Progress on Nonpoint Pollution: Barriers & Opportunities

Adena R. Rissman & Stephen R. Carpenter

Abstract: Nonpoint source pollution is the runoff of pollutants (including soil and nutrients) from agricultural, urban, and other lands (as opposed to point source pollution, which comes directly from one outlet). Many efforts have been made to combat both types of pollution, so why are we making so little progress in improving water quality by reducing runoff of soil and nutrients into lakes and rivers? This essay examines the challenges inherent in: 1) producing science to predict and assess nonpoint management and policy effectiveness; and 2) using science for management and policy-making. Barriers to demonstrating causality include few experimental designs, different spatial scales for behaviors and measured outcomes, and lags between when policies are enacted and when their effects are seen. Primary obstacles to using science as evidence in nonpoint policy include disagreements about values and preferences, disputes over validity of assumptions, and institutional barriers to reconciling the supply and demand for science. We will illustrate some of these challenges and present possible solutions using examples from the Yahara Watershed in Wisconsin. Overcoming the barriers to nonpoint-pollution prevention may require policy-makers to gain a better understanding of existing scientific knowledge and act to protect public values in the face of remaining scientific uncertainty.

Water is an important, dwindling resource. Water and aquatic ecosystems support industry, agriculture, outdoor recreation, aesthetic pleasure, aquatic food sources, and livelihoods. Massive, expensive efforts have been made to improve water quality and "repair what has been impaired."[1] These efforts have led to some important gains, but water quality is still poor in many rivers, lakes, and coastal oceans. Runoff of soil, nutrients, and other chemicals from agricultural, urban, and other lands is called nonpoint source pollution. In contrast, point source pollution comes directly from a pipe, such as at an industrial or municipal facility. Runoff of phosphorus – also called nonpoint phosphorus pollution – is a major cause of toxic algae blooms, oxygen depletion, and fish kills in streams, lakes, and reservoirs.[2] Why are we not making progress on nonpoint source pollution in water quality? What are the chal-

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lenges of producing science to predict and assess nonpoint management and policy effectiveness, and of using this science in management and political decisions? Finally, what changes are needed to improve water quality?

A major scientific enterprise is devoted to producing scientific knowledge to inform nonpoint policy and management through long-term monitoring, statistical analysis, and modeling. But is scientific knowledge actually reducing uncertainty about the causes of water-quality impairment and the effectiveness of control measures? Researchers are increasingly vocal about the challenges facing nonpoint-pollution science on sediment, phosphorus, nitrogen, and other pollutants.[3] For instance, it is well-established that end-of-pipe mitigation of phosphorus improves water quality, but proving the effectiveness of actions to control nonpoint-source phosphorus is challenging. It is extremely difficult to demonstrate causality when connecting water-quality conditions to policies and the behaviors of agricultural and urban residents. An increase in knowledge and data has therefore not always translated to more effective policy.

Once scientific knowledge is produced, why is it so difficult to use it as evidence in nonpoint pollution–related policy-making and management? Science does not determine public interests and values, but it can serve important purposes in policy-making and resource management.[4] It can identify problems, prioritize the location or type of interventions, identify the likely effects of actions before they are taken (including anticipating unintended effects), and evaluate the effects of actions after they are taken.[5] Science and society affect each other deeply.[6] It is important to understand how scientific evidence, models, uncertainty, and risk enter into the decisions of actors such as the Environmental Protection Agency (EPA), county conservationists, farmers, urban homeowners, and lake managers. We will illustrate how scientific information has been created and used to improve water quality in Wisconsin's Yahara Watershed, focusing on watershed nonpoint-pollution reduction and in-lake biomanipulation.

