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Key Points:
- Different stages in the development of watershed management programs have distinct needs from hydrologic models and data
- Interviews and focus groups with program stakeholders revealed many contexts with low requirements for model accuracy
- Hydrologic modeling responsive to user needs increases information salience, credibility, and legitimacy and improves uptake

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Who Are we Measuring and Modeling for? Supporting Multilevel Decision-Making in Watershed Management

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Abstract As watershed management programs have become more common globally, so have efforts to support these initiatives through hydrologic modeling and monitoring. However, these efforts are often guided by oversimplified assumptions of how management programs work and the quantity, quality, and type of information needed to support their planning, implementation, and evaluation. Semi-structured interviews and focus groups with project managers, funders, and participants in three watershed management programs in the Atlantic Forest of Brazil revealed a range of hydrologic modeling and monitoring needs of watershed management programs. We identify five opportunities for hydrologic information to support overlapping management contexts: (1) inspire action and support, (2) inform investment decisions, (3) engage with potential participants, (4) prioritize location and types of activities at regional to national scales, and (5) evaluate program success. Within these opportunities, understanding who will use the information generated and how they will do so is critical to increasing the salience, credibility, and legitimacy of modeling efforts. Hydrologic modeling and monitoring play a small but critical role in the larger context of program conceptualization, design, implementation, and evaluation; grounding these efforts in local contexts supports watershed management projects in relevant and effective ways.

Plain Language Summary Active land management for a variety of benefits, including sustaining and enhancing clean and ample water supplies, is becoming more common worldwide. To achieve these ends, watershed management programs need the support of hydrologic data and models, but promising efforts by the hydrologic community often go unused when the information program managers need is not well matched to modeling efforts. We interviewed a wide range of participants in water management programs in Brazil and found five key areas where modeling and monitoring can support these programs: (1) inspire action and support, (2) inform investment decisions, (3) engage with potential participants, (4) prioritize location and types of activities at regional to national scales, and (5) evaluate program success. Our study emphasizes the importance of focusing on who will use modeling results and tailoring efforts to meet these needs. When grounded in real-world contexts, hydrologic monitoring and modeling can play a small but critical role in supporting sustainable watershed management

1. Introduction

A range of watershed management programs, including integrated watershed management, green infrastructure projects, and watershed Payments for Ecosystem Services, are becoming common globally (Biddle, 2017; Bremer, Auerbach, et al., 2016; Salzman et al., 2018). As a result, a suite of hydrologic models have been developed or adapted to support their design, implementation, and evaluation, including common open source models such as SWAT, InVEST, and ARIES, as well as proprietary models such as HydroBID (Berger et al., 2007; Martínez-López et al., 2019; Moreda et al., 2014; Vogl et al., 2017). To increase uptake, the development and evaluation of such models increasingly consider practical use, namely, the impact on the community or problem for which it is developed, rather than technical performance exclusively (Hamilton et al., 2019).

We focus on a particular type of watershed management program, Watershed Payments for Ecosystem Services or Payments for Watershed Services (hereafter PWS), in which downstream water users compensate upstream actors for conservation actions believed to affect water quality and quantity. PWS programs aim to achieve a range of hydrologic outcomes, most notably increasing dry-season baseflows and/or decreasing sediment, either for reservoir maintenance or reduction of treatment costs at water intakes (Bremer, Auerbach, et al., 2016; Bennett & Ruef, 2016; Salzman et al., 2018). Accordingly, these programs have become an important area of focus for hydrologic modeling (Guswa et al., 2014; Kroeger et al., 2019; Vogl et al., 2017; Salzman et al., 2018; Bremer, Vogl, et al., 2016), yet integration of model outputs in decision-making remains limited.

Hydrologic modeling to support PWS often rests on the assumption that the primary use of models is to provide knowledge for “rational decision making” (Laurans & Mermet, 2014). In this conceptualization, biophysical and economic data are generated to decide which watersheds should be selected for projects, what actions—usually a combination of fencing, reforestation, and/or reducing the intensity of animal and crop agriculture—to take, and where in the watershed these actions should be prioritized in order to efficiently achieve cleaner and/or more abundant water. In the rational decision making context, there is increasing emphasis on “getting the science right when paying for nature's services” (Naeem et al., 2015), including through the expansion of hydrologic monitoring and modeling (Kroeger et al., 2019; Ochoa-Tocachi et al., 2016; Pynegar et al., 2018). Calls to “get the science right” are often based on a theoretical model in which PWS develop linearly in four stages: (1) identification of hydrologic issues of importance to downstream water users, (2) identification of upstream natural infrastructure or water management solutions, (3) design and implementation of management activities, and (4) evaluation of downstream hydrologic outcomes (Ponette-González et al., 2015). In this model, information flows linearly from scientists to decision makers who demand detailed and precise information for use in analyses such as cost-benefit assessments or efficiency optimization schemes (Guswa et al., 2014).

However, scholars of PWS and payments for ecosystem services more broadly have demonstrated that this theoretical model does not align with how programs actually play out on the ground (Kolinjivadi et al., 2014; Kolinjivadi & Hecken, 2019; Shapiro-Garza, 2013; McAfee & Shapiro, 2010; Nelson et al., 2019; Shapiro-Garza et al., 2019). With particular relevance to this study, the realities of on-the-ground biophysical and social constraints make the costs and logistical challenges of detailed hydrologic modeling and monitoring very high for many projects (Muradian et al., 2010; Santos de Lima et al., 2017, 2019). This is particularly true for many emerging watershed management programs located in the tropics, where there is limited eco-hydrological knowledge and where climate, soils, and vegetation differ dramatically from those of temperate sites. As such, existing models, generally developed for temperate sites, may not accurately represent hydrologic properties in the tropics (Hamel, Riveros-Iregui, et al., 2017; Ponette-González et al., 2014; Wright et al., 2018).

Moreover, watershed stakeholders have diverse needs and, in practice, use hydrologic knowledge in a variety of ways. Prior work has identified three main ways that information may be considered. *Instrumental* use, the use of information to directly inform decisions, is often assumed in theoretical models of “rational” decision making but represents just one way that information is used. *Conceptual* use describes the use of information to better understand and frame a problem. *Strategic* use describes the use of information to build buy-in (Bremer et al., 2015; Jax et al., 2018; McKenzie et al., 2014). Research in integrated environmental modeling has long recognized the complexity of the modeling process and its influence on policy (Refsgaard et al., 2007). The criteria of *salience*, *credibility*, and *legitimacy* are commonly accepted as critical for a project to effectively influence policy-making (Cash et al., 2003). In a watershed management context, these terms take on specific meaning (Heink et al., 2015) and provide a useful framework for evaluating the potential of hydrologic modeling to influence real-world decisions.

