Goals and principles for programmatic river restoration monitoring and evaluation: collaborative learning across multiple ....

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Overview

Goals and principles for programmatic river restoration monitoring and evaluation: collaborative learning across multiple projects

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River restoration is a relatively recent undertaking, with high levels of complexity and uncertainty involved. Many restoration projects have been monitored over the past three decades, however, results have rarely been compared across projects thereby limiting our ability to identify factors that influence restoration outcomes. Programmatic monitoring and evaluation (ProME) that builds on standardized surveys and systematic cross-project comparison allows for collaborative learning, transfer of results across restoration projects and for adaptive management and monitoring. We present a conceptual framework for ProME consisting of four goals and nine principles. First, ProME accounts for complexity, uncertainty, and change in order to contribute to sustainable river management over the long term. Second, ProME promotes collaborative learning and adaptation by standardizing the sampling design for the field surveys at multiple projects and by disseminating findings across stakeholders. Third, ProME verifies to what extent restoration has been achieved, i.e., it must quantify the size and direction of change. Fourth, ProME identifies why the observed effects were present, thereby improving our mechanistic understanding of river functioning. We conclude with potential extensions of the framework (e.g., evaluating cumulative effects of projects within a catchment). Our conceptual framework presents a structured approach toward a more systematic learning and evidence-based action in river restoration, while taking into account the wider picture of environmental change within which river restoration projects will inevitably operate.

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INTRODUCTION

River restoration (see Glossary in Box 1) is an important management intervention in many countries worldwide.[1,2] Substantial financial resources have been invested over the past three decades,[3,4] often as part of a regional or national restoration program. Despite such coordinated funding, monitoring and evaluation (ME) have usually been designed and performed as independent tasks at the project-level, i.e., without any further coordination with related projects from the same funding program. Independent project-level ME has provided important information on ecosystem behavior, recovery trajectory, and public acceptance,[2,5] but has not made full use of the unique opportunities offered at the program-level (i.e., regional or national scale), including

- generalization: transfer of results across restoration projects, programs, and river basins,[6,7]
- collaborative learning: facilitated exchange of lessons learned across stakeholders,[8]
- adaptation: continuous refinement of practical and scientific approaches,[9]
- justification of resources: increased credibility of restoration through a robust analysis of the effects,[10]
- causal understanding: toward a better understanding of mechanistic pathways and influencing factors (e.g., multiple stressors[3]),
- beyond today's challenges: toward informed management of rivers in a changing world.[11]

BOX 1

GLOSSARY

Restoration refers to all activities to assist the recovery of river ecosystems that have been degraded, damaged, or destroyed.[28] With '*restoration project*,' we mean the action (or *measure*) taken at a given site. Often multiple *techniques* (or *methods*) are applied, such as channel widening, and bank restructuring.[29]

There are several types of *monitoring* and *evaluation* (or *assessment or surveillance*) such as *baseline*, *status*, *trend*, *implementation*, *effectiveness,* and *validation monitoring*[20] or *surveillance*, *operational,* and *investigative monitoring.*[17] We focus on effectiveness and validation (e.g., what was the effect of the project on habitat availability?) as well as investigative monitoring (e.g., how does agricultural land use in the catchment influence the recovery of species diversity following restoration?).

We define *ProME* as a coordinated activity that draws together standardized surveys and systematic comparison of multiple projects implemented in a given region or state, potentially financed within a regional or national restoration *program.* The *stakeholders* form a transdisciplinary community with representatives from different disciplines (e.g., engineering, ecology, and social sciences) and fields of work (authorities, consultants, NGOs, and research).

ME is based on *indicators* (or *parameters*, *variables*, *attributes,* or *metrics*) that quantify and assess the condition of a river in the light of the restoration objectives.[5] A *reference* represents the target conditions to be achieved by the restoration, whereas a *control* represents the degraded conditions to move away from.[26]

Programmatic monitoring and evaluation (ProME) that builds on coordination, standardized surveys, and systematic cross-project comparison ('spatial replication') is largely non-existent.[6] There are many reasons for this, including a lack of incentives, e.g., from the funding agencies,[6] lack of guidelines, and lack of awareness. In addition, ProME, like other large riverine monitoring programs, presents technical challenges (e.g., study design, spatial and temporal replication, and sampling protocols) and procedural challenges (e.g., inadequate training, data collection errors, and lack of coordination) that need to be overcome to be successful.[12–14]

To help overcome these challenges and maximize monitoring benefits, we present a conceptual framework for ProME in river restoration comprising four goals and nine principles (Table 1). Goals reflect the aims and vision for doing ProME whereas principles describe the means to achieve the goals. Originally elaborated as a guideline to develop a national ProME in Switzerland, the framework has been expanded further to be applicable in an international context (Box 2).

