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Ecosystem Services: Challenges and Opportunities for Hydrologic Modeling to Support Decision Making

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Key Points:

- Decisions based on ecosystem services are the norm
- Support is required for decisions relating land use to water services
- The hydrologic community can contribute to better informing such decisions

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Ecosystem services: Challenges and opportunities for hydrologic modeling to support decision making

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Abstract Ecosystem characteristics and processes provide significant value to human health and well-being, and there is growing interest in quantifying those values. Of particular interest are water-related ecosystem services and the incorporation of their value into local and regional decision making. This presents multiple challenges and opportunities to the hydrologic-modeling community. To motivate advances in water-resources research, we first present three common decision contexts that draw upon an ecosystem-service framework: scenario analysis, payments for watershed services, and spatial planning. Within these contexts, we highlight the particular challenges to hydrologic modeling, and then present a set of opportunities that arise from ecosystem-service decisions. The paper concludes with a set of recommendations regarding how we can prioritize our work to support decisions based on ecosystem-service valuation.

1. Introduction

The field of water resources has a long and effective history of managing water to improve human well-being. Historically, much of the focus was on direct control and treatment of flowing water, and as engineers and managers we have built levees and water-treatment plants to control, contain, and deliver clean water when and where we want it. But this is no longer enough. Urban, agricultural, and industrial expansion has transformed and will continue to transform the landscape, affecting water resources in unanticipated ways that strain existing infrastructure. New approaches are needed to complement existing water-resource strategies, and the framework of ecosystem services provides one potentially valuable pathway forward.

Ecosystem services are the conditions and processes through which ecosystems, and the species that make them up, sustain and fulfill human life [*Daily*, 1997; *National Research Council* (*NRC*), 2004; *Millennium Ecosystem Assessment*, 2005; *Kareiva et al*., 2011; *Kumar*, 2012]. This concept of ecosystem services provides a means for interpreting the biophysical processes that occur on the landscape—photosynthesis, infiltration, or nesting habitat, for example—and organizing them by their effect on people—food production, groundwater available for drinking, or the joy of spotting a favorite bird. Specific to water, terrestrial alterations of flow and instream processes can be evaluated, for example, by their impact on the maintenance of base flows during rainless periods for drinking water or recreation, the attenuation of flood peaks and associated reductions in damages to property and life, or the retention of nutrients and sediment to reduce costs at a water-treatment plant [*Brauman et al*., 2007]. How valuable and important are these water-related services? How do they change if the landscape is modified? Are there trade-offs among different ecosystem services? These are some of the questions decision makers face when considering proposed developments and other changes to the landscape.

Approaches that incorporate ecosystem services are fast becoming the norm because they explicitly answer the question of why people should care about maintaining and managing biophysical processes [*Brauman et al*., 2014; *The Nature Conservancy* (*TNC*), 2013; *USEPA*, 2012; *Goldman et al*., 2010]. In their cover letter for the recent President's Council of Advisors on Science and Technology (PCAST) report on *Sustaining Environmental Capital: Protecting Society and the Economy*, PCAST co-Chairs Holdren and Lander wrote, "[the government] must not fail to address. . . the environmental and economic aspects of well-being that derive from. . . environmental capital—the Nation's ecosystems and the biodiversity they contain—from which flow 'ecosystem services' underpinning much economic activity as well as public health, safety, and environmental quality," [*Holdren and Lander*, 2011]. Because of the direct link to human use, reframing biophysical processes as services allows them to be valued, and government agencies and nonprofits have embraced ecosystem services in part because they can be directly integrated with existing decision-making frameworks such as cost-benefit analysis.

In many contexts, evaluating ecosystem services is no longer a choice. In March 2013, the Council on Environmental Quality, under the Executive Office of the President of the United States, released the "Principles and Requirements for Federal Investments in Water Resources," [*Council on Environmental Quality* (*CEQ*), 2013]. This document provides a common framework for the evaluation of Federal investments in water resources, and is applicable to projects under the U.S. Army Corps of Engineers, Tennessee Valley Authority, U.S. Environmental Protection Agency, and the Departments of Commerce, the Interior, Agriculture, and Homeland Security. Unlike previous versions, these new principles and guidelines require that the evaluation of projects "apply an ecosystem services approach in order to appropriately capture all effects (economic, environmental, and social) associated with a potential Federal water resources investment," [*CEQ*, 2013, pp. 6–7].