Salience or relevance describes what information is generated and reflects everything from the choice of hydrologic processes monitored or modeled (Brauman et al., 2007) to the type of outputs produced. A model, for example, might be designed to best balance predictions over a range of conditions (e.g., low to high flows) or to specifically reproduce behavior under a particular regime (e.g., wet vs. dry conditions). These differences in design in turn influence the calibration and validation criteria used in model development (Guswa et al., 2014). In addition, salience may relate to the type of constraints a model is designed to consider. For example, real-world constraints such as civil conflict or private property may make so-called “optimal” investment solutions impractical and inequitable (Kolinjivadi et al., 2015, 2017; Pascual et al., 2014). Similarly, hydrologic models may miss opportunities to focus on areas that provide important social (e.g., strengthening of women's cooperatives) and cultural (e.g., support of traditional practices and knowledge) benefits and values that are critical to the success and durability of projects (Bremer et al., 2018; Chan et al., 2017).

Credibility refers to the scientific adequacy of the technical evidence generated (Cash et al., 2003), which for watershed management encompasses data and model validity for the range of decision contexts in which outputs will be used. Gaps in biophysical understanding, as well as limited monitoring data, lead to high levels of uncertainty in modeling and in broader understanding of the biophysical system in tropical contexts (Hamel & Bryant, 2017; Ponette-González et al., 2014). The social and political context and diverse value systems under which these programs operate are also complex and have their own set of metrics, opportunities, and constraints against which credibility will be assessed (Kolinjivadi et al., 2017).

Legitimacy describes the process of knowledge production and whether it fairly encompasses different stakeholder perspectives (Cash et al., 2003; Posner et al., 2016). Regarding legitimacy, the science of the decision-making *process* has become an important area of study, emphasizing knowledge generated in collaboration with users as an important predictor of uptake (Posner et al., 2016; Saarikoski et al., 2018). It is also critical to consider the ways that data and modeling are influenced by local context and power dynamics (Kolinjivadi et al., 2017).

Broadening the perspective on how science influences policy, Hamilton et al. (2019) developed a framework for evaluating environmental modeling projects: core elements of the framework extend beyond the project-scale indicators (e.g., credibility, salience, and legitimacy) to address individual- and group-level impacts of modeling. These include the instrumental use of models as well as improved stakeholder communication, consensus, and commitment of different groups. Despite these conceptual guidelines, it remains challenging for modelers to understand, from the outset, how modeling outputs can and will be used in practice. As stated by Hamilton et al. (2019: 21), “water resource models are an obvious way for [scientists and decision-makers] to work together, but uneven power relations and the institutional differences between academic and public sector employment can stymie their role in mediating interests of the two groups.” In this context, our research seeks to understand the role that hydrologic modeling (and coupled monitoring) can play in supporting real-world watershed management programs.

In this article, we explore the potential role and use of hydrologic information in watershed management through three case studies in the Atlantic Forest of Brazil, where PWS programs in the form of water producer projects (WPPs) are proliferating (Figure 1). We identify key stakeholders and institutions (producers/participants, project managers, funders, and other key decision makers) in WPPs and their roles in and motivations for participating in the programs over time. Using this information, we infer whether, how, and when hydrologic information can support watershed management processes and decision making through the full program cycle (conceptualization, planning, implementation, evaluation, and adaptive management). Though PWS, and specifically WPPs, are but one small subset of projects of relevance to hydrologic modeling, this research highlights a more general question about the value of information generated by models and suggests a gap in understanding how modeling and monitoring efforts actually influence watershed management programs. Our findings are likely to be relevant to any project aiming to support land management for desired hydrologic outcomes.

2. Methods

2.1. Study Sites: Brazilian Atlantic Forest WPPs

WPPs in Brazil began as an initiative of the Brazilian National Water Agency (ANA) to support municipal-scale PWS projects aimed at improving water regulation and quality through enhanced soil protection. The National Water Agency sees these projects as a “laboratory” that can be used to develop lessons learned and stimulate greater investment in protecting soil and water resources (ANA, personal communication, 21

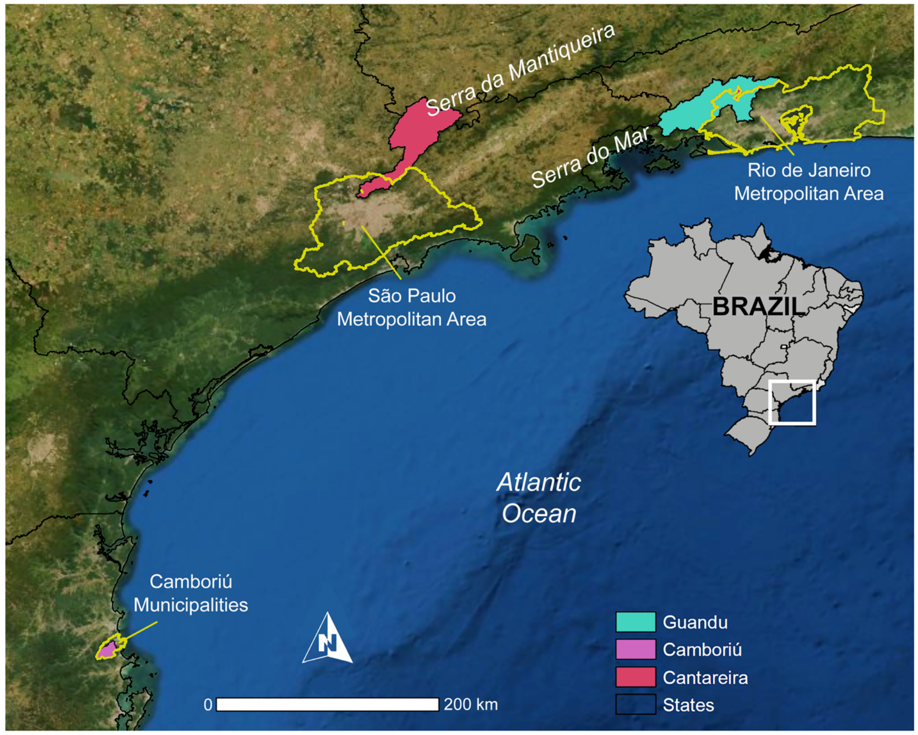

Figure 1. Main watersheds and target beneficiary areas (represented in yellow) in three focal water producer projects in Brazil. The Guandu watershed includes the Produtores de Água e Floresta program and is an important source of water for Rio de Janeiro. The Cantareira water supply system, where the Extrema Conservador das Águas is located, is an important water source for São Paulo. The Camboriú watershed includes the Projeto Produtor de Água da Bacia do Rio Camboriú, providing water for the municipalities of Camboriú and Balneário Camboriú.