BOX 2

RIVER RESTORATION PROGRAMS IN SWITZERLAND AND THE EUROPEAN UNION (EU)

Switzerland: The Swiss Water Protection Act was amended in 2011 with the mandate to restore 4000 river kilometers by 2090 (National Restoration Program). This corresponds to 25% of the heavily impaired river reaches and to 6% of the entire river network (65,000 km). Apart from river restoration, sufficient room for rivers and their natural processes should be secured by 2018. Furthermore, the negative ecological effects from hydropower exploitation (sediment deficit, hydropeaking, and fish passage) should be mitigated by 2030. The budget from the federal government is 40 million CHF/year for river restoration. Federal funding accounts for 35–80% of the project costs, depending on the ecological objectives followed and is allocated to the 26 cantons in 4-year funding cycles. ME is part of the funding, however, the requirements have not been specified further, thereby limiting collaborative learning and evidenced-based management. To help maximize the invested funding, the Federal Office for the Environment and the research institute Eawag launched a 2.5-year research project to develop a ProME for the National Restoration Program. Alternative strategies are being developed for both a STANDARD and EXTENDED ProME. The STANDARD ProME aims to verify to what extent the national objectives for river restoration have been met within the restored river reach. All river restoration projects receiving federal funding will be included in the STANDARD ProME. In contrast, the EXTENDED ProME aims to answer specific questions from practice at selected river restoration projects.

EU: Since 2000 EU member states are obliged to implement the Water Framework Directive (WFD) to reach good ecological and chemical status in rivers and other water bodies at the latest by 2027. In river basin management plans, the programs of measures describe the restoration and mitigation actions needed to achieve this. The ecological status is assessed by biological quality elements: phytoplankton, other aquatic flora, benthic invertebrates and fish and supporting information about the physico-chemistry and hydromorphology. Three types of monitoring are considered: (1) surveillance monitoring to assess trends in water body status, (2) operational monitoring to detect stressors and changes in water bodies at risk or where measures have been implemented, and (3) investigative monitoring to find causes and solutions where reasons for failing are unknown. Assessment procedures have been harmonized between EU member states (so-called 'intercalibration'). Albeit a tremendous improvement in ME throughout Europe, the design of monitoring programs is tailored to assess the status of individual water bodies and restricted to aquatic components while investigative monitoring is generally restricted to a single project or stressor.

Both the WFD and Swiss ProME are cyclical, in that there is regular assessment of the previous cycle which feeds into planning of the next. However, there are some differences. The proposed Swiss ProME goes beyond the WFD requirements through its explicit cross-project assessment of restoration measures in the context of catchments or watersheds. It also acknowledges that rivers, riparian zones, and floodplains interact, by including terrestrial as well as aquatic monitoring components.

The present framework builds on existing frameworks, both from restoration and other areas of (river) management.[10,15–24] Our framework adds to these existing frameworks by explicitly incorporating

- the transdisciplinary setting of river restoration in which stakeholders from different disciplines and fields of work interact,
- the high diversity of restoration projects, e.g., regarding impacts addressed, techniques used, size, or location,
- the wider management context where restoration is usually one management concern among many others,
- a long-term perspective, with environmental conditions and societal structures being highly dynamic and uncertain,
- a structured learning process, where knowledge transfer happens within a well-defined feedback loop.

Our framework is meant to provide guidance for the development of ProME. It is not the goal of the presented framework to inform the selection of sites to be restored (spatial prioritization[8,25]), nor to outline the steps needed for implementing successful projects[26,27] nor to define the specific procedure for ME at the project level.[5,21]

We outline potential extensions to the proposed framework and conclude with considerations for river restoration management and science.

FOUR GOALS

We propose four goals for the development of ProME in river restoration. These goals are interconnected and build on each other in a hierarchical way.

Goal 1: Account for Complexity, Uncertainty, and Long-Term Change

This goal emphasizes the need for an integrated long-term perspective for ProME, considering ecological, social, and economic aspects beyond the priorities of the present day.[30,31] This necessitates the flexibility to account for unpredictable and rapid transformations (or 'surprises') including those resulting from a changing climate envelope,[32,33] shifts in environmental agendas,[34] or from alteration of institutional capacities.[22] This goal also means that ProME is seen as one type of environmental surveillance among many others, such as monitoring for nature conservation (e.g., biodiversity monitoring) or hazard prevention (e.g., flood protection). The differing goals of these different types of monitoring programs should be fully recognized, in order to exploit the potential for valuable synergies, and avoid inefficient, costly overlaps, and duplications.

Goal 2: Promote Collaborative Learning and Adaptation

This goal highlights the fact that ProME provides the basis for a structured learning process for all stakeholders involved in river restoration. An evidence-based approach allows adaption of the way that we restore our rivers ('adaptive management'[9]) and how we monitor and evaluate the outcomes ('adaptive monitoring'[10]). Adaptive approaches, both for management and, to a lesser extent, for monitoring, have been much discussed in the past, but rarely implemented in practice.[10] A structured learning process enables identification of the gaps in our understanding as well as the degree of uncertainty involved.[22] Over the mid- to long-term, such structured learning reduces errors[9] and thereby increases cost effectiveness, i.e., the effectiveness of the funding that is spent.[2] This is of high importance given that funding for river restoration is often limited overall, and funding reserved for ME specifically is often non-existent.