Water pollution is typically viewed as an externality that does not directly subtract from the productivity of those responsible for the pollution, except indirectly or through social limits. This means that producers of pollution are not inherently incentivized to remedy it; the issue of assigning responsibility becomes even more difficult with the diffuse nature of nonpoint source pollution. The difficult issue of nonpoint source pollution has led to a proliferation of blended regulatory, incentive, and collaborative efforts to engage homeowners, municipal stormwater systems, and farmers in reducing nutrient and sediment runoff.[7]

Building scientific evidence for nonpoint pollution is long, slow, and scale-dependent. Given the rapid changes taking place in ecological and social systems, is the baseline moving faster than we can learn? We suggest that, in addition to science, political will and public value should play a greater role in decision-making to improve environmental outcomes.

There are a number of difficulties inherent in producing knowledge about nonpoint-pollution control. First, a growing number of studies from around the world show that it is extremely difficult to determine the efficacy of interventions aiming to reduce nutrient runoff from watersheds. In many cases, freshwater quality has not been found to have recovered even after decades of nutrient management,[8] and the divergent explanations for lack of success reflect the complexity of watersheds as social-ecological systems.[9] Despite the urgent need for management interventions to protect freshwaters, there is a high level of uncertainty about the efficacy of methods; indeed, there may be fundamental limits to our knowledge of this subject. It is not clear whether watershed management is making progress on uncertainty; for now, the success or failure of policies may be a matter of luck rather than knowledge. For this reason, it is important to consider the barriers to the production of knowledge about nutrient policy and management and the opportunities to improve scientific understanding in this area. We will explore the reasons for the difficulty of demonstrating causal effects of nutrient-management policies in large watersheds, including: long time lags between intervention and response, spatial heterogeneity (that is, a solution that works in one site may not work in another), simultaneous changes in multiple pollution drivers, and lack of monitoring.

Nonpoint pollution–management programs involve large areas with multiple nutrient sources; many individual land managers; spatially heterogeneous topography, soils, and ecosystems; and diverse streams and lakes. Specific practices for ameliorating pollution – such as buffer strips, cover crops, tillage practices, and wetland restoration – are usually tested on relatively homogenous sites at scales of a few hectares for a few years. While these methods are effective in short-term, small-scale field trials, little is known about how they scale up to whole watersheds.[10] At the watershed scale, new sources or sinks for phosphorus and new interactions along flowpaths could emerge and lead to surprising outcomes. It is plausible that spatial interactions (such as movement of soil from one area to another) contribute to the observed failures of large-scale nonpoint-pollution management.

Interventions to mitigate nutrient inputs also have delayed effects because of the slow response of nutrients in the environment.[11] Time lags ranging from one to more than fifty years have been measured between the initiation of a management intervention and the observation of an environmental response.[12] Projections estimate that interventions to cut off phosphorus fertilization of soil will take two hundred and fifty years to produce a new, low-phosphorus equilibrium in the agricultural lands of a Wisconsin watershed.[13] In a diverse set of watersheds, response times for nutrient interventions ranged from less than one year to more than one thousand.[14] Such long time lags pose serious difficulties for scientific inference and for sustaining the engagement of the public and policy-makers.

Furthermore, many factors that affect water quality change simultaneously. For example, precipitation, land use, agricultural management practices, and ecological characteristics of lakes and streams are always changing.[15] Effects of management interventions to improve water quality must be discerned against this background of multiple changing drivers, each of which affects water quality. The lengthy response time of the environment compounds this difficulty. Ecosystem scientists generally employ an array of approaches, including observing paired reference ecosystems, to distinguish between the effect of the intervention and that of other changing drivers.[16] However, these tools of inference are rarely applied to nonpoint pollution–management programs.

Lack of monitoring is a common defect in nonpoint pollution–control programs. Without before-and-after observations of nutrient loads and water quality, it is impossible to determine an intervention's effectiveness in reducing nutrient runoff. Because of the previously mentioned long time lags, monitoring must be sustained for years or decades. The monitoring of nonpoint-pollution projects rarely employs reference watersheds, which are commonly used in ecosystem experiments. Reference ecosystems help separate the effects of other simultaneous changes from the effects of the intervention. Two neighboring watersheds, one mitigated and the other not, may have similar biogeochemical and hydrological characteristics and experience the same weather, but only the mitigated watershed should show effects of nutrient management. If it becomes clear the actions are working, then the reference watershed can also be managed.