October 2016). The Nature Conservancy, a global environmental nongovernmental organization with activities in Brazil, also sees WPPs as part of their water security strategy and has partnered with ANA and other local, regional, and federal institutions to implement and scale up this approach. With the exception of the first WPP, the Conservador das Águas Project in the municipality of Extrema, these projects are structured with a project management unit composed of key institutional stakeholders who financially or institutionally support the project, including ANA, the local municipality, watershed committees, and other relevant actors (ANA, 2012).

Funding for these projects comes from diverse sources and evolves through time. Seed funding is generally provided by The Nature Conservancy and/or ANA, but this funding is meant to stimulate long-term secured funding through various, primarily public, entities including municipal governments, water companies, and watershed committees. Funding for the programs is often legally mandated (e.g., through federal, state, and municipal laws). Watershed committees, set up both by state and federal government, for example, are often important sources of funding, leveraging taxes on water use. There are also efforts to facilitate investment by larger water users (e.g., beverage companies) beyond watershed committees, but this has been a slower process.

2.2. Projeto Produtor de Água da Bacia do Rio Camboriú (Camboriú)

The Projeto Produtor de Água da Bacia do Rio Camboriú (Camboriú Water Producer) project was initiated in 2013 by the Balneário Camboriú Water Company (EMASA) in collaboration with several partners, including The Nature Conservancy, ANA, two municipalities, the Santa Catarina State Center for Environmental Information and Hydrometerology (EPAGRI/CIRAM), the Camboriú Watershed Committee, the State Sanitation Regulatory Agency (Agesan), and the Camboriú city council (Kroeger et al., 2019). The Camboriú watershed, which spans the municipalities of Balneário Camboriú and Camboriú, has a year-round population of ~170,000 that increases to nearly 1 million during the summer tourist season.

Table 1
Key Project Goals and Metrics of Success Expressed in Interviews Classified in Overlapping Categories of Cater Resources m, ecological, and Socio-economic

	Guandu	Extrema	Camboriú
Water resources	• Water quality (general) • Sediment reduction (metric: % reduction tied to basin land-based target) • Water quantity (general) • Water regulation • Aquifer recharge	• Water quality (general) • Sediment reduction • (metric: % sediment reduction tied to basin land-based target) • Water quantity (general) • Soil conservation • Increase infiltration	• Water quality (general) • Sediment reduction and linked treatment costs (metric: potentially ROI study) • Water quantity during high tourist season
Ecological	• Conserve and restore forest cover(metric: land-based targets at project and basin scale) • Biodiversity	• Conserve and restore forest cover (metric: land-based targets at project and basin scale) • Biodiversity	• Conserve and restore forest cover (metric: land-based targets) • Aquatic biodiversity
Socio-economic	• Job creation • Farmer income • Generate financial resources and bring visibility to municipality • Increase environmental consciousness and awareness • Demonstrate effective PES model • Secure long-term financing	• Increase environmental consciousness and awareness • Financial sustainability • Farmer income	• Increase environmental consciousness and awareness • Build trust between program managers and land owners • Demonstrate effective PES model

Note. Quantitative metrics are provided where available.
Abbreviation: PES: Payments for Ecosystem Services.

EMASA is particularly concerned about water availability during the tourist season as well as high treatment costs associated with elevated sediment levels. Official project goals, accordingly, are to reduce sediment concentrations and, in turn, treatment costs and accompanying water losses (see Table 1 for full list of objectives by WPP interviewees). In parallel, ANA has financed water retention basins to reduce erosion from roads. Camboriú is touted as a model project for WPPs financed by water companies and is used as an example to encourage water regulators to allow conservation tariffs on municipal and state water bills. Substantial hydrologic measuring and monitoring have occurred at Camboriú (Klemz et al., 2016); both SWAT and InVEST models have been run with land use data at both 30- and 1-m resolution to evaluate project impact on sediment (Fisher et al., 2017; Hamel et al., 2019; Kroeger et al., 2019)

2.3. Conservador das Águas (Extrema)

The Extrema Conservador das Águas (Extrema Water Conservation) project began in 2005 as the first Brazilian PWS Program (Richards et al., 2015). The Municipality of Extrema sits within the headwaters of the Cantareira Water Supply System, which provides 50% of the drinking water for the 19 million people in the São Paulo metropolitan area. The project is run and mainly financed by the Municipality of Extrema but also receives support from the Piracicaba-Capivari-Jundiaí (PCJ) Watershed Committee, The Nature Conservancy, ANA, and other institutions (Kfouri & Favero, 2011). Official program goals are to increase forest cover to create ecological corridors; reduce sedimentation and eutrophication of waterways through improved rural sanitation; promote integrated management of vegetation, soil, and water; and guarantee socio-economic sustainability through a PWS program (see Table 1 for full list of objectives by WPP interviewees). The Secretary of Environment of the Municipality of Extrema, who initiated and continues to direct the project, is now leading an effort to scale WPPs across more than 250 municipalities in the Mantiqueira mountains (Conservador da Mantiqueira project). Extrema is a heavily instrumented research watershed as well as project site (Acosta et al., 2016). Both SWAT and InVEST models have been run here to assess project impact on potential impact on high flows, base flows, and sedimentation rates (Mota da Silva et al., 2014; Ozment et al., 2018; Saad et al., 2018).

