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Communication

Monitoring and Evaluation: The Foundation for Lake and Reservoir Management

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Abstract: In this paper, we review the evolution of environmental monitoring, from its earliest days of exploration and increasing understanding of ecosystems and environment through the development of models and similar tools, to the current application of monitoring to assess project achievements. We note that information gathered through environmental monitoring is critical in evaluating the applicability of models and the accuracy of remotely-sensed information, and supporting the role of citizen science in the acquisition of environmental data. As monitoring increasingly is applied to project management, we identify the nexus between environmental and project management as needing to have purpose; observing that the purpose of monitoring evolves over time. This evolution is supported by the evaluation or assessment of the data—environmental and management related—over time, making monitoring and evaluation foundational for sound environmental management, restoration, protection, conservation, and understanding of ecosystem values.

Keywords: monitoring; evaluation; environmental data; citizen science; modelling; project management; socioeconomic value

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1. Introduction

Had someone mentioned monitoring a few decades back, thoughts would have immediately focused on the acquisition of environmental data as the basis for evaluating the status of a waterbody or other element of the natural environment. Data acquisition was seen as the basis for making ecosystem evaluations, the outcomes of which underpinned the direction and implementation of remedial actions. Insofar as nutrient pollution was concerned, programs such as the National Eutrophication Survey of the US Environmental Protection Agency [1] and similar programs worldwide [2,3] were initiated and carried out to determine the extent and criticality of nutrient enrichment of waters. Indeed, the pollution-directed core focus of the 1972 United States federal Clean Water Act (CWA) was to "eliminate" the discharge of pollutants in order to "restore and maintain the chemical, physical and biological integrity of the Nation's waters". Surveys commensurate with the achievement of this goal were supplemented by more local level investigations including those at the regional and provincial levels [4].

These programs were supplemented and supported by handbooks outlining good practices and standard methods for data acquisition. Of these, the American Public Health Association Standard Methods for the Analysis of Water and Wastewater [5] is one of the most well-known and widely-used reference guides. This volume is now in its 23rd Edition. Additionally, the International Biological Program (IBP) published a series of manuals on the collection of environmental data including data on water systems [6–9]. These and other publications were seen as necessary to standardize the monitoring of the earth's environmental systems. Eventually, in 1978, these efforts crystallized into the Global

Environmental Monitoring System (GEMS) which forms a platform to acquire and share environmental data, GEMS Water being the only active part of this vision which was established and continues to this day.

More recently, monitoring and evaluation have become associated with project and program management. The Global Environment Facility (GEF) adopted frameworks for implementing business management practices for monitoring and evaluation (M&E) of development and environmental protection activities during 1997, and the terminology and practice has since become synonymous with the project cycle in organizations around the world [10]. M&E in this context is the practice of acquiring data on the execution of activities, evaluating these data against milestones or anticipated project stages, and informing changes in activities to respond to unforeseen events or occurrences (adaptive management) as countries and institutions seek to implement programs such as the Millennium and Sustainable Development Goals.

This shift in understanding of the practices and processes of monitoring and evaluation also coincided with the increasing costs of staff and data gathering which provided an impetus to move toward more model-based assessments and remote sensing technologies. While the latter technologies have broadened the ability of agencies to collect information, that information has to be processed and evaluated against the more traditionally gathered environmental data. This so-called ground truthing also is an important but often overlooked element of modelling, where mathematical constructs may not always reflect the actual status of the environment. In an effort to redress some of this imbalance, citizen science is assuming an increasingly important role in the acquisition of environmental data. Furthermore, the analytical “reach” afforded by monitoring may be adversely limited by the cost of inclusion of parameters which provide fine-level insight on the intervention: response continuum. All too often high-level parameters (e.g., pH, conductivity) are relied on, but which provide very limited information in, for example, instances where isotope tracking of pollutants in a foodweb would be appropriate. In instances where easy-to-collect data such as water transparency play an informative role, citizen science is assuming an increasingly important role in the acquisition of environmental data which in part contributes to the understanding by local communities and stakeholders with regard to the multi-faceted values of ecosystem functions and services. In the latter instance, the progressive advent of “smart” technologies, which facilitate the collection of data absent the need for laboratory analysis, have revolutionized “at the lakeside” monitoring.

In this paper we examine the concepts involved in monitoring and evaluation in both its data gathering and project management forms and emphasize the roles of each in lake and reservoir management. This paper confronts some present-day issues, which despite their “age”, remain entirely relevant on a recurring basis. Monitoring approaches exist in a dynamic space that must respond to contemporary needs. As such, it is critical that monitoring be subjected to periodic evaluation to ensure that programs maintain their stated purpose of informing communities, policies and remedial practices.