Nonpoint control programs are sometimes evaluated by enumerating the number and size of conservation practices established instead of the nutrient characteristics of lakes and streams. While the number of conservation practices is important, reaching target nutrient loads and water quality is the ultimate goal. These metrics of water quality must be measured before and after the installation of the mitigation practices in order to evaluate the effects of the program.

How, then, should nonpoint pollution be addressed? Decision-makers and the public should expect slow responses and high uncertainty. Nonpoint-pollution management plans will be easier to explain if they include explicit plans for measuring and managing uncertainty. Sustained monitoring that includes measurements of nutrient outcomes is essential. Simultaneous monitoring of multiple subwatersheds (including a reference subwatershed) can reduce uncertainty by accounting for the effects of changes in weather, agricultural production, and development.

Policies for nonpoint-pollution management assume that outcomes will be predictable.[17] Models used for nonpoint-pollution planning tend to be complex computer programs with large numbers of parameters, often exceeding the number of observations from actual watersheds. Such models support a culture of spurious certainty that sets the stage for disappointment when freshwater ecosystem responses turn out to be slow, variable, and influenced by multiple changing forces. Instead, research is needed on the dynamics of uncertainty itself. For example, it would be helpful to observe unmanaged watersheds over the long term to understand how baselines are moving.[18] What is the frequency distribution of extreme nutrient loads and how is it changing? How can we best use landscape heterogeneity to understand multiple drivers through comparisons among subwatersheds? How can the planning process engage a broad cross-section of society, make the best use of science, and create realistic expectations about response time, variability, and uncertainty? Questions about the nature and management of uncertainty are moving to the foreground as society grapples with the expanding impact of nonpoint pollution on freshwaters.

How do management interventions affect complex systems such as lakes? Our ability to draw conclusions depends in part on experimental design and in part on how immediately the environment responds to a given change. During the 1970s, ecologists demonstrated that phosphorus pollution was the underlying cause of algae blooms in lakes.[19] In one key experiment, a lake was divided in half and enriched with carbon, nitrogen, and phosphorus on one side and only carbon and nitrogen on the other. Algae bloomed only on the side with phosphorus, clearly demonstrating the importance of managing phosphorous in lakes.[20]

In cases of point source–nutrient pollution, regulators can turn off the pollutant flow at the end of the pipe. In the celebrated case of Lake Washington, water quality dramatically improved in a short period of time after nutrient input from sewage was diverted.[21] The direct and immediate response of the ecosystem supported the belief that nutrient control was the cause of water quality improvements.

Wisconsin's Lake Mendota provides an opportunity to compare fast and slow responses to intervention and how they affect subsequent management decisions.[22] The lake's food web was manipulated by fish stocking and mortality to increase the abundance of *Daphnia pulicaria*, a highly effective grazer. The rise of *D. pulicaria* substantially improved water clarity in less than a year.[23] Previously, whole-lake experiments had compared manipulated and unmanipulated lakes and determined that food-web changes could improve water clarity.[24] Lake Mendota's sharp response to food-web manipulation corroborated these expectations.

In contrast, Lake Mendota's response to management of nonpoint phosphorus inputs has been quite slow.[25] There has been no statistically discernible change in lake water quality in more than thirty years, despite extensive efforts to mitigate nonpoint pollution entering the lake. Gradual changes in the watershed phosphorus budget have likely contributed to the lake's slow response.[26] Decades of management have been frustrated by simultaneous increases in manure concentration, precipitation, the number of large rainstorms, and impervious surface area.[27] These changes in phosphorus-pollution drivers, occurring simultaneously with changes in management practices, have allowed for conflicting interpretations of the effects of management on the lake. These interpretations are equally plausible, but each has starkly different implications for policy, complicating the jobs of managers and policy-makers.