2.4. Produtores de Água e Floresta (Guandu)

The Produtores de Água e Floresta (Guandu Water and Forest Producer) project began in 2009 in the Rio Claro Municipality of Rio de Janeiro State. Initially implemented by Instituto Terra, a local nongovernmental organization, philanthropic support gathered by The Nature Conservancy was crucial in the beginning of this program. However, at the time of this research (2016–2017), the program was

Table 2
Participants in Semi-Structured Interviews and Focus Groups

Level	Guandu	Extrema	Camboríu
International/national/state	• The Nature Conservancy • National Water Agency • State Environmental Agency of Rio de Janeiro	• The Nature Conservancy • National Water Agency	• The Nature Conservancy • National Water Agency • CIRAM-EPAGRI - Santa Catarina State Center for Environmental Information and Hydrometerology
Basin	• Guandu Watershed Committee • Agency of the Guandu Watershed Committee	• PCJ Watershed Committee	• EMASA founder • EMASA program coordinator
Municipal	• Instituto Terra • Municipality of Rio Claro Environment Secretary	• Municipality of Extrema Environment Secretary • Municipality of Extrema	• City Council of Camboriú • FUCAM –Environmental Foundation of Camboriú • Muncipality of Balneário Camboriú, Environment Secretary
Farm	• Focus groups (4)	• Focus groups (4)	• Focus groups (3)

temporarily being managed by the Agency of the Guandu Watershed Committee with funding primarily from the Guandu Watershed Committee (for PWS payments) and the State Environmental Agency (for restoration from forest offsets). The project is considered a pilot whose aim is to establish and consolidate PWS projects that can then be scaled up throughout the Guandu Basin (Ruiz, 2015). The Guandu Basin currently provides 80% of the water and 25% of the hydropower generation for more than 11 million people living in the metropolitan region of Rio de Janeiro (Petry et al., 2016). Guandu's official goals are to increase water regulation and reduce sediment loads by protecting and restoring Atlantic Forest (see Table 1 for full list of objectives by WPP interviewees). While monitoring equipment has been installed in this watershed (Petry et al., 2016), to our knowledge, no models have been run here.

2.5. Interviews and Focus Groups

We conducted semi-structured interviews (Creswell & Plano Clark, 2018) with program managers and all members of the Project Management Unit (PMU) (Table 2) (We did not interview the Camboriú Watershed Committee who, at the time of interviews, had limited involvement in the project and was not interested in participating in the study or in the case of Extrema, with key funders and decision makers). Questions focused on roles in the project, motivation for participation, metrics of success, perceived information needs, and perceived successes and challenges.

We also conducted 11 focus groups or community listening sessions (four in Extrema, four in Guandu, and three in Camboriú) consisting of 4–10 program participants and program managers (Wilburn et al., 2017). Themes focused on opinions of the project and strategies for improving effectiveness, equity, and durability in the future. Focus groups deliberately included program managers to facilitate dialogue between managers and participants. We acknowledge the potential for this to inhibit sharing of perspectives by program participants, but this tradeoff was deemed acceptable given the focus on tools to improve communication between participants and project management. Interviews were conducted in November 2016 and focus groups in June–July 2017.

Interviews were recorded and transcribed, and detailed notes were taken during focus group sessions. We classified interviewees and focus group participants by the level at which they work (international/national/state, basin, municipality, farm) as well as by their often multiple and overlapping project roles, which emerged from our understanding of the programs and phases of development as well as from previous work on collective action, payment for ecosystem services, and watershed management (Berger et al., 2007; Bremer, Auerbach, et al., 2016; Kolinjivadi et al., 2015; Ostrom, 2009). Finally, we coded transcriptions and focus group notes into emergent themes using a grounded theory approach (Charmaz & Belgrave, 2012) to develop decision contexts in which hydrologic monitoring and modeling could usefully support WPPs.

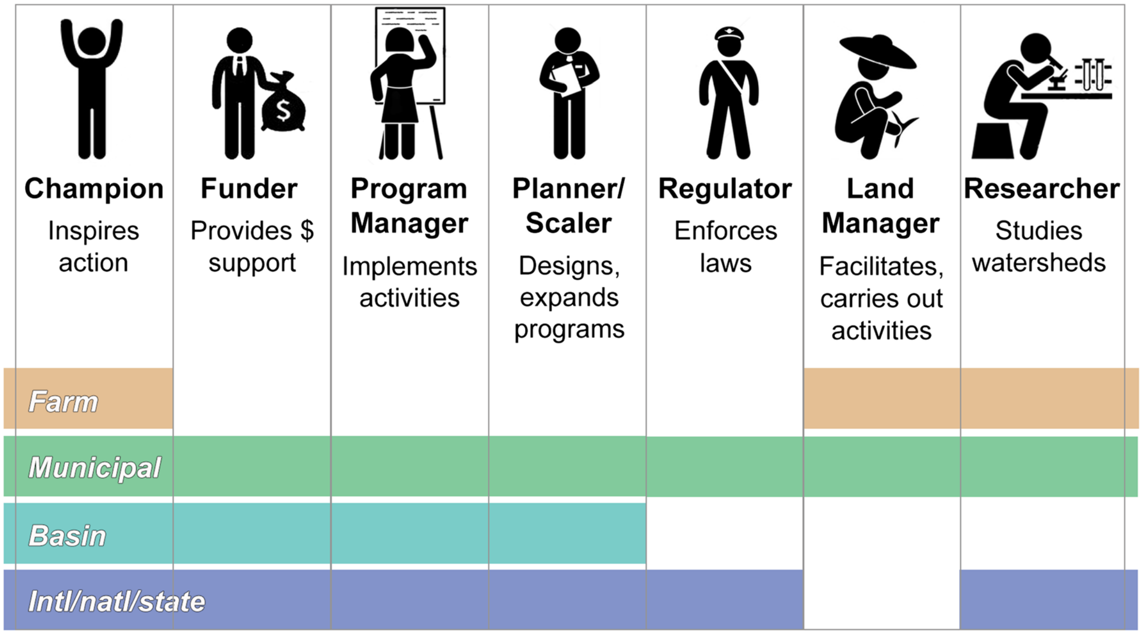

Figure 2. Roles of water producer project institutions and stakeholders and the most common levels at which they work. Champions, those who inspire action, are found at all levels. Funders, program managers, and planners/scalers commonly work at all but the farm level. Regulators, who implement relevant legal regulations such as the forest code, generally operate at the municipal and international/national/state level, whereas land managers exist at farm and municipal levels. Finally, while actors at all levels observe and take part in watershed research, the main research occurs at the farm, basin, and international/national/and state levels.

3. Results and Discussion

3.1. Watershed Producer Programs Have Multiple Stakeholders With Diverse Motivations, Goals, and Expectations

WPPs are multiscaled, nested programs that include stakeholders at farm, municipal, basin, state, national, and international levels. Few of these actors have technical hydrologic training, but all have interest in hydrologic outcomes (alongside other environmental, economic, and social goals). Municipalities are typically the political building block of WPPs and the level at which program managers interact with farmers and other participant landowners. Municipalities also sometimes provide funding. International, national, state, and basin level land and water management organizations are important for funding as well as for regional and basin-scale prioritization and replication. Within these nested levels, we identified multiple and overlapping stakeholder roles: champions, funders, program managers, scalers and planners, regulators, land managers, and researchers, each with their own motivations for participation (Figure 2 and Table 3).