Federal mandates recognize that monetization is just one way to measure value, however, and often not the best one when complex multifaceted decisions must be made [*CEQ*, 2013; see also *Thompson and Segerson*, 2009]. Valuation may be as simple as explicitly accounting for the fact that a landscape provides services of importance to a community. An advantage of valuation in common terms, such as money, is that it enables comparison of multiple services and assessment of the trade-offs among them.

Many ecologists and economists have been engaged in assessing and valuing ecosystem services for some time, and we believe there is a need for greater involvement by hydrologists in this effort. We are not advocating that ecosystem services become the only basis for decision making. Rather, such an approach can augment and enhance the consideration of the benefits that lands and waters provide and help avoid unintended and unwanted consequences of land-use change [*Olander et al*., 2012].

Incorporation of water-related services into decision making requires robust and flexible means of predicting the effects of land-use and land-cover changes on valued water resources. This presents a significant challenge. Water-related services, such as the provision of clean water or the mitigation of flood damage, depend on the amount, timing, location, and quality of water. These characteristics are affected by complex interactions among climate, topography, and geology, along with land cover, land management, and other human modifications of the landscape.

This paper identifies research directions for our community to provide the knowledge and tools required to incorporate water-related ecosystem services into land-use and land-management decisions. We organize the conversation around three types of landscape decisions made within an ecosystem-service framework and identify six specific challenges and three opportunities associated with hydrologic modeling. The paper concludes with recommendations for advancing hydrologic research to support ecosystem-service valuation.

2. Ecosystem-Service Decisions and Hydrologic Modeling

Any decisions related to ecosystem services will require the integration of knowledge from many fields, along with the active and transparent engagement of stakeholders. Hydrologists will be called upon to predict the timing, amount, and quality of water at a location of interest, such as a point of withdrawal. These biophysical characteristics are, in turn, transformed into the value they provide to people. As an illustration, Figure 1 presents three different valuations of daily streamflow at a location of interest. The linear model (1a) may represent valuation in the presence of a large reservoir such that high flows on 1 day directly compensate for low flows on another. The second model (1b) indicates a threshold response; for example, this could represent a situation in which a water ban is triggered by low flows or for which recreational activities require a minimum flow. A more general nonlinear model (1c) indicates the high marginal value of some streamflow and diminishing returns of greater discharge, perhaps indicative of run-of-river uses. In this work, we do not focus on how such valuations are determined. Rather our interest lies in the implications for hydrologic modeling and research when such valuations are the basis for decision making. In the sections that follow, we present and elaborate on three common types of land-use/land-management decisions: scenario analysis, payments for

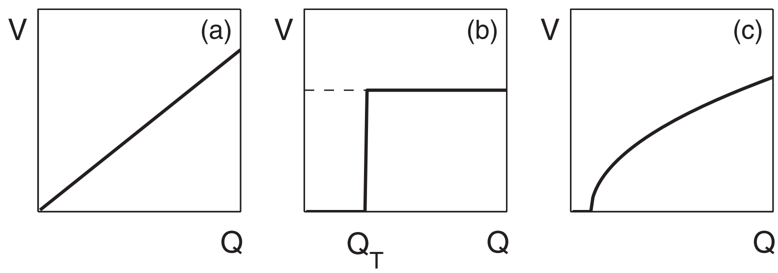

Figure 1. Example valuation curves for daily streamflow, Q: (a) linear, (b) threshold, and (c) nonlinear.

watershed services, and spatial planning. Associated with these decision contexts, we articulate six challenges for hydrologic modeling. Though these challenges are motivated by the decisions, it should be understood that they are not unique or confined to any one type of decision context. Rather, they are interconnected and extend across a wide range of ecosystem-service decisions.

2.1. Scenario Analysis

Perhaps the most familiar type of decision is scenario analysis, i.e., comparing the relative values of a countable set of alternatives. For example, one may wish to quantify the impact on drinking water of converting a forest to agricultural land or determine the value of restoring a riparian wetland. Or, perhaps, the scenarios are more subtle, such as the effects of shade-grown versus traditional coffee on the costs of sedimentation and dredging in a downstream reservoir.