2. Water Quality Monitoring

In the early years of the twentieth century, a number of expeditions were conducted to various parts of the world to collect data on waterbodies, their chemistry, physics and biological composition. These expeditions were in response to the growing awareness that the responses of waterbodies differed, based upon their location within the landscape, land uses, and climatic conditions [11,12]. These studies included data gathering from Asia [13], Africa [14], and the Americas [15], and the knowledge gained from these expeditions and other studies gradually brought the focus of water quality investigations onto plant nutrients, specifically carbon, nitrogen and phosphorus. While studies continued to highlight the role of other elements such as the micro-nutrients, the publication of the seminal paper by Redfield brought the focus firmly onto phosphorus as the most controllable of the three macro-nutrients [16]. Controllable in this sense was an expression of the ease with which the specific elements were able to be removed from sewage prior to discharge into the natural environment. The preeminent position of phosphorus in this treatment train was further reenforced by the publication in the mid-1960s of the phosphorus–chlorophyll relationship [17], which finding provided the foundation for the later work of Vollenweider and the Organization for Economic Cooperation and Development (OECD) [18,19], which is discussed further below.

During the mid-twentieth century, several notable environmental failures resulting in public outcries prompted widespread monitoring of environmental conditions as increasing discharges of wastewater, with varying degrees of treatment, had led to massive algal blooms around the world [20,21]. This, in turn, resulted in the development of improved wastewater treatment processes such as the activated sludge process [22] that addressed concerns regarding nitrogen and phosphorus [23]. More recently, in response to the observed continued enrichment of surface waters, efforts to control nitrogen and phosphorus have turned toward the management and control of nonpoint or diffuse sources of these nutrients [24]. Recent years have enfolded a progressive movement towards watershed level, "source to sea" governance programs for water resources.

Concurrent with this search for a "controlling" or "limiting" nutrient which could address the need to limit the enrichment of the aquatic environment was the search for an "indicator" organism or community of organisms that would serve to document the determination of water pollution. Bacteria, especially *Escherichia coli*, had performed this role in part since the nineteenth century [25]. *E. coli* continues to be a focus for wastewater treatment with standards promulgated by the World Health Organization [26]. More recently, emphasis has been placed on fecal coliform: fecal streptococcus ratios as being relevant to distinguishing human coliform contamination from contamination by other mammals, while the emergence of gene tracking technologies has allowed even more precise determination of bacterial sources [23,27].

In the natural environment, the use of indicator organisms was spurred on by the use of various organisms to describe the status of rivers and streams [28], and the development of various biological indices for use in fisheries management [29]. The use of such indicator species has resurged with its use as part of volunteer monitoring programs [30], and in wider applications as part of water quality indices such as those developed for use in the inter-tropics [31,32].

2.1. Water Quality Modelling

The escalating costs associated with water quality monitoring programs and the publication of the phosphorus–chlorophyll relationship and various iterations of the OECD models, as well as the inability of monitoring to provide the forecasts necessary to support the development of wastewater and stormwater management practices which were becoming increasingly sophisticated and expensive, spearheaded a move toward the use of mathematical relationships as the basis for justifying water quality interventions [33,34]. From these basic beginnings, water quality modelling has become more significant as the basis for water quality management. Modelling is the critical element of the total maximum daily load (TMDL) allocations adopted by the United States Environmental Protection Agency (US EPA), for example, and is increasingly used in managing catchments (=watersheds, drainage basins) [35,36]. While modelling does provide the ability to forecast future conditions in waterbodies, modelling utilizes average lake responses and conditions, and not all waterbodies respond to interventions in an average manner [37]. The application of TMDL protocols is globally generic and provides a means of auditing nutrient load generation in a manner which dovetails with regulatory protocols such as South Africa's waste discharge:charge system (WD:CS) for wastewater effluents. Consequently, environmental monitoring remains a vital element in the toolbox of environmental management practices.