At the farm level, land managers participate for a variety of reasons. While they receive monetary incentives, participation is also motivated by deeply held relational and environmental values (Bremer et al., 2018) as well as a desire to comply with the national forest code. As found elsewhere (Bremer et al., 2014; Richards et al., 2017), the greatest impediment to participation is often a lack of trust in government and other institutions, rather than insufficient compensation for opportunity costs. Municipal level actors emphasized multiple environmental (e.g., water and forest cover protection) and economic (e.g., job creation and visibility) motivations for participation. An exception was the Camboriú water company (EMASA), which focused primarily on water regulation and sediment reduction benefits; however, EMASA also pointed to the importance of building awareness and consciousness around watershed management practices. Basin level actors (e.g., watershed committees) focused on linkages between increasing forest cover and water regulation throughout the basin, whereas state, national, and international actors were primarily interested in creating effective, durable, and replicable PWS models. There was general consensus that, while valuable, payments should never be the primary reason for conservation, particularly given the potential for program payments to end (Table 3).

Table 3
Level, Roles, Motivations, and Metrics of Success in Water Producer Projects

Level	Roles	Motivations	Metrics of success	Example (s)
International/National (e.g., National Water Agency (ANA) and The Nature Conservancy (TNC))	Champions;Funders (seed); Planners/scalers	Pilot and scale "green infrastructure" throughout Brazil and beyond; Make programs functional and scalable	Scalable models/institutional structures; Natural infrastructure for multiple benefits	ANA focused on water regulation and soil protection views WPPs as natural laboratory to create viable models and build local capacity
State (e.g., state environmental authorities)	Funders; Regulators	WPP as way to implement environmental laws (offsetting)	Effective, durable, scalable institutional structures for PES; Hectares reforested/protected; Some interest in hydrologic outcomes	INEA (State Environmental Agency of Rio de Janeiro) provides offset funding to pay for restoration in Guandu
Basin (e.g., watershed committees; water companies)	Funders (primary); Planners/scalers; Program managers	Water quality and regulation; watershed committees wish to expand	Hectares protected/reforested; Improved quality and regulation; Effective, durable, and scalable PES	Guandu and PCJ watershed committees invest in PES as expansion of historical focus on sanitation and leakage and part of mandate to help protect water and watershed
Municipal (Municipality Ministry of Environment; Municipal water company)	Champions; Funders; Managers; Regulators	General environmental protection and economic growth; Watershed protection	Hectares protected/reforested/ sustainably managed; Number of participants; Sediment reduction	Extrema - head of Ministry of Environment conceptualized the program, inspired support and now working with TNC and others to scale across 280 municipalities
Farm/community (farmers and communities)	Land managers	Payments as a way to diversify income; Compliance with the forest code; Environmental values	Fair payments; Diversified benefits packages; greater involvement in project plannin	Land managers participate for multiple reasons including existing environmental and social values as well as payment and need to comply with forest code

Note. Extrema = "Conservador das Águas"; Guandu = "Água e Floresta"; Camboriú = "Projeto Produtor de Água da Bacia do Rio Camboriú.
Abbreviations: PES: Payments for Ecosystem Services; WPP: water producer project.

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Figure 3. Overlapping decision contexts occurring across water producer projects (WPPs), including the type of decision and the primary actors involved in the decisions (see icon legend in Figure 2). (1) "inspiration" involves *champions* who inspire others to form or engage with a WPP. (2) "investment" entails decisions by *program funders* around whether and how much to fund a WPP. (3) "engagement" entails decisions by *land managers* (municipalities and farmers) on whether and how they want to participate in the project. (4) "Siting and implementation" involves decisions by *program managers* and *scalers/planners* on where and what activities to carry out. (5) "evaluation" involves assessing program success, which is conducted in different ways by many actors, including land managers and program managers, but most formally by *researchers.*

3.2. Monitoring and Modeling Needs Vary by Decision Context

The diversity of actors, motivations, and expectations described above translate into a diversity of demands on hydrologic information generated by modeling and monitoring efforts. These demands arise at different points in the development of a WPP and generally relate to decisions that stakeholders need to make. We therefore refer to them as "decision contexts," although they encompass situations that do not require explicit decisions, such as the early phases of advocacy and inspiration for setting up a WPP. Figure 3 summarizes the decision contexts: inspiration, investment, engagement, siting and implementation, and evaluation, as well as the main actors involved in these contexts.

We argue that hydrologic modeling can usefully be seen through the lens of these decision contexts. In doing so, these decision contexts provide guidance on the salience, credibility, and legitimacy of the information that these tools need to provide. In the following sections, drawing from the three case studies, we detail each decision context and propose a set of guiding principles for hydrologic modeling, and, where relevant, monitoring. The decision contexts are presented in roughly sequential order, although we recognize that frequent iterations and interplays occur between the different stages. While the emphasis is on models in decision contexts 1–4, hydrologic monitoring is critical for model calibration and validation and is central for decision context 5 (evaluating success). In practice, dedicated monitoring equipment is often installed to support decision context 5, so local monitoring data may not be available during earlier decision stages. However, a growing number of programs, including the WPPs in our study, are establishing monitoring in early program stages to better be able to evaluate program success over time.

3.2.1. Decision Context 1: Inspiring Action and Support

A first key decision context is "inspiring action and support" (Figure 3, circle 1). As found in broader examples of collective action (Ostrom, 2009), interviewees from each of the three WPPs in our study pointed to the importance of at least one local champion who inspired others to join and support the watershed management project. In theoretical models of "rational decision making" (Laurans & Mermet, 2014), it is often implicitly assumed that hydrologic model results inspire action by providing quantitative evidence demonstrating specific impacts (Guswa et al., 2014; Ozment et al., 2018). However, our case studies support the idea that strong leaders, rather than data and models alone, inspire action (e.g., Gibbs, 2002) and that WPP actors are often motivated by diverse hydrologic, ecological, socio-economic, and political goals. Therefore, modelers who seek to generate impactful information should work with local champions who are the source of inspiration and who can communicate model results in locally appropriate and relevant ways.