Hydrologic modeling to inform the evaluation of scenarios suffers from well-known challenges—process understanding, mathematical representation at different temporal and spatial scales, and parameter uncertainty—along with others that are more specific to the ecosystem-service framework. We do not attempt an exhaustive review of hydrologic modeling, and our brevity in acknowledging the traditional challenges should not be interpreted as an attempt to downplay their importance. In the sections below, however, we focus on those challenges that are particular to or exacerbated by ecosystem-service decisions.

2.1.1. Challenge 1: Process Understanding, Scale, Model Representation, and Parameter Uncertainty

Modeling to support ecosystem-service valuation requires appropriate decisions regarding process inclusion and mathematical representation, spatial and temporal scale and resolution, and model parameterization. While this is no different from other hydrologic modeling efforts, there are three characteristics that are particularly significant for ecosystem-service decisions. The first relates to the fact that ecosystem-service decisions are decisions about use and management of the landscape. Therefore, models to support these decisions must be designed to represent parcel-level changes to land use and land management. This has implications for model scale, resolution, structure, and input data [e.g., *Frisbee et al.*, 2012; *Hrachowitz et al.*, 2010; *Tetzlaff et al.*, 2010]. Additionally, a scenario analysis implies at least one state of the landscape that does not exist. This precludes the ability to calibrate model parameters to existing conditions. In contrast to forecasting, in which it is the rainfall forcing that is varied, ecosystem-service scenario analysis is fundamentally about changing the hydrologic pathways and processes. Therefore, our models must be such that parameters can be inferred from known characteristics of the landscape without calibration [*Blöschl et al.*, 2013]. Additionally, even the model structure might change, as a hydrologic formulation that is appropriate for a forest may be inappropriate for another landscape [e.g., *Ogden and Stallard*, 2013]. Last, many of the settings in which there is a desire to employ an ecosystem-service framework are data poor [e.g., *Ponette-González et al.*, 2014]. Thus, models to support ecosystem-service decisions must accept spatially explicit land-use and management input, must be usable with limited data and without calibration, and must be flexible in their structure.

2.1.2. Challenge 2: Nature and Strength of the Landscape Signal

Ecosystem-service decisions are land-use and land-management decisions. Often, the desire is to understand how changes to land management of an upland parcel will affect a downstream water resource. This can present a signal-to-noise challenge if only a small part of the watershed is affected by the land-use or land-management change [e.g., *Schilling and Spooner*, 2006; *Stednick*, 1996; *Bosch and Hewlett*, 1982]. Additionally, even landscape changes to the entire watershed may have a secondary effect on hydrologic response relative to uncertainty in climate or geology. Effects of seasonal or interannual variability of precipitation or uncertainty about the subsurface may overwhelm the landscape signal [e.g., *Porporato and Rodriguez-Iturbe*, 2013]. Moreover, the sign and magnitude of the landscape effect may vary with other characteristics of the system. For example, in a wet year, a forested watershed may have greater base flow than an urbanized one, due to increased infiltration; in a dry year, however, the higher rates of transpiration may lead to lower base flow in the forested catchment [e.g., *Price*, 2011; *Bruijnzeel*, 1988]. Last, while land cover may change quickly, as in the burning or clear cutting of a forest, the hydrologic effects of that landscape change may evolve over a longer time [e.g., *Davenport et al*., 2010; *Brown et al*., 2005; *Likens and Bormann*, 1995], introducing hysteresis into the relationships.

2.1.3. Challenge 3: Providing the Right Information for Attribution of Value

The value of a water resource is always contingent on who is using the water, where, and for what purpose. As a result, there is never a straightforward answer to the question "How much is the water worth?" Economics has an abundant literature on how best to assign monetary value, ranging from market pricing to survey questions about willingness to pay. Overviews of these concepts and methods include *Freeman* [2003] and *Thompson and Segerson* [2009], while *Young* [2005] and *Olmstead* [2010a, 2010b] address applications of these methods to water resources. Like hydrologic measurements and models, these economic methods are often imperfect and require specialized knowledge, especially when market prices are not available. Of most importance to hydrologists is that valuation can only be undertaken for a good or service used by people. This requires going beyond changes to streamflow, nutrient concentrations, sediment loads, and groundwater levels to the resultant effects on human health and well-being. This translation may be more straightforward for some services, such as hydropower production, but for others, such as the impact of a change in recharge on the existence value of a groundwater spring [e.g., *Rolfe*, 2010], the task is more difficult. Moreover, in an uncertain environment, the information needs may vary depending on the risk preferences held by decision makers. For risk-neutral decision makers, information about expected outcomes may be sufficient; for those who are risk averse, however, information about the distribution of possible effects is necessary. Models must designed with the appropriate end-use in mind [*Keeler et al*., 2012].

