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Uncertain monitoring and modeling in a watershed nonpoint pollution program

Chloe B. Wardropper[a,*], Sean Gillon[b], Adena R. Rissman[c]

[a] Nelson Institute for Environmental Studies, University of Wisconsin, Madison 550 N. Park St. Madison, WI 53706, USA

[b] Food Systems & Society, Marylhurst University, Formerly Department of Forest and Wildlife Ecology, University of Wisconsin-Madison 17600 Pacific Highway, Marylhurst, OR 97036, USA

[c] Department of Forest and Wildlife Ecology, University of Wisconsin-Madison1630 Linden Drive, Madison, WI 53706, USA

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ABSTRACT

Performance-based programs governing land use rely on environmental measurement, prediction, and assessment. Yet complex, nonlinear social and environmental change can lead to uncertainties in quantification and forecasting and create challenges for operationalizing programs. This research examines the roles that environmental monitoring and modeling uncertainty play in experimental land and water governance through an analysis of a regulatory water quality program in Wisconsin, USA. The case demonstrates how uncertainties in measurement and prediction of pollution runoff shape program design and participant perceptions. We draw on interviews, a survey, participant observation, and policy document analysis to illustrate how regulators and participants (including municipalities, sewerage treatment plants, farmers and nonprofit organizations) perceive and react to uncertainty. Because current and future water quality data are based largely on model estimates, but regulatory compliance will likely be based on measured in-stream outcomes, participants must evaluate potential risks of involvement. Stakeholders have relied on partnership building and legal modifications such as extended compliance timelines to reduce the risks associated with uncertainty. Experimentation under uncertainty led to sustained stakeholder dialogue, and an iterative process of deciding how monitoring and modeling should be used to track and prove program progress.

1. Introduction

To track progress and create accountability, mechanisms of land and water policy often include the production and use of environmental monitoring and modeling data to define and account for program performance and adapt to changing conditions (Asdal, 2008; Boonman-Berson et al., 2014; Koontz et al., 2015; Nagasaka et al., 2016). Indeed, there has been a surge in the design and implementation of monitoring, reporting, and verification systems in environmental governance (Turnhout et al., 2014), as well as in public institutions more generally (Moynihan, 2005). Yet there are limits to accurate measurement and prediction of programmatic outcomes (Rissman and Smail, 2014). Social and ecological systems are usually complex, nonlinear, and strongly influenced by stochasticity and social contingency (Lane, 2014). Demonstrating and predicting program outcomes through measurement and quantification, therefore, is fraught with uncertainty. Performance-based programs governing land use, premised on inherently uncertain estimates of expected outcomes, illustrate the challenges of incorporating environmental monitoring and modeling into governance. The challenges lie in both the limitations of data production, and the social, political, and cultural contexts within which data are co-produced, as a product of both scientific practice and social processes (Jasanoff, 2004; Wyborn, 2015).

This paper examines monitoring and modeling uncertainty in land and water policy through a case study of an experimental water quality management program. The program is a regulatory compliance option for phosphorus pollution reduction in Wisconsin, USA, called the Watershed Adaptive Management Option (WAMO). Runoff of nutrients such as phosphorus from urban and agricultural land degrades water quality in the Midwest and in the Gulf of Mexico (Rabalais et al., 2002). Our case study program is located in the Yahara Watershed in south-central Wisconsin. This effort, dubbed Yahara WINs (Watershed Improvement Network), has been billed as a novel approach to watershed conservation, similar to water quality trading (The Economist, 2012). The program coordinates and increases application of conservation practices on farm fields and other targeted, high-runoff areas by redirecting pollution reduction funds from the sewerage plant and municipal "point sources" of pollution to runoff from diffuse "nonpoint

* Corresponding author.
E-mail addresses: wardropper@wisc.edu (C.B. Wardropper), sgillon@marylhurst.edu (S. Gillon), adena.rissman@wisc.edu (A.R. Rissman).

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sources" of pollution. Yahara WINs reconfigures nutrient governance within the watershed, as regulators, wastewater treatment plants, municipalities, farmers, and environmental advocacy groups must work together in new ways to improve water quality.

Our analysis focuses on the complex roles uncertainty plays in the process of watershed-scale governance. Monitoring and modeling nutrient movement in the watershed is essential for locating sources of runoff, determining their pollution load, and estimating resulting pollution concentrations downstream. Yet empirically verifiable and reliable measurements and predictions are difficult to achieve, for reasons described below, and uncertainty can be a destabilizing force in policy development and implementation. We suggest that this program can be contextualized as employing an experimentalist approach to environmental governance, an iterative process of goal setting and revision among actors in multi-level governance situations characterized by uncertainty (Overdevest and Zeitlin, 2014; Sabel and Zeitlin, 2012). In framing this program in this way, we illuminate the risks and benefits of governance experimentation in the face of uncertainty (Ansell and Bartenberger, 2016). Yahara WINs rests on uncertain environmental measurement and prediction; and it engenders perceived and real risks to participants and the environment, including the threat of regulatory enforcement, lost revenue, and failure to achieve environmental outcomes. On the other hand, in this case study, experimentation also opened a space for stakeholder dialogue and programmatic co-production that could lead to more adaptive and locally acceptable watershed pollution control in the future. In the next section, we describe the uncertainties involved in water quality monitoring and modeling, and the characteristics of an experimentalist approach to governance under uncertainty.