The Camboriú WPP provides an example of the importance of local champions even within the context of strong legal and political enabling conditions. An oft emphasized part of the Camboriú WPP is the role of modeled and empirical data demonstrating linkages among watershed management, sediment concentrations, and water treatment costs (Kroeger et al., 2019). However, these data were only meaningful given a strong and connected local champion, a former intern at the water company who later became program manager. Inspired by a trip to the Extrema WPP and her university courses focused on participatory approaches to watershed management, and backed by a company regulatory law which required EMASA to invest in watershed protection, she galvanized EMASA, The Nature Conservancy, ANA, and other partners to start the WPP project. Important challenges she faced in this process were convincing EMASA that the program made sense compared to other options (e.g., trash clean ups and environmental education) and sustaining long-term commitment to the project.

In this decision context, modeling and monitoring focused on the links between forest cover and sediment delivery to the water intake (or other desired outcome) may help to solidify support (Kroeger et al., 2019; Klemz et al. 2006). Model salience is key to a clear explanation of biophysical connections within the watershed to raise awareness and communicate the implications of land management, which can help enable collective action (Ostrom, 2009). For credibility, results need not be highly accurate; information from regional models providing coarse insight about the general direction and magnitude of potential project impact is likely sufficient(e.g., Abell et al., 2017; McDonald & Shemie, 2014). As regional data often suffice at this stage, local monitoring data will be helpful, but may not always be necessary. There was, however, clear demand for model results that are valid under a range of forcings, or scenarios, rather than only under the current hydrological regime defined by historical climate and land use, a characteristic which we refer to as robustness (e.g., Abell et al., 2017; McDonald & Shemie, 2014). Case studies in comparable watersheds were generally considered useful as long as similarities in land use, climate, soil, vegetation, or other explanations of why the results could be extrapolated were clearly analyzed. However, local hydrologic and ecological monitoring data may make these comparisons more compelling. The legitimacy of these results will be conveyed by the champion, so connecting with that person is key.

3.2.2. Decision Context 2: Informing Investment Decisions

A second key decision context, "informing investment decisions" (Figure 3, circle 2), often overlapping with the first decision context, relates to whether and how much financial and other resources an institution or actor will invest in a project. In this decision context, it is often assumed that a *salient* model requires an economic assessment module for decision-makers to assess the magnitude of watershed impact. In the context of our study WPPs, substantial effort has focused on convincing "downstream" funders (e.g., watershed committees and city water companies) to invest using model outputs (e.g., Ozment et al., 2018). However, we found that municipalities and civil society actors generally provide funding based on broad environmental goals, not just hydrologic outcomes, and, in practice, model outputs were not a primary driver of funding decision making.

While we did not find evidence of return on investment modeling or similar efforts being the main reason for investing in a WPP, some actors continue to advocate for modeling as a way to galvanize additional larger scale funding (Kroeger et al., 2019; Ozment et al., 2018). For example, the Extrema municipality Secretary of the Environment, who championed the project, explained that the municipality was convinced of project benefits based on local knowledge and observations (a type of monitoring). However, they expressed interest in quantification of benefits to convince additional funders like the São Paulo water company (SABESP), which could help to expand their program within the municipality as well as facilitate scaling of the initiative to other municipalities. In cases like this, focusing on thresholds in watershed response may be a useful strategy to nudge funders (Guswa et al., 2014). For example, in the Cantareira system where Extrema is located, it was estimated that benefits of interventions started to level off after the first 4,000 ha of reforestation and protection, suggesting that return on investment will also level out at that threshold (Ozment et al., 2018). In another example, a state-level stakeholder thought the most critical information models could provide for the Guandu context was the minimum area of intervention needed to obtain a quantitative goal such as a 10% decrease in sedimentation. Such information can be used strategically but will rarely be sufficient without the legitimacy provided by trusting relationships between key stakeholders and investors.

Where return on investment studies are carried out in the hope of inspiring future investment (Kroeger et al., 2019; Ozment et al., 2018), credibility is important given high uncertainty due to data and modeling limitations. To address this issue, modelers may want to focus on characterizing confidence intervals and assessing forcing uncertainty to provide robust results that are valid across the range of model forcings, e.g., alternative land management scenarios or "extreme" scenarios such as complete deforestation (Hamel, et al., 2019; Hamel & Bryant, 2017; Refsgaard et al., 2007). Though monitoring programs are often designed for direct data analysis (Bremer, Vogl, et al., 2016), we found that short and incomplete data made this difficult at least at current project stages. However, existing monitoring data has proved useful for model calibration (e.g., Hamel et al., 2019), and can improve credibility even when the data time-series, and thus the range of forcing conditions, is limited. These robust results can help build persuasive narratives to share with stakeholders. Ultimately, funding decisions are based on multiple factors (Laurans & Mermet, 2014; Santos de Lima et al., 2017, 2019; Rogers & Fiering, 1986), so models and coupled monitoring systems that can account for other metrics (e.g., carbon, biodiversity, and livelihoods) may be more appealing. Perhaps more important than data and model credibility is trust and relationships with modelers themselves. The process of building, running, and presenting models will be most effective when done in a way that builds these relationships, thereby increasing the legitimacy of the outputs (Posner et al., 2016).

3.2.3. Decision Context 3: Engaging Potential Participants

The third decision context (Figure 3, circle 3) involves decisions that potential participants at the farm or community level face about whether and how to participate in a project. A rational economic actor framework assumes that farmers and communities decide to enroll in PWS based on economic costs and benefits, opting to participate if the payments are higher than the opportunity costs. However, our findings suggest that deciding whether or not to participate is not just based on payments versus opportunity costs but also on histories of trust (or distrust) in conjunction with other values and motivations (Wilburn et al., 2017). For example, in Guandu, at the time of interviews and focus groups, nearly 100% of local farmers were participating in the program. Our interviews suggest that this was the outcome of a long-standing relationship between Instituto Terra de Preservação Ambiental (ITPA) and the community. In addition, the program structure provides additional incentives for smaller landowners, making the program more equitable and appealing to smaller farmers. In contrast, the Camboriú program is better funded, but, at the time of this research, faced challenges enrolling participants due to a long history of distrust of public institutions.

Our focus groups and interviews with farmers reinforced that motivations to participate were not just financial but tied to environmental and relational values associated with protection and care for the land (Bremer et al., 2018; Chan et al., 2016, 2017; Wilburn et al., 2017). Ensuring that these values are highlighted and maintained in program design and implementation was seen as very important. At the same time, landowners who relied on their land for revenue were interested in better incorporating land uses that provide opportunities for long-term livelihood benefits, including, for example, agroforestry systems. Positive equity implications of greater inclusion of such working landscapes in payment for ecosystem services has been reported elsewhere in Latin America and globally (Bremer, Auerbach, et al., 2016; Jindal et al., 2012; Shapiro-Garza, 2013).

