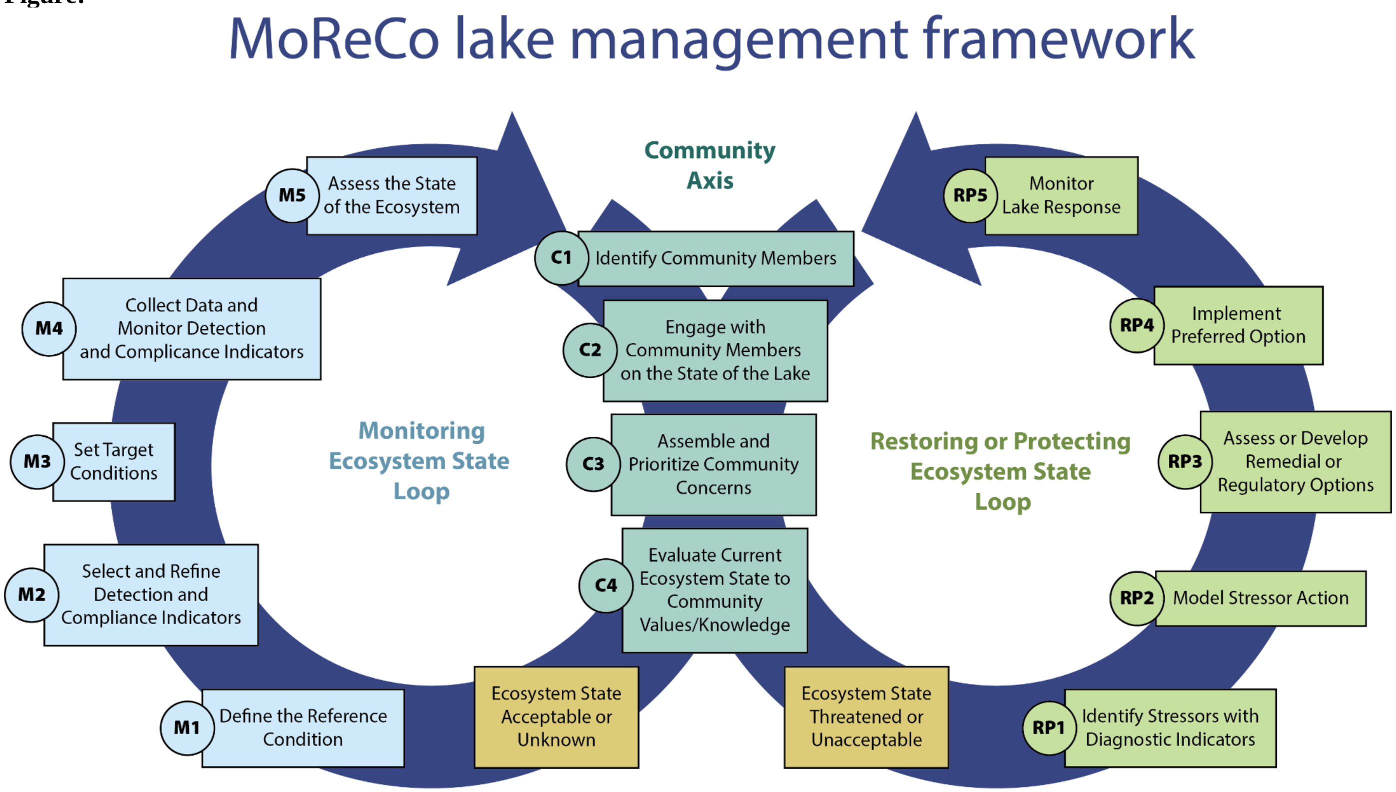

Figure 1. MoReCo (Monitoring, Restoring/Protecting, Community Engagement) lake management framework diagram consisting of a Community Engagement Axis (S1–S4) surrounded by two loops, the Monitoring Ecosystem State Loop (M1–M5) and Restoring/Protecting Ecosystem State Loop (RP1–RP5). Although the steps of the framework are presented in a sequential fashion, there will be cases where the process will require revisiting earlier steps (e.g., during RP3 it may be necessary to move back to C2 and

C3 to gather community input). For clarity, we have not included these instances in the diagram; rather, examples are discussed in the text.