Goal 3: Verify to What Extent Restoration Has Been Achieved

This goal requires verification of the response of a system to the implemented activity, i.e., ProME must provide the data base to demonstrate achievement of pre-defined objectives. One can distinguish between primary responses and secondary or tertiary responses.[20] For instance, the primary response to a local river widening can be that the diversity of aquatic habitats increased.[35] The secondary and tertiary responses, respectively, would then be that, as a function of the increased habitat diversity, the diversity of fish species or functional groups also increased, with major consequences to ecosystem processes such as leaf-litter decomposition or algal biomass production.[36] If there is a legal mandate for improving river condition by means of river restoration, this goal also means confirming that the mandate has been executed and achieved.

Goal 4. Identify Why the Observed Effects Were Present

ProME must facilitate a better understanding of why the observed effects were manifested. This goal refers to the inherent challenge of studying real-world trajectories. Many unforeseen and unknown factors can interact with the implemented measures in complex ways (synergistic, antagonistic[37]), leading to complex ecological feedbacks and surprises.[38,39] Such interactions cannot be inferred from only measuring the size and direction of change (goal 3). Well-designed and well-executed ME has the potential to identify the driving factors, to reduce or at least quantify uncertainty and to improve our ability to forecast potential outcomes.[32] It will also provide information to increase our understanding of causal relationships and to make generalizations from site-specific ME, which in turn can feed into adaptation (goal 2).

NINE PRINCIPLES

To achieve the four goals, we suggest nine principles (Table 1), which will be discussed in the following sections. We provide a justification for each principle ('why?'), and describe the requirements and consequences of its implementation ('how?'). Furthermore, we illustrate the linkages among principles and give examples from our work in Switzerland.

Principle 1: Assure Stakeholder Commitment (Vision, Funding, Personnel, Time)

Why? ProME is a risky endeavor. Risks range from misleading conclusions arising from limited time perspectives[23] to divergent expectations from different stakeholder groups,[40] limited relevance for management[10] or cost overruns due to failed estimates of the resources required.[41] To avoid ineffective approaches or 'train wrecks.'[42] ProME must have a sound foundation, i.e., it must be built on collaborative partnerships of committed stakeholders and their organizations or institutions.[6,10,31] Collaboration and commitment comprise financial, personnel, and temporal resources for the required duration.

How? A prerequisite for transdisciplinary commitment is that there is common ground[7]—a shared vision of the goals, procedures, and benefits of ProME. The process of establishing common ground requires substantial time, work, patience, and social skills,[9] and is best achieved at the outset of the program.[10] Working with shared tenets can support the process by making it more transparent.[7] It is recommended to focus on 'shared points of agreement' and avoid continuing protracted arguments on differences. The goals listed above proved to be a useful starting point for elaborating a ProME in Switzerland. They were collaboratively developed by federal government authority and research representatives within two half-day workshops based on a previous suggestion by three of the authors. The acquisition of financial, personnel, and temporal resources may need strategic decisions from the program partners. To do so, ProME needs to be treated as a distinct and priority activity for all stakeholders involved, with a clear schedule, allocated staff, and a specific budget. This implies that ProME is considered as much a management concern as a scientific activity.[6,10,32] The spending time-frame of ProME must be organisationally decoupled from other phases (e.g., construction phase). Building up a long-term and trustful partnership also requires discussion and clarification of roles and responsibilities early in the process, covering tasks like controlling and archiving data, data analysis, and communication of results.

Principle 2: Evaluate Against Clear Objectives

Why? ME aims to verify to what degree pre-defined ecological, social, and economic objectives have been met.[5,26] The process of objective setting in river restoration often builds upon the 'guiding image' concept[43] that describes the dynamic ecosystem structure and function to be achieved considering the consequences of irreversible landscape changes.[44] Collaborative objective setting results in a common language and understanding of what is generally aimed for which in turn eases communication, including beyond ProME (principle 8).

How? Projects to be included in ProME must follow shared objectives ('program objectives') in order to warrant comparisons across projects (principles 5 and 6). Program objectives must be established at the outset of the program, and might be revised over the course of time (principle 9), e.g., due to shifting baselines.[45] Even if there is no universal guiding image for all rivers in the program,[26] a list of overarching objectives can be formulated in a structured way by using objective hierarchies.[40] Where there is a legal mandate for river restoration, program objectives need to reflect the objectives stated in the law. Program objectives have to fulfill certain criteria to become operational. These criteria are often summarized with the acronym SMART—specific, measurable, agreed-upon (some authors use achievable or assignable), relevant (or realistic), and time-bound.[46–48] Apart from program objectives, individual projects can follow more detailed or additional project-specific objectives in order to meet the local requirements. Divergent objectives should be omitted, i.e., project-level objectives should be in agreement with program objectives.