Our findings suggest that, for the studied WPPs, it is not necessary to develop sophisticated compensation models that quantify biophysical and economic benefits derived from particular locations in the watershed and compare these to the cost of implementation (Polasky et al., 2008). While our interviews and focus groups did not reveal a strong interest in formal modeling or monitoring per se, our interviews did reveal a strong reliance on local observations of change, including perceptions that drought impacts had not been felt as strongly in one municipality because of high levels of forest protection. Future efforts may usefully explore community-based, participatory modeling and citizen monitoring efforts that incorporate local knowledge and goals. Focusing modeling and monitoring efforts on locally defined goals (e.g., including assessments of the benefits of income-generating land uses and water availability at the farm scale) and incorporating local knowledge would likely increase the legitimacy of knowledge generated.

3.2.4. Decision Context 4: Designing, Siting, and Implementing Projects and Activities

A fourth key decision context is the design, siting, and implementation of project activities (Figure 3, circle 4). Siting of WPPs is prioritized at national, regional, and basin scales, whereas prioritization of activities for any given project occurs at subwatershed and farm scales. Project prioritization is primarily carried out by ANA and The Nature Conservancy at the national scale and watershed committees at the watershed scale, who determine which municipalities to support in the development of new projects. Prioritization of investments can also occur at regional and global scales. In a linear science-to-policy model, projects and activities are sited based on hydrologic models that identify sites in the watershed with the highest potential contributions to water quantity and quality goals (McDonald & Shemie, 2014). Our case studies reveal that many factors influence siting decisions, including enabling and constraining conditions such as whether or not there is a strong local champion to advocate for particular areas, whether landowners trust local institutions equally or unequally across watersheds, and whether there is an existing or potential legal framework to support investments over the long term. As examples, the Guandu and PCJ (where Extrema is located) watershed committees considered hydrology alongside whether municipalities had strong local partners and existing local laws to generate PWS payments. The municipality of Rio Claro, for example, was chosen as a priority site both because it contributes to three water collection points and because it benefits from the long-term presence of the local nongovernmental organization Instituto Terra de Preservação Ambiental (a key local champion) and a Municipal PWS law. This illustrates how interactions among decision contexts can serve to affect any given phase of WPP development.

Once a project has begun, project managers, in collaboration with landowner participants, face the decision of where to work and what activities to undertake. In our research, we found that a mix of feasibility, legal definitions of effectiveness, and local perceptions of effectiveness are more important drivers of decisions than modeled outputs of potential impact. Within-farm prioritization is generally done based on existing forest code priority areas (slope steepness, location of spring, and riparian zones), which program managers generally believe map well to areas important for water quality and quantity. Within the framework of the forest code, projects used different siting criteria based on local opportunities and constraints and broader program philosophy. Guandu, for example, is the only program with an incentive scheme that specifically targets small landowners through a sliding payment schedule in which payments are smaller per hectare where a greater amount of land area is enrolled. In contrast, Camboriú began by targeting larger landowners to quickly increase area enrolled and because these were the landowners most willing to enroll in the beginning of the program. While EMASA and The Nature Conservancy conducted a return on investment study to prioritize investments within the Camboriú watershed (Kroeger et al., 2019), at the time of interviews, outputs have not driven activities because, due to low enrollment stemming from distrust of formal institutions, the program has enrolled any landowner in the basin who is willing.

Siting of programs and activities is one of the most commonly touted demands for and uses of hydrologic models in ecosystem service and watershed management applications (e.g., Kroeger et al., 2019; Polasky et al., 2008). Given that a range of criteria are used in siting decisions, hydrologic models may increase their salience by generating qualitative information on the type or general location of conservation activities with high impact. In the case of Brazil, the forest code dictates key areas for investment, but watershed management projects may need to prioritize different interventions or priority areas within those constraints. Credibility requirements at this stage are mixed, suggesting that modelers should focus on assessing the robustness of siting information by highlighting areas where uncertainty is the lowest, such as locations where different data sources converge (Hamel & Bryant, 2017). Monitoring programs that engage citizens and help provide context to local observations may also increase credibility (Conrad & Hilchey, 2011).

There is also an important opportunity here to improve conceptualizations of spatial targeting exercises (Kolinjivadi et al., 2015). Rather than focusing on the technical aspects of prioritization or assessment of potential benefits, more importance should be given to hydrologic models as "useful surfaces of engagement" (Escobar, 1999: 13) or as boundary objects (Liu et al., 2008), whereby locally defined goals and knowledge are integrated into the modeling process in innovative ways. These modeling efforts could include multiobjective optimization where nondominated alternatives that favor objectives in different way are optimized and then deliberated upon, rather than focusing on finding a single "optimal solution" (Pareto, 1896). This would improve both the salience and legitimacy of model outputs, which are unlikely to be used if they do not reflect the values of local farmers and communities in prioritization exercises.

3.2.5. Decision Context 5: Evaluating Program Success

The final decision context relates to program evaluation and adaptive management (Figure 3, circle 5) in the context of understanding what is "working" and what could be adjusted. Many actors, including funders, project managers, participants, and researchers, are interested in understanding program outcomes and adjusting where appropriate. In our interviews, water regulation followed by sediment reduction was the most important metrics of interest, similar to the findings of Bremer, Auerbach, et al. (2016) evaluating projects through Latin America. In our study cases, there was interest in monitoring impacts to communicate success and to adaptively manage watersheds, and monitoring systems were thought to help build trust among program supporters when data are transparently shared. Widely deployed monitoring and associated modeling would theoretically provide the most *credible* quantitative evidence of impact (Naeem et al., 2015), and support assessment of model uncertainty. In the study WPPs, however, there was limited money for installation and upkeep of monitoring equipment, personnel were under-funded, and data records were often incomplete in space and time and difficult to interpret. In addition, hydrologic impacts are unlikely to be apparent in the hydrologic record for interventions implemented only in the last several years. These factors lead to high levels of uncertainty (Santos de Lima et al., 2017, 2019), making success difficult to evaluate and findings difficult to communicate.