2.2. Citizen Science and Water Quality Monitoring

Citizen science or volunteer monitoring has become an important part of environmental monitoring in response to the ongoing needs for ground-truthed information or hard data in the validation of model output and in establishing linkages to communities. Moreover, such involvement of citizen resources aligns directly with the public trust whereby citizens are beneficiaries of a public trust in water functions, together with the sovereign nation, as co-trustees of life-supporting natural resources such as water. As an increasing proportion of civil society professionals and others reach retirement age, the quality and extent of citizen science involvement continues to increase [38]. This phenomenon is seen around the world [39–41] and it is an essential element of connecting citizens to their environment [42]. While the significance of citizen science is still developing, there is little doubt that it plays an important part in environmental monitoring in the 21st century. What is missing in some developing countries such as South Africa, for example, is any commitment towards ensuring that "retiring" accumulated professional wisdom and experience is translocated into the citizen science arena. This unfortunate situation often arises from a lack of recognition that human resource capacity is not confined to within state agencies but in fact is present and available throughout society. As such the challenge becomes how to effectively harness and nurture this resource on a sustainable basis. Indeed, the distribution of humans across the surface of the earth is such that citizen science can augment data collection (and analysis) across a range of environments, providing the necessary linkages between environments, media, and communities [43–45]. In the socioeconomic arena, citizen participation data have been used in some processes of measuring the values of ecosystem functions and services (including water quality and other aspects) [46–48].

3. Project and Program Monitoring

In recent years, the term monitoring increasingly refers to tracking the progress of a project or program and involves an emphasis on achievement of "milestones" which often include financial elements (budgets and budgetary expenditures). While often seen as a "bookkeeping" or "box-ticking" exercise, such monitoring is a response to the increasing costs associated with environmental interventions. Such monitoring generally follows a sequence from activity (an action or series of actions to meet a specific purpose) to output (a report, document or agendized meeting with minutes) to outcome (a change or response to the output or outputs). Like environmental monitoring, project monitoring involves the acquisition of data or other information, including financial information, to track compliance with a predetermined series of actions. Planning is essential as it should establish a milestone or series of milestones against which progress can be tracked.

Various frameworks have been developed to guide such project monitoring programs, including the driver-pressure-state-impact-response (DPSIR) framework [49], root cause analysis, and logical framework [10], although other terminology can be applied; for example, impact is often substituted for outcome, both of which refer to the results of an activity stemming from the project output. Figure 1 presents a generalized outline of project and program monitoring, which begins with the identification of a problem or concern that leads to an action being initiated. In terms of the aquatic environment, this sequence is typically initiated by citizens (or a community) who observe a situation that differs from their expectation or by an agency who suspects or determines that certain requirements such as legally-established contaminant levels have been exceeded. Such observations then lead to an investigation and specific recommendations arising therefrom (the output). Investigations may require an agency or other entity to conduct studies, or observations may be based upon the outputs of citizen science that help to quantify the concern and support a specific response. That response generally requires change within a community, whether a civil society community or an industry-related community of practice. Such change can be voluntary or required by law as in the case of water laws adopted by governments. Such change results in a new set of conditions being observed which are either acceptable to the community or which initiate a new set of actions. The most effective projects and programs are collaborative and cooperative between government and civil society, between experts and citizens.

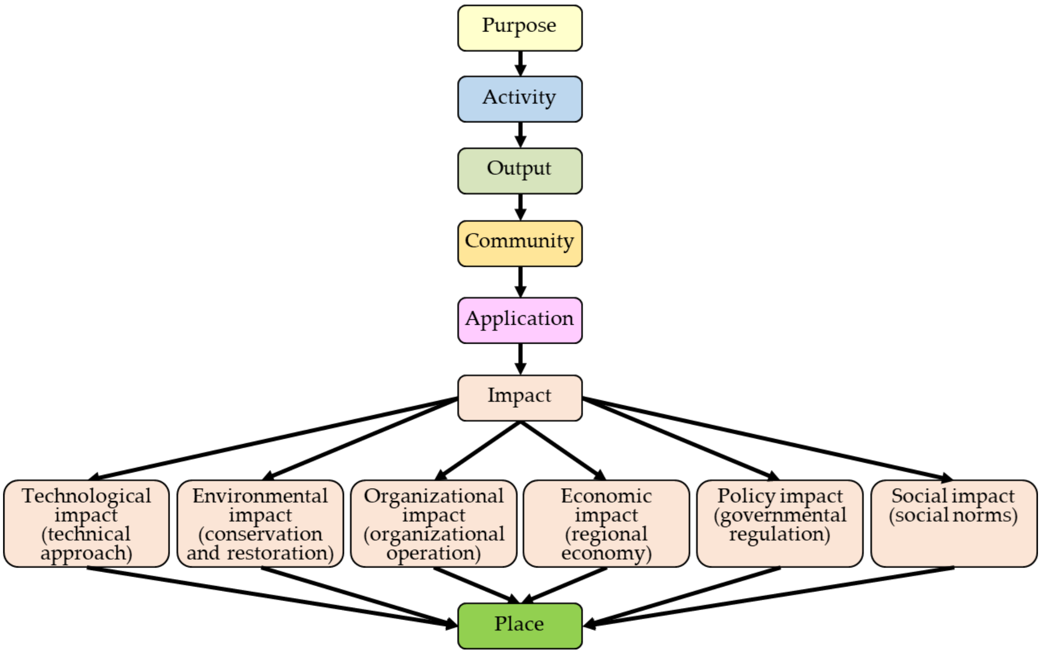

Figure 1. A common framework of program monitoring and evaluation.