Efforts to use scientific information as evidence to improve water quality face many challenges. Greater attention has been paid to the production of water quality science than to how that science is subsequently used as evidence in water-quality management and policy. Science has three primary roles in the formation of water-quality policy: 1) identifying and describing problems; 2) predicting the likely effects of potential choices; and 3) evaluating the effects of prior actions.[28] We will identify the barriers to using science in each of these three major arenas. First, underlying disagreements about public values and preferences influence how science is interpreted and used. Second, there are many disputes over the assumptions used to create models and the validity of their results. Institutional barriers such as complex regulatory environments can slow the uptake of new information.[29] In terms of solutions, individuals and organizations can learn and change their behavior or routines and social networks can enhance learning and quicken the diffusion of information.[30] Even if scientific information informs individual and organizational learning and management choices, it may not affect political decisions about funding or legal environmental protection.[31] Here we identify the roles that science plays in nonpoint policy and management, describe the barriers and opportunities for use of science in decision-making, and summarize the reasons it has been so difficult to reduce nonpoint source pollution.

The nature of nonpoint management itself presents challenges for policy and governance, in turn influencing the potential roles for scientific information.[32] Nearly all economic development and resource use – including primary production of food, fiber, and minerals and secondary processing into consumer goods and built infrastructure – produces some water pollution. Nonpoint-pollution sources are numerous and often well-organized, and each contributes only a small proportion of the pollution. Agricultural land use has a privileged status in environmental policy-making, which makes regulating agriculture difficult politically.[33] The beneficiaries of clean lakes and rivers for fishing, swimming, the habitat, and aesthetic pleasure are less cohesive, organized, and funded than pollution-producing industries, although business interests can also be powerful allies for clean water. In many ways, producers of pollution have a powerful sociopolitical presence, and this influences how scientific information is used for water-quality management.

Use of scientific information is one tool for improving decision-making, but science does not speak for itself. Scientific information becomes evidence in the minds and hands of actors with different positions, incentives, and viewpoints. The social-psychology theory of motivated reasoning suggests that people interpret information in light of existing beliefs.[34] At an organizational level, information that supports agency missions is more likely to be used – and also more likely to be funded in the first place – while other potential research is left undone.[35] Scaling up to whole watersheds, the diversity of stakeholder objectives and worldviews means that disagreements about the meaning of scientific information, such as modeled predictions, are inevitable.

Disagreements about values and goals often underlie disagreements about science in decision-making.[36] Once a goal has been established, scientific information can be used to help reach it. But if political actors are unable to agree upon values or goals, then the tendency is to shift the debate to technical disagreements over models and data sources.[37] However, it is not simple or realistic to wait to reach political agreement before beginning a modeling process to determine how to reach that goal, since both politics and scientific development are iterative, ongoing processes. Further, science influences goal-setting itself, since scientific information is often used to identify problems for action. Information about environmental conditions and trends must be translated into evidence of a problem if it is to inform a policy or management agenda.[38] Agenda-setting and problem identification are inherently sociopolitical processes that involve the framing and social construction of information.

Defining water-quality problems has been a long-term goal of water-quality monitoring and research. Water-quality laws, such as the Federal Water Pollution Control Act in the United States (the Clean Water Act, or CWA), established processes for setting water-quality standards for water bodies. The definition of how much pollution constitutes a problem depends on the uses of the water body in question; stakeholder-based definitions of water-quality problems vary widely. Typical indicators of water-quality problems include poor water clarity levels and high concentrations and total loads of sediment, bacteria, nutrients, and other chemicals in the water. Positive qualitative indicators such as fishability and swimmability (absence of algae blooms or fish kills) are also taken into account.