2.2. Payments for Watershed Services (PWS)

Payments for Watershed Services (PWS) are agreements under which a landowner is compensated for specific management actions that maintain or improve a water resource. The questions are how big an impact a landowner's actions make on the water resource of interest, and how much she should be compensated. For example, a recent analysis in Kona, Hawai'i addressed the question of whether it was financially beneficial for the local Department of Water Supply to pay upgradient landowners to manage their properties to increase groundwater recharge [*Brauman*, 2010]. These PWS are an increasingly popular type of incentive program, with over 100 identified in recent surveys [*Bennett et al*., 2013; *Stanton et al*., 2010]. China has transferred billions of dollars in funds and grain subsidies to incentivize land conversion to reduce erosion and flooding through its National Forest Conservation Program and its Grain to Green Program [*Liu et al*., 2008]. And, since 2000, The Nature Conservancy has been engaged in Water Funds with partners throughout Latin America. Multimillion dollar projects in Brazil, Colombia, Ecuador, Mexico, Panama, and Peru collect fees from water users and use those funds for forest conservation along rivers, streams, and lakes [*Goldman et al*., 2010; *TNC*, 2013].

This context of payment for services builds upon scenario analysis; at a minimum, there will be two scenarios: the current state, and one or more future or alternate states that are more or less desirable [e.g., *Brauman et al*., 2014]. In addition to the challenges presented above, payments for watershed services also add the complexity of attributing value to a particular landholding along with the challenges of expressing the service values in monetary terms and ensuring that contracts are followed [*Porras et al*., 2013; *Wunder*, 2013]. Additionally, PWS have become particularly popular in tropical regions. Hydrologic science in the tropics remains limited, however, and the extent to which knowledge gleaned from temperate watersheds can be translated to the tropics remains unclear [*Ponette-González et al*., 2014].

2.2.1. Challenge 4: Monetization

Monetization is appealing because it puts ecosystem services into the same common currency that people use to value other needs and desires. This focus on monetization adds an additional challenge related to valuation. In scenario analysis, it may be sufficient to determine the relative ranking of the scenarios, i.e., is scenario A better or worse than scenario B. Payments for watershed services, however, require that the change in service provision between the scenarios be quantified monetarily. Even if we leave the translation of biophysical services to dollars to the economists, the hydrologic information necessary to do so will be greater than what is needed to rank a set of scenarios.

2.2.2. Challenge 5: Interaction Effects and Valuation at the Parcel Level

Even when monetization is possible, PWS also require a mechanism for attributing that change in value to specific actions. Since water moves through the landscape, service value will be affected by the uses of land along the entirety of flow paths and not just the management of a particular parcel [e.g., *Bagstad et al.*, 2013a]. Scenario analysis can incorporate these interaction effects implicitly, since the value comparison can be made at the watershed scale. A payment for services, however, necessitates a finer determination of cause and effect. For example, upland development may increase runoff amount but lower its quality. Downgradient vegetation buffers and wetlands may improve that water quality. The resulting question of how much each part of that landscape contributes to the overall increase in the provision of clean water is challenging.

2.3. Strategic Spatial Planning

The third type of decision, spatial planning, encompasses questions such as "Where is the best location to site industry?," "What parcel of land is the highest priority for conservation?," and "Which best management practices are most cost effective across a range of parcels in cultivation?" [e.g., *Polasky et al.*, 2008]. Even remaining constrained by what is plausible, this decision context expands scenario analysis to a near-infinite set of possibilities, and the lack of well-defined choices adds a layer of complexity. In addition to the three challenges identified with scenario analysis, spatial planning also suffers from (at least) the challenge associated with interaction effects and parcel-level valuation. Without a transparent stakeholder process to identify scenarios a priori [e.g., *Peterson et al.*, 2003], prediction of the spatial distribution of costs and benefits of services in addition to the total value becomes particularly important. Without such knowledge, we risk unintended impacts to equity and social justice.

In addition to the challenges already described, spatial planning also raises an additional challenge related to robustness and optimality.