Principle 3: Coordinate With Related Activities

Why? Rivers are subject to various and often conflicting management interventions (e.g., hydropower expansion, flood risk management, and irrigation). Apart from interfering with the recovery trajectories of river restoration projects, these interventions are often also surveyed by their own ME programs. Different organizations or administrative units are responsible for different management areas, and information exchange between these programs and levels of organization can be restricted due to geographical distance, administrative structures, or other constraints in time, vocabulary, and culture.[49,50] Lack of exchange can result in an independent development of multiple and often highly specialized ME programs, with approaches and jargon reflecting particular disciplines. Furthermore, separate programs might be interested in similar topics, but might apply different indicators to evaluate them. Important opportunities are missed such as an increased cost-effectiveness, a larger data base for more powerful

TABLE 1 | The Nine Principles for ProME, Their Meaning and the Steps Taken for Implementation in Switzerland.[1]

Principle	What It Means	Ongoing Implementation in Switzerland[1]
1. Assure stakeholder commitment (vision, funding, personnel, time)	Formation of long-term partnerships of key stakeholders based on shared visions	• collaborative development of shared goals for ProME within two half-day workshops (research, federal authority) • build-up of long-term partnership for practice-oriented river research ('Swiss Rivers Program') • intense exchange with national and international stakeholders (advisory groups, conference workshops) • *decoupling of the spending time-frame for ProME from construction phase*
2. Evaluate against clear objectives	Formulation and verification of agreed-upon objectives on restoration outcome	• formulation of SMART objectives for river restoration (from local to national scale) • representation of these objectives within an objective hierarchy • iterative discussion of the objective hierarchies with the different stakeholder groups
3. Coordinate with related activities	Creation of synergies and common language across management sectors	• regular exchange with existing and planned ME activities at the national scale (water quality, conservation) • use of the same or comparable methods (e.g., for sampling macroinvertebrate communities)
4. Answer well-defined questions	Identification of key questions from practice to be answered in a systematic way	• collection of open questions from different stakeholder groups • identification of key questions to be addressed in the first years of ProME based on selected shared criteria (policy relevancy, urgency, interest for communication) • *establishment of a conceptual model illustrating the current state of knowledge (incl. gaps)*
5. Standardize the sampling design (indicators, methods, spatio-temporal scale)	Standardization of the design to allow for comparability and explanatory power	• identification of available indicators and their spatio-temporal scale of effect (e.g., response time) • selection of indicators for ProME based on agreed-upon criteria (e.g. robustness, acceptance, ease of measurement) • *training and inter-calibration for all persons involved in the surveys*
6. Compare multiple projects	Spatial replication to account for spatial variation in the observed effects	• characterization of project diversity (e.g., differences in technique used, biophysical setting, human pressures etc.) • identification of the most useful design to account for project diversity (mBA, mBACI, EPT[2]) • *identification of control and reference sites* • *involvement of professional statisticians in the design process*
7. Decide on where and when to learn	Distribution of funds according to the learning potential and stakeholder needs	• selection of sites for EXTENDED ProME (Box 2) based on agreed-upon criteria (transferability, relevance) • definition of the required time intervals for knowledge transfer from STANDARD and EXTENDED ProME (linked to the time frames of funding and other policy cycles)

(*continued overleaf*)

TABLE 1 | Continued

Principle	What It Means	Ongoing Implementation in Switzerland[1]
8. Process and disseminate the findings	Feedback of findings to the stakeholders and wider public	• identification of the required products (format, content, scale of inference) for dissemination • identification of timing and frequency for dissemination • *clarification of responsibilities for analysis, dissemination etc. (e.g., data governance table)* • *establishment of an accessible data-base with quality-controlled raw data*
9. Review the program at regular intervals	Reflection and adaptation of the program based on lessons learned	• *planned-in reflection phase at regular intervals and under consideration of policy cycles* • *documentation of the learning process* • *follow up of the technical and social developments*

[1] The implementation is ongoing (see Box 2), with certain steps being planned, but not implemented yet (in italics).
[2] EPT, extensive post-treatment design; mBA, multiple before-after design; mBACI, multiple before-after-control-impact design; ProME, programmatic monitoring and evaluation. See also principle 6.

statistical analyses and interpretation of results and a common language across management sectors and for dissemination of results.[50]

How? ProME for river restoration requires coordination with existing and planned (ME) activities at the same (e.g., national) scale. Coordination can have different forms and intensities, ranging from shared visions, organizational and technical exchange[50] to the use of the same or at least comparable methods. For instance, objective hierarchies (principle 2) can be framed to be applicable to other sectors of river management, i.e., to provide a holistic, integrative perspective on sustainable management.[51] Selected indicators from ProME can be used in programs from other management sectors, such as for flood protection projects which, in many countries, have to fulfill key ecological criteria as well. Organizational coordination requires a regular exchange with representatives from related activities in management and research. Technical opportunities such as shared data bases, synthesis reports,[52] or web-platforms[6] facilitate exchanging raw data, knowledge, and experiences (principle 8).

Principle 4: Answer Well-Defined Questions

Why? River restoration is a relatively recent endeavor. Many practical and scientific questions are open, both regarding management and monitoring. Some questions can be directly linked to the objectives that are followed (principle 2), for instance by asking whether habitat diversity was increased following local river widening (primary response[20]). Questions can also be more investigative and address the causes for an observed effect (e.g., which factors affect the recovery potential of local fish assemblages following in-stream placement of wood?). ProME offers a great opportunity to answer key questions in a systematic way.[10] Prioritization is needed to identify the key questions at the onset of the program and also later in the review phase (see principle 9). Focusing on questions eases the way down to the indicators to be measured (principle 5), without getting lost in time-consuming, ineffective debates about what to monitor.[10]