As outlined above, effective monitoring, i.e., monitoring which embodies a high probability of providing a clear empirical indication of the outcome of an intervention, can be costly. However, the costs of monitoring that only provide "administrative comfort" are likely to be infinitely more costly in that the water resource may be irretrievably harmed. Fortunately, there is an increasing availability of technologies which support data gathering by non-specialists or which reduce the reliance on laboratory analysis–with the associated time and cost factors.

4. Discussion

The nexus between environmental management and project or program management can be summarized in the word "purpose". It is not infrequent that environmental monitoring takes on a "life of its own" with the emphasis being on the work, and the work consumes time and effort such that there is no time available for analysis or evaluation. In many instances this equates with the "administrative comfort" monitoring mentioned above, all is deemed to be well while results are being filed away on a regular basis, creating the "seen to be doing something" characteristic of many bureaucracies. In addition and equally frequently, environmental monitoring carries on well beyond the initial expected lifespan as there is little time or inclination to evaluate the data and its relevance. That is not to say that long-term monitoring has no value: the value of long-term monitoring is demonstrated by the Long-Term Ecological Research Program of the US National Science Foundation which has recently completed 40 years of study [50], with their findings informing policies and practices at the global scale. To this end, the ongoing project has "purpose" and there is frequent review and analysis of the data collected. In general terms, however, experience shows that all too many monitoring programs are temporally short, spatially inadequate and lacking the inclusion of high-value outcome parameters.

In a similar fashion, the US Geological Survey (USGS) conducts regular monitoring of the nation's environment. In recent years, their efforts have been directed by the needs of communities with monitoring programs transitioning to Trophic State Index (TSI) monitoring. These data are reported annually [51], with the reporting occurring digitally in recent years. These regular data collection activities are further supported by limited-term, targeted data collection and research activities [52]. These data, in turn, are utilized by local governments, planning authorities, research institutions and universities as authoritative sources of data and analysis [53]. Consequently, these data have a purpose in guiding the decisions made by various organizations and influencing actions such as land use planning, stormwater management, and regional water quality management. These latter activities conform to project or program monitoring with regular updates being mandated by US federal laws such as the Clean Water Act [54], and supplemented by state and local requirements [55]. For example, regional water quality management plans should be updated at (approximately) decadal intervals to account for changes in population, land use, and the state of wastewater treatment including stormwater treatment [56–58]. Such decadal reviews typically coincide with the decadal census undertaken by many countries, thus ensuring the continued currency of the plans and recommended actions. These updates also ensure that the plans and resulting infrastructure continue to meet the purpose for which they were initially intended, and that emerging issues and concerns can be addressed.

Clearly, monitoring is required in these cases for several purposes: to ensure that the desired impact or outcome of the intervention is being achieved, to account for the changing nature of contaminants (as in the case of pharmaceuticals, carcinogens and mutagens, for example [59–61]), and to account for changing societal demands that are in the public interest and for changing affordability of communities in balancing economic development and environmental conservation. The Southeastern Wisconsin Regional Planning Commission (SEWRPC), for example, has produced several editions of their lake and catchment management plans to account for changing communities and community expectations, such continued and dynamic realignment conforming the principles of the public trust in water [62–64]. In the case of Pewaukee Lake, the initial plan addressed wastewater treatment as a primary mechanism to manage in-lake water quality. The subsequent editions addressed catchment-related concerns including stormwater and lake use, while interim plans addressed other concerns such as public recreational boating access [65]. Consequently, monitoring data provided the necessary insights into the response of the waterbody to various interventions that included modification of the flow control structures at the outlet of the Lake [66]. Agency-collected data were supplemented by citizen science data collected under the auspices of the Citizen Lake Monitoring Network [67], and remotely sensed data.