2.3.1. Challenge 6: Optimality and Robustness

As discussed above, the ecosystem-service value of a particular land holding or management action depends on the uses of land throughout a watershed. These interaction effects indicate that spatial planning must go beyond the simple identification of regions of high or low service value in the current state. Spatial planning requires the prediction of water services for the multitude of landscape configurations being considered. This becomes more complex when it is desirable to make decisions that are robust with respect to future climates and future land-use decisions. In such cases, the number of scenarios to be investigated can become overwhelming [*Peterson et al.*, 2003] and may require a separate process to reduce their number.

2.4. Opportunities

In complement to the challenges presented above, the decision context of ecosystem services provides some opportunities for advances in hydrologic modeling. In this decision context, the goal is neither hydrologic truth seeking nor truth representation. Indeed, our imperfect process understanding, limits of our observations, and challenges of scale and representation make such a goal elusive. In the face of such uncertainty, the desired outcome is a model that is useful, i.e., one that can inform a decision process and lead to a better land-management decision than one derived without the model. This point is emphasized by the recent Federal Principals and Requirements:

"The level of detail required to support Federal investments in water resources may vary, but should not be greater than needed to inform the decision-making process efficiently and effectively. The level of detail, scope, and complexity of analyses should be commensurate with the scale, impacts, costs, scientific complexities, uncertainties, risks, and other sensitivities (e.g., public concerns) involved in potential decisions," [*CEQ*, 2013, p. 8].

This decision orientation is distinct from other hydrologic modeling efforts that aim to reproduce field observations or to forecast stream response. Thus, it provides the chance to think about our models in new ways and to identify new lines of inquiry. For clarity, we group the opportunities below into three categories. While they are presented sequentially, these opportunities are highly coupled and should not be interpreted as separate or hierarchical.

2.4.1. Opportunity 1: Decision Context Allows Focusing of Model Output

While the challenges articulated above are daunting, the decision-making context provides opportunities for model simplification. In particular, the valuation of a service can be used to inform and narrow the required biophysical predictions. For example, it is generally not necessary to predict the timing and magnitude of

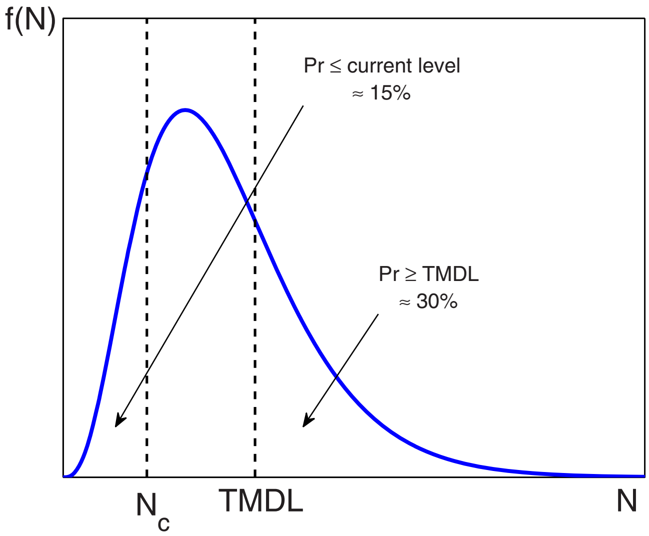

Figure 2. Hypothetical distribution of nitrate load following a land-use change. N_c represents the load before the conversion, and TMDL represents the maximum allowable load.

streamflow response to a particular rain event in order to determine the value of base flow. Rather, it is important to characterize the distribution of flows under specified climate and land-use scenarios. For example, referring back to Figure 1, if the valuation curve is linear, as in 1a, then one need only predict the mean streamflow in order to determine the total value. If the value curve exhibits a threshold (1b), then the required knowledge is the fraction of time that the flow exceeds Q_T. Even the nonlinear valuation function in 1c requires knowledge of the flow-duration curve only, and not the runoff response to individual precipitation events.

2.4.2. Opportunity 2: Desired Output Constrains Required Processes and Parameters

Relatedly, just as the decision dictates the required model output, that output can be used to constrain the processes and parameters that must be included in a hydrologic model. This is not new—most hydrologic models are clear about their design and intent, either as flood-routing models or water-quality models or groundwater models [*Garen and Moore*, 2005]. Nonetheless, it is worth highlighting this opportunity to simplify and focus efforts on processes of relevance [e.g., *Brauman*, 2010]. Regarding model parameters, the desired output can also provide insight to the value of additional information when combined with an understanding of the required level of certainty (see below). This can help guide and prioritize field measurements and data-collection efforts.