Financial investment in monitoring equipment and scientific guidance for siting this equipment will help address some of these challenges, and efforts are already underway (Bremer, Vogl, et al., 2016; Higgins & Zimmerling, 2013; Ochoa-Tocachi et al., 2016). Some variables, such as stream depth, can be easily and frequently measured with simple low-cost tools, while others, such as stream discharge, require greater investment (e.g., weir, flume, current meter). There is also value in other forms of hydrologic data that do not require scientific instruments. For example, observations of springs, pictures of watercourses, or records of water shortages in the municipality can serve as useful alternative sources of information in the long run. Collection of this type of data has been reported by our interviewees in Extrema and Guandu. Hydrologic outcomes are also only one metric of success considered by program managers and participants, who consider a suite of social, political, and ecological outcomes; monitoring of a range of these *salient* outcomes will also increase the legitimacy of evaluation efforts as it broadens the focus to a range of goals prioritized by different actors.

3.3. General Implications for Hydrologic Modeling and Monitoring

Findings from our interviews and focus groups have implications for hydrologic modeling and/or monitoring in all decision contexts. Major implications are related to the salience of hydrologic information. First, many hydrologic modeling studies are not designed to evaluate the processes of highest interest to stakeholders. For example, in WPPs, many stakeholders are interested in reduced peak flows and increased base flows, yet the majority of modeling studies focus on sediment retention given the more robust modeling results (watershed response to land use change is more established for sediment than base flows; Brauman, 2015; Ozment et al., 2018; Saad et al., 2018). This highlights the need to consider all aspects of credibility, salience, and legitimacy in modeling efforts; while robustness increases credibility, focusing modeling efforts on generating robust findings is only useful if those findings address issues of salience to stakeholders.

Second, designing and running models at the appropriate scale are critical. Hydrologic model results are most easily expressed at watershed scales, but, in the context of WPPs and likely other watershed management programs, information at several scales is needed: regional and basin scales are of most interest to evaluate the likeliness of success from a hydrologic standpoint, and project managers need information at subwatershed or municipality scales. Watershed experiments are often done at the plot scale and extrapolating these results to larger scales represents another important and related challenge (Jencso et al., 2009).

Credibility requirements for model outputs have important implications for both modeling and monitoring investments and communication of uncertainty. First, we find that, in all decision contexts, model outputs are not primarily used instrumentally (McKenzie et al., 2014) or as the sole criteria for decision making, and monitoring efforts are not at a stage where results can be used to instrumentally inform decisions. As a result, investment in improved accuracy of models may have limited value at this point, as a recent study in the Camboriú watershed suggested (Hamel et al., 2019). Instead, models are currently used to increase awareness and communicate the implications of land management (Brugnach et al., 2008). The most useful models will improve understanding of how land use affects hydrologic outcomes of interest in comparison to other factors such as changes in climate, water demand, and built infrastructure. Second, monitoring programs can be designed to increase model salience and credibility, both by selecting measurements of specific interest to decision makers and participants (Hamel et al., 2019) and by improving model calibration. Third, given that accuracy of modeling exercises will often be low in the complex social-ecological systems that characterize watershed management programs, it is critical to effectively communicate uncertainty (Santos de Lima et al., 2017). The legitimacy of modeling outputs rests on this, and our findings concur with Santos de Lima et al.'s (2017: 147) assertion that: "transparent treatment of uncertainty is fundamental to managing expectations, build trust among actors and maintain credibility of PES practitioners."

Developing and running hydrologic monitoring programs and models that are *salient*, *credible*, and *legitmate* in these decision contexts often means engaging with multiple organizations and institutions and working as part of interdisciplinary teams. Hydrologic modeling efforts seeking to provide useful input should allow for sufficient time to understand this context and narrow in on key factors that could usefully be included in prioritizing efforts alongside other types of information. This phase may also include the search for additional resources to run different models or collect different data that might be more appropriate in the context. Though time consuming, the process of doing so will increase the legitimacy of model outputs.

The accuracy of model outputs rests on the design and calibration of model processes, both of which hinge on the availability of quality monitoring data. However, we found that local data were frequently unavailable or insufficient to use in this way. Camboriú has one of the most advanced monitoring systems within WPPs and was designed as a model system to evaluate impact and contribute to an on-going return on investment study (Klemz et al., 2016; Kroeger et al., 2019). However, even in this context, the frequency, continuity, duration, and spatial extent of data were limited due to insufficient investments (Hamel et al., 2019). To capture the full range of watershed response, particularly in the tropics where precipitation and streamflow are flashy, monitoring design must account for human and financial resources to maintain monitoring equipment over long time scales and a range of conditions.

4. Conclusion

Hydrologic modeling and monitoring to support watershed management has often rested on the assumption that decision makers use hydrologic information in an instrumental way to design and implement projects. Our case studies of WPPs demonstrate that the use of hydrologic information is far more nuanced and varies considerably across decision contexts for any particular project. Echoing broader critiques of conservation-efficiency watershed management program conceptualizations (McAfee & Shapiro, 2010), we find that, in practice, programs take a variety of social and political concerns and opportunities into account (Muradian et al., 2010; Shapiro-Garza, 2013; Shapiro-Garza et al., 2019).

Being attentive to user needs regarding the salience, credibility, and legitimacy of model outputs and monitoring efforts to inform them makes it far more likely that information will be used (Cash et al., 2013; Heink et al., 2015; Posner et al., 2016). Though doing so requires substantial up-front investment in understanding the needs, motivations, opportunities, and constraints of different actors in the watershed, our findings also demonstrate that hydrologic modeling for PWS often has lower accuracy requirements for credibility than might be assumed. Since information is not generally used instrumentally, models do not need to accurately mimic the entire watershed but rather represent the key processes that are relevant to the PWS program (e.g., the watershed long-term response to land use change, rather than the precise response to each storm; Guswa et al., 2014). Monitoring programs can be best designed to increase model credibility by providing local calibration data. Critically, the processes by which models and modelers will find relevance and assess credibility requirements will also provide them with legitimacy. Co-developing hydrologic models with watershed management stakeholders, including discussing and defining objectives with relevant stakeholders and incorporating socio-economic and political realities into the modeling framework, will improve salience, credibility, and legitimacy simultaneously.

As a result, hydrologic models and monitoring data can offer potential "useful surfaces of engagement" (Escobar, 1999: 13) or boundary objects, not necessarily just as tools to attribute hydrologic outcomes. Alongside other tools, approaches, and knowledge systems, these models should be considered as one part of a broader planning effort. This requires careful attention to equity and power dynamics and the role of models and scientific data in empowering or marginalizing certain voices and visions (Kolinjivadi et al., 2014; Pascual et al., 2014). The data that models provide are a function of how we design the latter, and models and their outputs should be carefully situated within broader systems of knowledge.

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Erratum

In the originally published version of this article, Figure 2 contained an error. The figure has been updated, and this version may be considered the authoritative version of record.