Monitoring cannot be done away with, but what can be done is to ensure that monitoring be done more efficiently, both in terms of what is monitored and why, and how the parameter is measured (e.g., expensive and time-consuming wet chemistry versus "lakeside" sensor-based measurement). This is especially relevant in countries such as South Africa and probably in most others as well. Additionally, sensor-based monitoring can draw in citizens (farmers, vets, agricultural extension officers) into a continuum of monitoring capability which ranges from full laboratory analysis at the one end to Secchi disks wielded by lakeside property owners at the other, and a progression of sensor-based, test kit and other technologies in-between. Using such a range of technologies can (a) spatially expand the network of monitoring capabilities and (b) in all likelihood expand the basic citizen-level understanding of water chemistry. While there will be concerns expressed about quality control and quality assurance (QA/QC), such concerns regarding the accuracy of observations can be accommodated by the routine dissemination of test samples (as is done as part of many volunteer sampling programs with chlorophyll testing and measuring of other parameters such as algal toxins) to participants in a form of "inter-laboratory comparative analyses". In many cases, 100% accuracy is not the goal, but rather the focus should be on getting data either from as many sites as possible or from a single site very frequently. In cases where citizen science and agency data differ, the responsible agency must either (a) accept the citizen-obtained values as correct and act accordingly or (b) conduct their own monitoring in parallel with the citizens—a process which should eventually "prove" which technologies provide reliable results in waters of different "types".

In addition, the evolution of lake and environmental quality modelling has supplemented observational data and the resultant models provide the ability to forecast future conditions [68,69]. Such forecasting allows the development and introduction of remedial measures in a timely manner, with costs budgeted and amortized over a period of years. Nevertheless, as noted above, modelling results should be ground-truthed against observational data to ensure that the waterbody is responding in a predictable manner. The variety of factors acting on a waterbody can modify the responses of a specific waterbody such that the model outputs differ from the observed situation in the lake or impoundment [70]. In such cases, as in all cases, evaluation of the data is an integral part of the process of management and is closely associated with the monitoring effort.

Evaluation will allow and underpin changes or modifications to the monitoring program, both from a managerial perspective and from the perspective of retaining relevance for environmental assessment. In the lake and catchment management programs of the Southeastern Wisconsin Regional Planning Commission, evaluation of the responses of waterbodies to point source controls in the form of wastewater treatment plants and processes has resulted in an additional emphasis on nonpoint sources of contamination. While there is currently little appetite in the state Legislature for placing further regulations on farmers, who represent the largest land areas draining to waterbodies in the state of Wisconsin, the farmers themselves have often adopted more efficient farming practices as a cost-saving device. In the case of George Lake, one of the farm owners embarked on a nutrient management planning program to prove the academics wrong. However, the individual soon discovered that input costs were reduced as agrochemical consumption was reduced. This reduction in ploughing and tillage and agrochemical application, in turn, benefited the downstream waterbody by reducing nutrient inputs and sediment in runoff [70]. The reduction in nutrient inputs led to an improvement in lake water quality, which benefited the entire riparian community.

5. Conclusions

Monitoring and evaluation form essential components of both environmental management programs and project management activities. Whether the monitoring involves field measurements, modelling, or remote sensing, it is important to track the condition of natural resources and to understand the response of systems to external (or internal, in the case of alum application, for example) stimuli. Failing to conduct appropriate monitoring (including ground-truthing modelling data and remotely sensed data) can lead to the failure of often costly interventions. Even in the case of long-term trend monitoring, data acquisition should be periodically evaluated to ensure that the relevant parameters are being monitored, and programs should be amenable to modification as needed. Emerging concerns such as cyanobacterial toxicity or the presence of potentially mutagenic or carcinogenic materials and pharmaceuticals in rivers and lakes need to be considered. The inclusion of such parameters is often a financial consideration so there is a tendency to rely on modelling rather than field observations, but model outputs need to be tested against actual field conditions. In such cases, long-term sampling may not be required if the model results approximate the actual observations, but these should be periodically checked to ensure that such agreement is maintained. Legally required plan updates, for example, may provide a basis for undertaking such field checking of model outputs. In a similar fashion, monitoring is necessary to track progress in plan implementation and application of remedial measures. In this regard, citizen science provides an opportunity to extend its data gathering capacity and supplement environmental outreach efforts by connecting citizens directly to the data that underpin policy and regulation. As communities change and evolve over time, issues of concern may change or be resolved. Consequently, without monitoring and evaluation, significant effort can be mis-directed. Environmental management requires a comprehensive, collaborative and cooperative effort between governments and citizens to identify concerns, generate solutions, and implement policies and activities that work to the resolution of concerns. For these reasons, monitoring and evaluation form an essential foundation for environmental management from an environmental point of view, from a project or program point of view, and from a socio-economic point of view.

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