2.4.3. Opportunity 3: Informing Decisions Requires Less Certainty

Unlike the certainty required to reject a null hypothesis in a statistical test, decision analysis necessitates a different view of uncertainty. This is good news given the challenges of scale, representation, and data availability. Decision theory, threshold analysis, adaptive management, and resilience thinking all represent different approaches to decision making under uncertainty [*Polasky et al*., 2011], and even highly uncertain predictions of biophysical effects can provide value for a wide range of decisions.

Consider a hypothetical decision about whether to approve a development project that would eliminate a particular forest. The development project would provide some economic benefits. However, the transformation of the forest may also increase nitrate loads in a neighboring river, potentially exceeding the TMDL (total maximum daily load). Compensating for this would require investments to upgrade treatment capability at some cost. To determine whether to move ahead with the project, one would like to compare the benefits of the development against the potential risk and costs of treatment.

Predictions of the post-development level of nitrogen in the stream might be represented by the probability distribution pictured in Figure 2. In this example, the probability that the nitrate load would be *less* than or equal to its current level is ~15%, so the effect of forest conversion on nitrogen levels is likely not statistically significant. However, there is also a 30% probability that the new load will exceed the TMDL, and a decision maker may be unwilling to take such a risk. Or, if the decision context were an expected-value cost-benefit analysis, the project would fail if the benefits of development were less than 0.3 times the cost of the treatment-plant upgrade. Our example is not to suggest any one best way to make decisions but rather to highlight the fact that even uncertain predictions have value.

3. Ways Forward

A major challenge in the valuation of water-related ecosystem services is that the demand for hydrologic knowledge and information outstrips our current ability to provide it. However, we believe a greater integration of decision approaches with hydrologic modeling efforts provides an important path forward. While the challenges are still large, there are opportunities where appropriate framing of the hydrologic modeling effort can lead to better decisions.

To support the ecosystem-service framework, we must consider hydrologic models as tools for informing decisions in addition to their role in improving our hydrologic understanding. In that context, those models need to incorporate and produce relevant information at decision-appropriate scales in space and time. For ecosystem services, this will usually imply a focus on the effects of land-use and land-cover changes, and the ultimate output is service valuation, which is related to biophysical response. As discussed in section 2.4, appropriate model structure will depend on the decision context, the desired biophysical outputs, and the dominant hydrologic processes.

3.1. Ongoing Modeling Efforts

With high demand for tools that facilitate the valuation of ecosystem services, a number of modeling approaches have been employed. With respect to water, some approaches have employed existing hydrologic models, such as SWAT [*Neitsch et al*., 2011] and VIC [*Liang et al*., 1994], and adapted them for ecosystem-service valuation [e.g., *Bekele et al*., 2013; *Liu et al*., 2013; *Notter et al*., 2012]. Other approaches start from the ecosystem-service viewpoint and include a range of services across disciplines. The former approaches have the advantage of building on well-established models and decades of development and testing. Since those models are focused on hydrology, however, they often lack an explicit link to beneficiaries and do not permit comparison across ecosystem services and assessment of trade-offs. Additionally, there are still the issues of scale, representation, and uncertainty, and the demands on modeler skill and input data can be quite high [*Vigerstol and Aukema*, 2011].

The models that can be classified first as ecosystem-service models can be further separated into simple, screening tools, and those that are spatially explicit, and *Bagstad et al*. [2013b] provide a detailed review and comparison of the functionality of 17 ecosystem-service models. Of those that are spatially explicit and publicly available, ARIES (Artificial Intelligence for Ecosystem Services) and InVEST (Integrated Valuation of Environmental Services and Tradeoffs) are two of the best known.

ARIES is designed to represent the flow of ecosystem services from sources to users, potentially interrupted by sinks [*Villa et al*., 2014; *Bagstad et al*., 2013a]. Sources and sinks may be considered beneficial or detrimental, depending on the nature of the service. For water supply, sources would be precipitation and interbasin transfers and would be beneficial to the downstream users. In the case of excess nutrients, however, sources have negative impacts, and it is the presence of sinks on the landscape that provide the ecosystem service [*Bagstad et al*., 2013a]. Routing from sources to users is done through agent-based probabilistic models. Typically situated in a Bayesian framework, these models can be updated or modified based on local data and conditions [*Villa et al*., 2014].