How? ProME must address a set of well-defined and agreed-upon key questions. An iterative discussion is therefore needed because key questions can differ substantially between stakeholders. Managers might raise rather site-specific questions whereas scientists prefer addressing more general relationships.[7] The discussion can be mediated in a step-wise procedure.[53] In a first step, questions are collected. In a second step, key questions are identified based on selected shared criteria. Criteria for selection can be manifold, addressing, for example, time and funding. Monitoring projects can fail due to a lack of focus ('collect now, think later'[10]). The questions must therefore be well-defined and tractable, and the expected outcomes be formulated as testable hypotheses.[10,27] Formulation of hypotheses requires a sound knowledge of the existing international literature. A conceptual model illustrating the current state of knowledge can be helpful for supporting the discussion.[10,27]

Principle 5: Standardize the Sampling Design (Indicators, Methods, Spatio-Temporal Scale)

Why? The sampling design comprises the indicators used, the methods to measure them and the spatio-temporal scale of surveys. The indicators quantify the

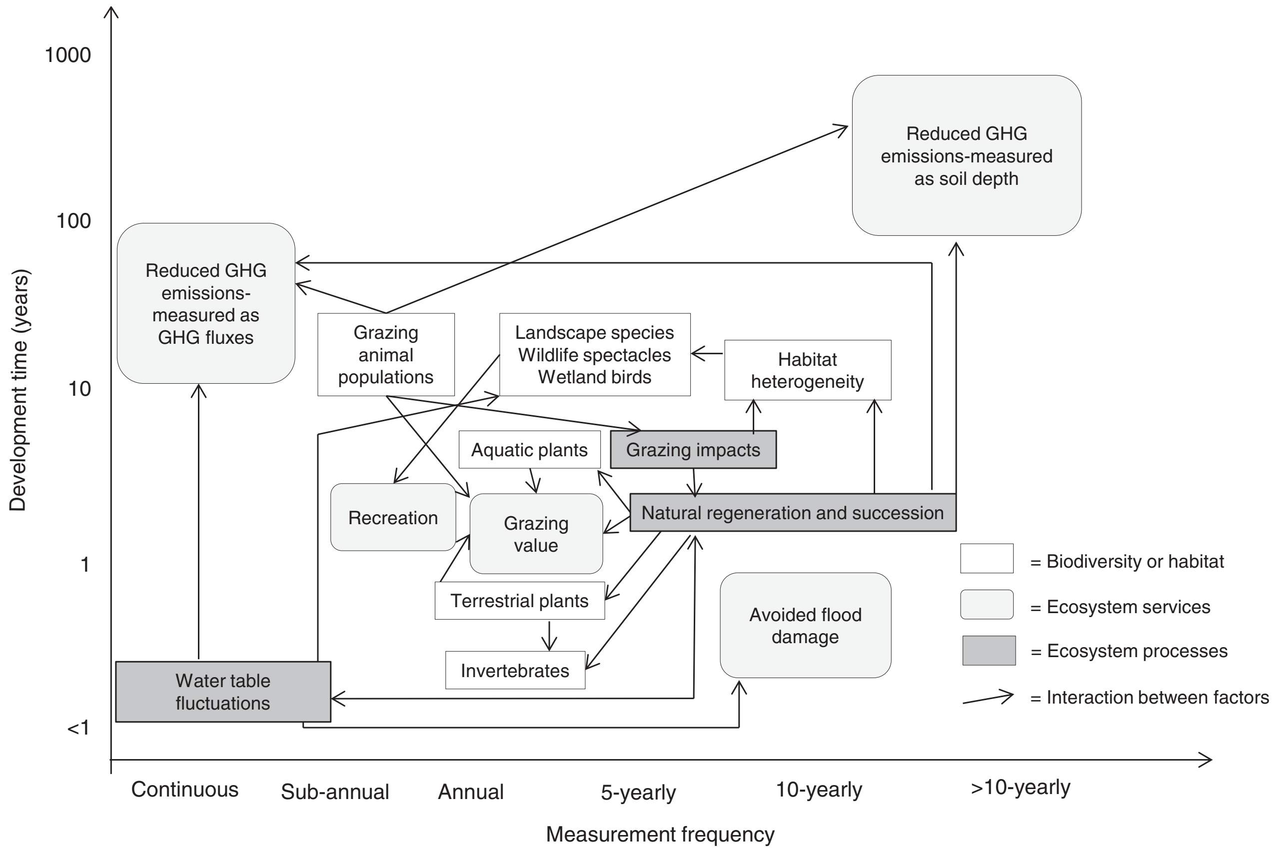

FIGURE 1 | Conceptual model for wetland restoration monitoring in the UK.[54] Different indicators for biodiversity (white boxes), ecosystem services (light gray), and ecosystem processes (dark gray) show different response or development times (*y*-axis) and necessitate different measurement frequencies (*x*-axis). GHG, greenhouse gas.

objectives that were set (principle 2) and the specific questions addressed (principle 4). A given indicator can be measured with different methods. The spatio-temporal scale matters, as all indicators are scale-specific (see Figure 1 for an illustration from wetland restoration monitoring). Some indicators will operate at a patch scale of a few meters while others may operate at a reach scale of up to several hundred metres. This might require some indicators to be monitored over longer stretches of river than others, with attendant cost implications. The scale of the restoration also needs to be considered. For example, the responses and methods to monitor small projects that cover a few hundred meters are different from those that cover several kilometers. Moreover, response time varies a lot among indicators with some responding very quickly to restoration (e.g., pool area) and others responding very slowly, such as development of woody riparian vegetation.