The voluminous data from water-quality monitoring does not by itself meaningfully inform water-quality management: these data must be interpreted and linked with public values in order for the science to be truly useful.[39] Monitoring schemes must be designed with the likely use of the information in mind so that their sampling is statistically relevant to those goals. Unfortunately, many large-scale monitoring efforts have not yielded information that fits the needs of managers and policy-makers. For instance, the EPA's Environmental Monitoring and Assessment Program (EMAP) struggled because it was viewed as out of touch with policy needs and exhibited a lack of consideration of how values drive information interpretation (despite warnings from the National Research Council and the Science Advisory Board).[40]

Predicting the likely effects of potential choices is also a challenge due to the limitations of models and prediction. As managers and policy-makers debate options, they rely on conceptual and quantitative models to make predictions about the intended and unintended results of alternative courses of action. Debates over the validity of model predictions are long-standing. In the nonpoint-source arena, models can estimate the sources of pollution, predict the efficacy of different types of solutions, prioritize spatial locations for management, and determine compliance with regulation.[41] Implementation often differs from modeled plans in unpredictable ways: for instance, reliance on voluntary farmer participation means that planners typically cannot predict or control where agricultural conservation practices will be applied.[42]

Models are widely misunderstood as "truth machines" in environmental policy.[43] Because models are often poorly constrained and sometimes have large and unclear errors, stakeholders are able to mount legitimate and significant challenges to the use and selection of models. Sometimes doubt is sown deliberately to discredit unfavorable data or model estimates.[44] But because models are better at estimating average conditions in a large area than assigning accurate estimates to particular parcels of land, individuals may be justified in their skepticism of the fit of models to their particular farms or residences. People generally have a tendency to think of their own situation as exceptional and to underestimate their risks compared to the average. As Carl Walters, a biologist and quantitative modeler, has concluded, "We cannot assure policy-makers that our models will give accurate predictions: they are incomplete representations of managed systems."[45] Critics suggest that models emphasize quantifiable over difficult-to-quantify objectives and shift the debate from values to technical terms.[46] To this end, environmental policy expert Daniel Sarewitz has written, "The abandonment of a political quest for definitive, predictive knowledge ought to encourage, or at least be compatible with, more modest, iterative, incremental approaches to decision making."[47]

Regardless of these shortcomings, models of nonpoint source pollution can and do play critical roles predicting the effects of incentive and regulatory programs. For instance, the Soil and Water Assessment Tool (SWAT) is a watershed-based model that was "developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, [and] land use and management conditions over long periods of time." SWAT is a "continuation of thirty years of nonpoint source modeling" that simulates the water, sediment, and nutrient balance at the land surface.[48] Water-quality regulations have necessitated these complex models for estimating point and nonpoint-source contributions to surface water pollution. In this case, the CWA prompted the Agricultural Research Service to develop the SWAT model in the early 1970s.[49]

Under the CWA, jurisdictions must develop a Total Maximum Daily Load (TMDL) for impaired waters: a calculation of the maximum amount of a pollutant that a water body can receive and still meet water-quality standards. As of 2014, sixty-eight thousand TMDLs had been developed in the United States. TMDLs and their implementation plans translate model results into responsibilities split among point sources and urban and rural nonpoint sources. For instance, SWAT provides the basis for allocating necessary reductions under the Rock River TMDL in Southern Wisconsin. In the Yahara Watershed, which flows into the Rock, modeling has contributed to goal setting, prioritization, and implementation.

In the Yahara Watershed, however, SWAT did not provide reliable estimates for phosphorus loads from agricultural subwatersheds when compared with measurements from U.S. Geological Survey streamgages.[50] SWAT substantially underpredicted agricultural phosphorus loading from agricultural subwatersheds, in part because it was not yet modeling late-winter runoff of manure and sediment on frozen ground. Farmers are also often skeptical of model results; a representative of the Wisconsin Farmers Union claimed that "landowner lack of trust in models" was a repeated issue. This mistrust is deepened by discrepancies between model estimates averaged over space and time and farmer experiences of individual fields.

Model limitations are becoming better recognized; some have suggested that their failure to predict measured outcomes makes SWAT and other similar soil erosion–based models "unsuitable for making management decisions."[51] SWAT and other models are based on techniques that have been minimally updated since the mid-1980s despite advances in understanding of soil phosphorus availability and transport, leading to a situation in which "the quality of commonly used models may now lag behind the demand for reliable predictions to make policy and management decisions."[52] However, analysis of model findings continues to reveal some of their limitations and lead to updates. Despite their imperfections, models are critical for regulatory policy and will continue to be used and improved in the absence of alternatives.