To provide a tool that enables the evaluation of trade-offs among multiple ecosystem services, including water-related services, the Natural Capital Project is developing InVEST [*Tallis et al*., 2013; *Kareiva et al*., 2011]. These models are physically based, spatially explicit, and are intended to include multiple levels of complexity. Currently, the water-supply models operate at the annual scale, and a seasonal model is under development; the water-quality models predict the spatial distribution of sources of nutrients and sediment. Partnered with these models is a newly released tool, RIOS (Resource Investment Optimization System), which combines the biophysical production of the InVEST models with knowledge and information about infrastructure costs, available resources, and social context to identify the best locations for conservation and restoration activities [*Natural Capital Project*, 2013].

A significant challenge for the ecosystem-service models is how to appropriately and transparently incorporate hydrologic-process knowledge, while retaining the operational simplicity desired by decision makers [*Bagstad et al*., 2013b; *Vigerstol and Aukema*, 2011].

3.2. Next Steps

Given the challenges and opportunities presented above, we have developed a set of next steps for the hydrologic-modeling community. This list is not intended to be exhaustive nor to suggest that all hydrologists direct their efforts to these tasks, but rather to provide a set of hydrologic research directions that will support the valuation of ecosystem services.

1. There are still many outstanding science questions regarding how water makes its way through the landscape [e.g., *Price*, 2011; *Blöschl et al*., 2013]. Thus, there is a continued need for field investigations of hydrologic processes at catchment scales. This is particularly true in urban watersheds and in the tropics [*Ponette-González et al*., 2014]. To best support ecosystem-service decisions, such data-collection efforts would seek to quantify the impacts of changes in land use and land management.

2. In addition, the rise of informatics tools presents an opportunity to mine existing data to better understand the effects of land use and cover on hydrologic responses [e.g., *Maidment et al*., 2009]. Statistical relationships and regressions that emerge from such efforts may or may not be directly extensible to other places [e.g., *Eigenbrod et al*., 2010]. Nonetheless, the insights that emerge from such empirical relationships can generate new hypotheses for further investigation.

3. Complementing existing data, the rise of PWS presents a unique opportunity to directly monitor the effects of landscape modification at decision-relevant scales. While resources are often scarce, we recommend that implementation of payments for watershed services incorporate a thoughtful program of monitoring, preferably directed by hydrologists—not only for evaluation of the efficacy of a particular program but also to provide the information that will help us build our larger understanding of land-use and land-management effects on watershed services and improve future decisions.

4. The variety of potential ecosystem-service decisions related to water calls for variety in the complexity and scale of hydrologic models. In addition to striving for models with higher resolution and incorporation of more processes, we also recommend the continued development of simple hydrologic models with fewer data requirements and coarser resolution. While their precision may be lower, in many cases they may be the best tools to inform a decision process in data-poor environments. Ideally, such model development would involve economists and decision makers to match the model scope and output to decision context.

5. With a range of models from which to choose, appropriate selection will hinge on a proper understanding of the uncertainty in model outputs. Therefore, in complement to model development, we recommend continued efforts to characterize the uncertainty of those models under a range of conditions. Particularly useful would be opportunities to test multiple models in a common setting [e.g., *Bagstad et al*., 2013c]. And, rather than papers that demonstrate the accuracy of well-calibrated models, we suggest that efforts to characterize the uncertainty of uncalibrated models will provide information valuable to decision makers.

6. Last, given the plethora and sophistication of existing hydrologic models, we suggest that much could be done to integrate these models with decision tools. We see opportunities to develop methods to convert biophysical outputs to water-related services and attribute those values back to the landscape. Doing so would enable decision makers to draw upon state-of-the-art hydrology, while providing a means of translating biophysical output to service valuation and informing decisions.

4. Conclusion

The concept of ecosystem services has gained significant traction among environmental decision makers as a way of incorporating the value of natural processes and conditions that benefit human health and well-being. Since so many environmental decisions are water related, the hydrologic-modeling community must bring its expertise to the conversation. If we do so effectively, we have an opportunity to improve environmental decisions and help achieve a sustainable future.

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