How? A certain degree of standardization in the sampling design is needed to guarantee comparability across projects within ProME (principle 6). Standardized methods and indicator selection must be jointly agreed upon within ProME, i.e., robust and accepted methods have to be used throughout the program, without changing protocols half way through. Training and inter-calibration are needed for the people doing the field surveys. ProME must be performed on the scale of effect, i.e., the spatio-temporal scale at which effects are expected to be expressed. Timing and duration of ProME must allow the dynamics of the indicators studied to be captured, such as response time after restoration or interannual variation before and after restoration. In this way, spending time-frames for funding can be adapted to account for the required spatial distribution, timing, and duration of ProME.

Principle 6: Compare Multiple Projects

Why? Spatial replication refers to the comparison of multiple restoration projects across different conditions. It allows a monitoring program to account for spatial variation in the observed effects,[20] to identify mechanistic pathways and to quantify the relative importance of other explanatory variables of restoration outcomes.[20] These explanatory variables (e.g., agricultural areas in the catchment, longitudinal fragmentation or stream size) represent key environmental attributes, including stressors, that can influence the recovery trajectory in the restored reaches, even when operating outside the restoration area. Spatial replication is underrepresented in the restoration literature. Studies that have used it, however, show promising results and inspiring insights.[36,55–57] For instance, a meta-analysis of 91 European river restoration projects[55] demonstrated that the biological effects measured were considerably correlated with project age, river width, and agricultural area upstream (Figure 2).

How? ProME requires the comparison of multiple projects, either by multiple before-after or before-after-control-impact[58] designs or by an extensive post-treatment design (EPT[20,21]). Comparison requires a certain degree of standardization in the survey design to guarantee methodological comparability (e.g., indicator selection; principle 5). Furthermore, comparability should be carefully reflected in the light of project diversity. For example, the techniques that are used have to be understood in detail in order to make mechanistic links.[9] Apart from comparing projects, the trajectory of change has to be analyzed in relation to changes also taking place at reference or control sites.[26] References or controls need to be identified within ProME and they need to be adequate, i.e., they should be as similar to the restored reach as possible in terms of catchment area, geology, evolutionary history, flow, etc.[20,21] References and controls should keep their role in the program and explanatory power, over time, i.e., they should not undergo alteration, such as restoration of the control. Rigorous statistical design is needed for analysis of ProME.[10] The involvement of professional statisticians in the design process will often be essential.[59]

Principle 7: Decide on Where and When to Learn

Why? A restoration program may consist of several hundred projects from which one could potentially learn. For instance, in Switzerland, 300 restoration projects are planned to be implemented in the coming 4 years (S. Haertel-Borer, personal communication). However, not all of these projects are equally suited for answering the selected questions (principle 4); prioritization is needed. Apart from the spatial aspect of learning, there is also a temporal dimension. First, many policy processes are cyclical, i.e., management objectives or funding are being re-negotiated at regular

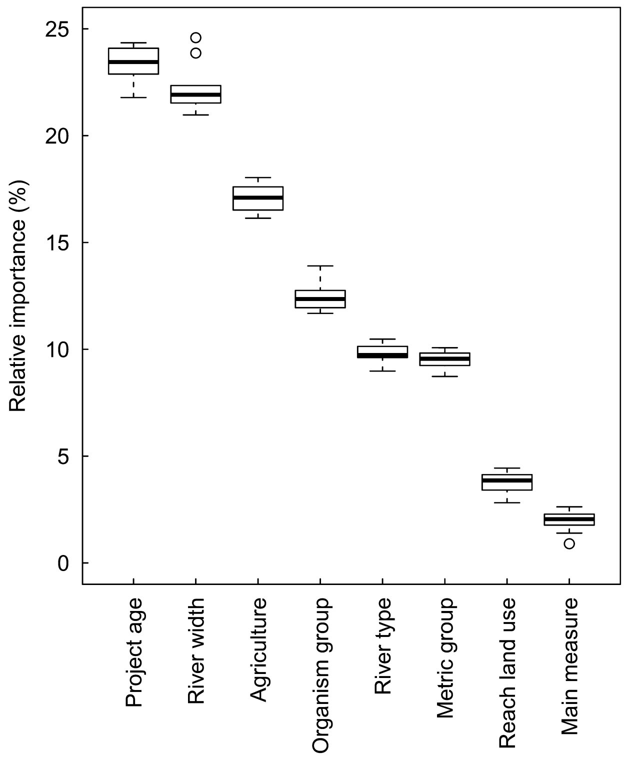

FIGURE 2 | Example of an extensive post-treatment analysis synthesizing the outcomes from 91 restoration projects in European rivers on fish, invertebrate, and macrophytes assemblages (richness/diversity and abundance/biomass).[55] The relative importance (%) of eight variables (or predictors) on combined effects for all organism groups is shown. Box-plots indicate quartiles, range, and outliers of 10 replicate model runs (boosted regression tree model; total variance explained = 0.41; n = 353 response ratios). Project age and river width account for the highest relative importance. Reprinted with permission from Ecological Indicators, Ref. 55. Copyright 2017 Elsevier.

intervals (e.g., every 4 years in Switzerland). Harmonizing ProME with these policy cycles facilitates feeding back the lessons learned for adaptive management (principle 8). Second, the time required to answer a question will vary depending on the question itself (principle 4) and the design used (principle 5).