2. Uncertainty in measuring and predicting environmental program performance

Adaptive approaches to environmental governance are meant to address the dynamic, variously scaled, and diverse characteristics of social-ecological systems (Ostrom, 2009). Adaptive policies rely on measurement and modeling to track outcomes and adapt approaches in the face of ongoing and predicted social-ecological change (Koontz et al., 2015). Verifiable and reliable measurements and predictions of social-ecological change are, however, elusive in hydrological and other contexts (Lane, 2014). Likewise, incomplete information or personal perceptions may hamper users' understanding of sources of uncertainty in the data they use (Nowotny et al., 2013). Furthermore, monitoring and modeling uncertainty alters political discourse, and can sometimes lead to conflict if the uncertainty delegitimizes policy choices (Patt, 2007).

In this paper, we focus on two types of epistemic uncertainty, as defined by Regan et al. (2002). First is measurement or systematic error, which include equipment operator error or instrument error, or a bias in sampling procedure. Second is model uncertainty, which generally occurs as a result of variable choice or determinations of ecosystem processes. In this section, we explain common challenges with uncertainty in the context of water quality monitoring and modeling.

2.1. Uncertainty in water quality monitoring and modeling

In water quality policy and management, monitoring tracks and records current physical states. In freshwater systems, nutrient pollution levels or the number and type of macroinvertebrates in a stream are commonly monitored indicators. Water quality modeling abstracts from actual conditions to make generalizations for larger areas or for predictions of the future. Watershed pollution models are mathematical, computer-based, and simplified representations of landscape processes that create and transport pollutants, determining water quality. Mechanistic models incorporate understandings of known ecosystem processes, such as rainfall, erosion, and stream transport, to illustrate and sometimes predict trends in water characteristics. The use of models has become ubiquitous, both in physical science research (Burt and McDonnell, 2015), and in public administration (Pilkey-Jarvis and Pilkey, 2008).

Monitored pollution levels collected by automated gages or by hand offer a tangible representation of existing conditions, even if those conditions are fleeting and their causes not attributable. Many hydrologists and others advocate for the use of monitored water quality data wherever possible because, first, hydrologic models' accuracy is based on an incomplete understanding of fundamental water cycle processes, including interactions with land management and biogeochemical cycling; second, extrapolation beyond calibration conditions is required to estimate runoff throughout an entire watershed (Burt and McDonnell, 2015). Yet monitoring has limitations, including that a limited number of monitoring sites often prohibits understanding water quality conditions across an entire watershed. Rainfall variability makes relying on monitored data to accurately report nutrient reduction progress over short time scales much more difficult. Monitoring is also poorly equipped for attributing the source or mechanism of pollution. Processes outside of the control of environmental management programs, then, hamper administrators' ability to employ simplified metrics with certainty (Gillon et al., 2016).

Modeling nonpoint pollution levels with a mechanistic model in a large urban and agricultural watershed is a high-level uncertainty project (Rissman and Carpenter, 2015; Walker et al., 2003). Sources of modeling uncertainty include system boundary definition, parameters and structure, technical (computer) implementation, and inputs, which together shape model outcome uncertainty (Walker et al., 2003). There are a large number of potential watershed runoff model inputs, including management decisions of individual farmers or landowners; heterogeneous topography and soils; climate and weather patterns; and streams and lakes with diverse depths and rates of flow. Modelers may consider common land management practices, such as cover crops and tillage practices on farms, but may not be aware of all relevant practices to include if they are not reported by landowners (Jackson-Smith et al., 2010). Even among common land management practices, water quality impacts are well-known in the short term at a small geographic scale, but their effects are not as clear across a large watershed (Sharpley et al., 2009). Model parameters may not accurately reflect the actual range of environmental change, which can grow or shrink to levels outside what would be expected by standard errors. For instance, climate is increasingly affected by global changes, which may not be incorporated in watershed model assumptions about system boundaries (Kratz et al., 2003). Time lags in the effects of land management also create difficulties in estimating the future impacts of current practices (Meals et al., 2010). Hamilton (2012), for example, showed that response times to nutrient reduction interventions in a diverse set of watersheds ranged from one year to more than a thousand years. Thus, modeled estimates of pollution levels may be inaccurate due to these dynamic factors.

2.2. Uncertainty in experimental governance

This paper illuminates the benefits and risks of experimental environmental governance given uncertainty in measurement and modeling. Science and policy scholars have long accepted that the data produced through scientific methods and used to support environmental governance are political and contextual (Kuhn 1962/1970Kuhn 1962/1970; Braun and Kropp 2010). As Lane (2014, p.933) puts it with respect to hydrological science, "Concerns over the extent to which scientific knowledge can be a rational basis for decision-making suggest that science does not flow linearly or simply into decision-making as might be assumed. To replace the linear model, it is appropriate to see science and society, including decision-making, as in a state of co-evolution, with one impacting the other." Scientific knowledge and practice, such as water quality monitoring and modeling procedures

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