A third major role of science is to assess the effects of actions after they have been taken. Several barriers can impede assessment, including limited information, limits of causal inferences, and conflicting interpretations based on values and political preferences. After a course of action has been selected and implemented, long-term monitoring can indicate changes in conditions, but evaluations compared to a reference site are needed to make causal inferences about the effects of an action. Furthermore, information about "what works" often cannot be translated from one local context to another.[53]

One barrier to assessment is the fragmentary nature of water-quality data in the United States. The National Water Quality Inventory under the Clean Water Act requires states to report water quality assessment to the EPA. As of 2014, only 43 percent of lakes, 37 percent of estuaries, 28 percent of rivers, and 1 percent of wetlands had been assessed.[54]

In practice, the evaluation of compliance with new policies for enforcement purposes is typically based on behavioral changes, not on measured water-quality outcomes. Agencies often evaluate their effectiveness by relying on the same models that were used to predict the effects of interventions; therefore, if behaviors do not actually result in desired environmental changes, there would be no data to show this. However, a limited number of policy-makers are experimenting with performance-based management, which evaluates measured environmental outcomes rather than measurements of technology or behavioral changes (for example, edge-of-field monitoring on farms).

Evaluation is also a political process. Even when scientists demonstrate an effect (or lack thereof), it might not become the dominant narrative about a policy or program. Evaluations and performance information are constructed by actors to advance their interests.[55] For instance, organizations may promote their programs as successful even without substantial information about their effectiveness. Even the question of who has access to information is dependent on political and personal values. For instance, conservationists may wish to obtain farm- and field-scale information on soil phosphorus and land-use practices, but farmers may be reluctant to share those data, since they could be used to assign blame or intensify water-quality requirements.

Significant barriers face efforts to improve the use of science in decision-making. These include matching the supply and demand for science and communicating between the cultures and incentive-structures of scientists and managers.[56] Deeper issues challenge us to rethink how we use science. Perhaps we should not consider better use of science to be the ultimate objective, but rather better decisions.[57] Asking a question about better decision-making requires a normative view of what is socially desirable. Although in a broad sense, clean water, agricultural production, and thriving cities are all socially desirable, making tough decisions about trade-offs between these goals will require compromise and continual renegotiation. Social scientists examine the roles of science through multiple lenses, including discourse analysis of the social construction of information, psychological study of evidence and persuasion in decision-making, and systems models that examine the change in both social and ecological components of watersheds.

Organizational learning systems have been designed to advance the use of information in decision-making. Research on learning organizations examines how organizations learn and change their routines based on new information. Scenarios are one strategy that organizations can deploy to examine uncertainties and alternative future trajectories. Furthermore, organizations can learn about how to learn more effectively and develop new institutional structures and informal networks to facilitate learning.[58] However, efforts to build learning organizations may be impeded by institutional fragmentation; limited capacity; organizational culture; the different timelines and incentives of scientists, managers, and policy-makers; and the command-and-control paradigm (top-down management).

Nonpoint pollution challenges our ability to measure, predict, and regulate. Scientific information is limited by few experimental designs, complex causality, and the difficulty of creating solutions to fit heterogeneous spatial and temporal scales. Barriers to using the scientific information we *do* have arise in part from the conflict over values and goals for water and land use. Yet "thinking practitioners" have successfully improved water quality and used scientific knowledge to inform management, policy, and governance despite these many barriers.[59] There is no denying that science plays critical roles in goal-setting, planning, and evaluation. In the contentious process to extend Clean Water Act regulation to agricultural and urban nonpoint sources, models are cast in starring roles to prioritize implementation and assign responsibility. An examination of the use of science in management, policy-making, and governance reveals the coproduction of science, modeling, and nonpoint control systems. Overcoming the barriers to nonpoint-pollution prevention requires that stakeholders and policy-makers renew their commitment to learning from scientific information and at times act in the face of uncertainty.

ENDNOTES

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