How? Collaborative learning within ProME does not happen on its own, but requires careful planning. Strategic decisions from the program partners are needed, i.e., the program partners have to agree on where they want to learn and for how long.

Where to learn (i.e., from which projects): Several criteria must be considered for project selection for ProME, including

- *transferability*: projects which are representative of the topics of interest and from which the knowledge can be transferred to comparable projects,

- *interpretability*: requires projects in catchments with minimal interference by additional stressors outside the focus of the selected questions,
- *temporal persistence*: projects which are suitable for long-term monitoring due to few expected changes in the catchment,
- *availability of reference and control sites*: projects which have available references and controls.

When to learn: Timing and duration of ProME must account for the duration of the required work (principle 5) and the requirements of policy-makers and stakeholders, so that clear answers are delivered in a timely manner. Some questions might be more urgent than others (see principle 5), e.g., one might prefer addressing quick wins in a first round of ProME and then treat other relevant, but less urgent questions in a second phase.

Principle 8: Process and Disseminate the Findings

Why? ProME creates masses of data that need to be processed, analyzed, and disseminated as effective products. Products have to fulfill different requirements, which depend on the target audience. For ProME, two broad target groups can be distinguished—(1) the program partners and other stakeholders that are directly involved in river restoration and (2) the wider public. Feeding back the findings from ProME, i.e., the answers to the specific questions (principle 5) to the program partners is the basis for adaptive management and collaborative learning. Distributing information on river restoration to the wider public promotes a wider understanding of the strengths and challenges in river restoration practice and helps to justify the resources used and to manage expectations. New policy can be informed,[60] including in other fields such as hydropower mitigation, flood risk management, and nature conservation, which all revolve around the same river channel and hydrological regime and should be well integrated.

How? Depending on the target group, products can have very different formats (e.g., quality-controlled raw data, newspaper articles, technical recommendations, Facebook posts, and short movies for environmental education).[6] Careful pre-discussion with the future users is needed as there is a risk of high costs and low benefits. Quality-controlled raw data from ProME must be archived in a central searchable database that is accessible to all program partners. Apart from the analyses within ProME, the data base should allow for an independent learning process by different stakeholder groups. Central storage of and access to data requires clear responsibilities and standardized procedures for database management, quality assurance, and quality control. Data sharing must be actively promoted, i.e., by financial incentives in the funding process. Data ownership has to be clarified. Positive and negative outcomes must be shared.[23] Processing, analysis, and dissemination requires allocated resources (see principle 1) and can be done by the program partners or via mandates to external specialists, e.g., for knowledge transfer.

Principle 9: Review the Program at Regular Intervals

Why? Over the course of ProME, lessons will be learned from answering specific questions about how we restore and how we monitor (principle 5). This results in a refined understanding of river restoration and its effects and, in turn, in updated assumptions, reframed problems, and a redefinition of the type of knowledge required.[9] Adaptive monitoring as stated by Lindenmayer and Likens[10] is an iterative process in which question setting, data collection, analysis, and interpretation are followed by a review or reflection phase and, potentially, an adaptation of the program. Included in this acknowledgment of lessons learned is the consideration of environmental, technical, and socio-cultural change. The development of novel techniques may allow for cheaper or more effective field surveys and analyses to be incorporated in ProME (e.g., remote sensing).[61] Shifts in societal perception or environmental agendas may require previously unconsidered aspects to be included. Unpredictable large-scale processes such as climate change can lead to surprising ecosystem transformations necessitating adaptation in management and monitoring.[33]

How? Regular systematic review and potential adaptation of ProME must be explicitly planned from the beginning. Lessons learned must be collected explicitly and in a structured way in order to make them available for later decision-making about the next steps in ProME.[9] Careful documentation is needed to illustrate the learning process and to make it traceable,[9] also in retrospect. Such transparency is particularly crucial in transdisciplinary partnerships with several stakeholders involved. As with the initial launch of ProME, reflection and decision-making on

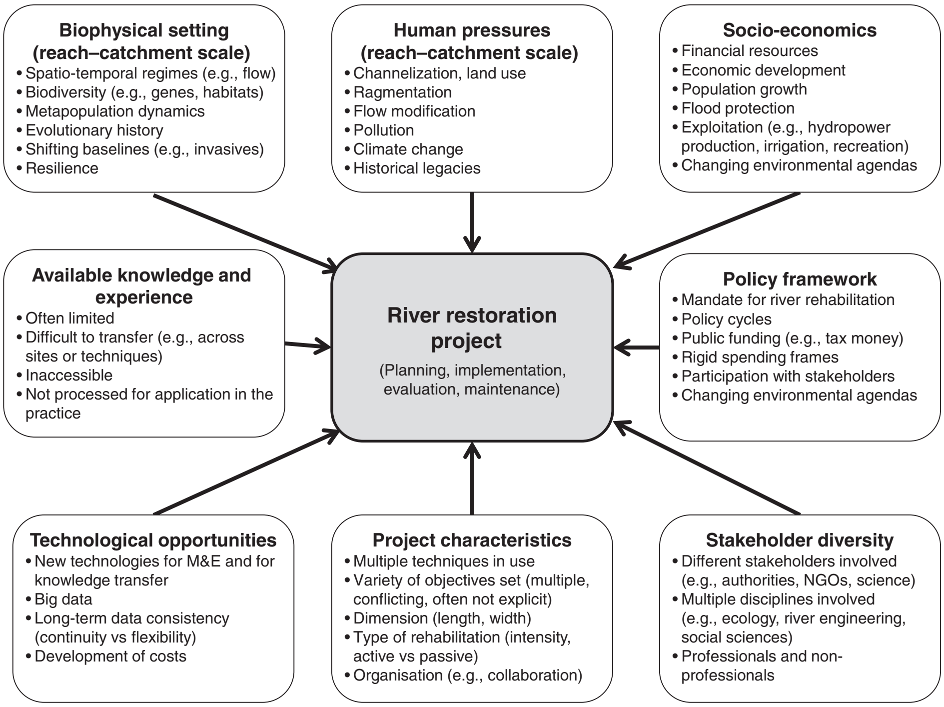

FIGURE 3 | Illustration of the wider context in which restoration projects are planned, implemented, evaluated, and maintained. Factors can be interlinked (not shown).

whether and how to adapt ProME must be a collaborative activity involving all program partners. The socio-cultural and technical development has to be closely followed in order to capture emerging issues and future challenges. Providing data consistency over the long-term is an important prerequisite for analyzing responses that can be slow or time-lagged.[10] The costs and benefits of a program adaptation have to be critically evaluated, i.e., one has to find a good balance between continuity and flexibility.[16]

BEYOND THE SUGGESTED FRAMEWORK

The framework suggested above offers many opportunities for extension and synergies.

First, instead of comparing project by project, within and beyond project boundaries, cumulative effects of multiple restoration projects and other management measures could be analyzed. This idea builds on the concept of distinguishing ORUs (Operational Restoration Units) that are based on organizational 'landscapes' that consider policies, stakeholder requirements, and planning agendas.[30] The ORU idea is partly treated in our concept by integrating explanatory variables in the analyses that account for influencing factors beyond the given restoration project. However, addressing cumulative effects could also require specific adaptations of the sampling design.

Second, hypothesis testing as outlined in principle 4 can be further strengthened by running systematic field experiments[31] over several years at specifically selected, spatially replicated sites where the techniques used are standardized as far as possible in order to increase comparability. Similar approaches have been used in the literature, both for river restoration[56,62] and for other management areas such as environmental flows[63,64] and have yielded interesting insights. For instance, Gowan and Fausch[56] found that habitat indicators such as mean depth or pool volume increased significantly within 1–2 years after in-stream restoration of six Rocky Mountains streams compared with untreated control sections. The increase in abundance and biomass of adult, but not juvenile, trout was mainly due to immigration from beyond the reach boundaries.

Third, universities and other institutes of higher education could develop specific student projects or training courses to answer selected questions, e.g., regarding mechanistic links. Program funders could be encouraged to facilitate such possibilities for education and further development.

Fourth, the findings from ProME could be supported by additional indicators and data retrieved from citizen science following standardized protocols.[65,66] Participation of local volunteers can be very fruitful, for instance by expanding the spatio-temporal scale of the surveys, with more frequent sampling and larger areas covered than within professional surveys. However, aspects related to data quality, data availability, data influence, and social contexts of citizen participation have to be carefully considered.[65–67]

CONCLUSIONS

More coordinated ME activities are needed in order to make full use of the opportunities offered and the resources spent within river restoration. Our conceptual framework for ProME presents a structured approach toward a more systematic learning and evidence-based action in river restoration, while taking into account the wider context within which river restoration projects will inevitably operate (Figure 3). However, transferring a conceptual framework into practical application is a challenging endeavor—an acid test for all underlying assumptions. Consideration of the following aspects can facilitate the process:

- Compare alternatives: Very comprehensive approaches to ProME run the risk of substantial costs or later cost-overruns, e.g., due to tasks that were underestimated or completely overlooked in the budgeting phase. A critical estimation of costs is needed beforehand by means of a structured comparison of ProME alternatives that also takes into account time-consuming preparation and coordination work (e.g., principles 1 and 3).
- Carry out implementation monitoring: Good knowledge and documentation of the characteristics of each project (e.g., techniques used, objectives set, and intensity of restoration; Figure 3) are needed for a thorough analysis of the effects of river restoration. This stresses the importance of sound implementation monitoring as part of ProME.
- Run a pilot test: A practical application of the planned surveys in the real world situation provides a useful check of the strength and weaknesses of the chosen approaches and the robustness of the estimates regarding temporal, personnel and financial resources.

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