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Wicked Tools: The Value of Scientific Models for Solving Maine's Wicked Problems

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Wicked Tools:

The Value of Scientific Models for Solving Maine's Wicked Problems

by Tim Waring

"Wicked problems" are urgent, high-stake socioeconomic-environmental challenges that often involve ideological conflict and have no "best solutions." Using examples from Maine's Sustainability Solutions Initiative projects, Tim Waring describes how scientific models can be used to address these kinds of problems. When well-constructed and tested models are used to address policy-relevant issues, include input from stakeholders, and integrate social, economic and environmental dynamics, they can become "wicked tools" to address some of society's biggest challenges.

At the turn of the millennium, I lived in Florida and worked for the South Florida Water Management District (SFWMD). This state agency was responsible for managing the state's water for human use while at the same time maintaining the greater Everglades ecosystem. On face value, these dual goals seem relatively simple. But, as I learned, managing water in South Florida is, in fact, a "wicked problem."

The term "wicked problem" is not just a New England colloquialism, but also a term used by planners, scientists and policymakers to describe the sorts of complex interlinked socio-economic-environmental challenges common today. Wicked problems are urgent, complex, have high stakes, and low tolerance for error. Wicked problems often involve strong ideological conflicts between stakeholders, and have no best solutions, and are often connected to a web of other problems in such a way that "solving" one wicked problem could make another one worse.

The attributes of a wicked problem are as follows (paraphrased from Rittel and Webber [1973]). Wicked problems

- have no single definition
- have no best solutions
- have no stopping rule
- have no ultimate test of a solution
- have no enumerable set of solutions
- are always unique
- have only one-shot solutions
- may be symptoms of other problems
- contain multiple relevant, potentially contradictory, perspectives
- are too important not to solve

Water management in South Florida is a wicked problem. Floridians need water to drink, clean and bathe, and use water for their lawns, and in industries. But Floridians also love and value the Everglades as a source of unparalleled recreational opportunities, spectacular biodiversity, and as a unique natural heritage. Both the growing coastal cities and the Everglades ecosystem require huge amounts of freshwater. There is only a limited amount of water available, and its delivery (via rainfall) is unpredictable. Managing the complex network of water supply canals and floodwater control infrastructure and water management areas is a wicked problem all to itself. It gets truly complex, however, when we must also include and sustain the Everglades.

To sustain the Everglades, the SFWMD has to answer a vast array of complex questions. What nutrient levels are required to maintain the natural Everglades vegetation without choking its waterways with algae and invasive plants? How should water be channeled to maintain the unique tree islands and characteristic ridge and slough landscape that naturalists and hunters most value? What timing and velocity of water flow across the swamp will sufficiently scour accumulated debris from the channels, and maintain critical alligator, fish and wading bird habitat? How did the historical Everglades look and function before the canals were created in the early 1900s? How closely should a restored Everglades match that earlier state?

Amazingly, the SFWMD has been largely successful in its mission to serve both the cities and their natural treasure. A critical part of that success has been the strategic use of carefully designed water- and ecosystem-management models. The Everglades Landscape Model (ELM), a massive biogeochemical computer simulation model, which I helped improve, is an example of one such management power tool. Two characteristics made the ELM successful. First, the ELM was a scientific and engineering marvel, combining the most rigorous scientific understanding of every aspect of how the Everglades functioned with all of the best data on the Everglades, current and past,

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to create a virtual Everglades ecosystem. With startling accuracy, the ELM simulated the water and nutrient flows and the plant and algal growth across the million-acre Everglades and surrounding areas over 50 years. Second, the ELM allowed managers to evaluate the future ecological impacts of complex and permanent water management decisions, the sort that entail billion-dollar infrastructural changes and can only happen once. They were able to model the impact of these decisions without moving a shovel-full of dirt. The ELM allowed the SFWMD to escape some of the wicked-ness of the wicked problem it faced, and to design policies and infrastructure that protected both city and swamp.

> ...scientific models....provide a means for complex and technical matters to be handled transparently and objectively even by people who share different views on the subject.

Of course, Florida is not the only place with wicked problems. Maine has its own wicked problems, from collapsing fisheries and economic stagnation to water contamination and rural poverty, from energy security to climate change and urban sprawl. We need scientifically sophisticated, empirically robust, and policy-relevant models designed to address our wicked problems. The Sustainability Solutions Initiative (SSI) has begun numerous projects that employ scientific models to these sorts of wicked problems, so that planners, legislators, decision makers and citizens across Maine can better evaluate how the choices of today influence the future of our state.

WHAT IS A SCIENTIFIC MODEL?

Scientific models are the core element of modern science. They are where theory meets data, where assumptions are tested, and where predictions are created. There are many types of models, from physical models (scale replicas of various landscape or engineering systems) to conceptual models (including flowcharts and maps) to formal scientific models. All of these types of models are valuable in various contexts, but the most important, and perhaps the hardest to understand, are the formal scientific models.

Simply, formal models are special domains in which the rules of pure logic are employed to achieve accuracy and validity. Models are used to test the validity of assumptions, to predict outcomes, and to help to explain data. A formal model is an abstract and simplified system of logic (usually equations or algorithms) meant to capture important features of the real world. Here I will use the term "model" to refer to this type of system. The reason that models are so valuable is that they employ objective logic to create reproducible results. Models allow scientists, engineers, and practitioners to use logical inference to examine the results of explicit assumptions and theories about how the world works, and turn those assumptions into new, testable predictions.

Like any powerful tool, scientific models must be used with care. Researchers must assess that the model is logically consistent (*internal validity*) and provides a useful picture of reality (*external validity*). To design such a model, researchers use *deductive logic*, drawing on algebra and calculus to test model assumptions and to demonstrate that the results fit the premises of the model. Once a model is built, researchers will often employ *inductive logic* to extrapolate the results and test model predictions in new contexts.

There are many uses of scientific models. For example, a business owner might use a statistical model to determine what factors drive business traffic. An engineer will employ mathematical models composed of one or more equations to calculate the best location for support columns for a bridge. A regional planner might use a simulation model with hundreds or thousands of interacting individual components to examine the likely future outcomes to alternative development policies. Mathematical, statistical, and computational models are applied everyday to improve society. In each of these examples, the value of the model output is a unique and exact result of the logical structure of the model. This is the power of scientific models—they provide a means for complex and technical matters to be handled transparently and objectively even by people who share different views on the subject.

SCIENTIFIC MODELS AT WORK FOR SUSTAINABILITY IN MAINE

At the University of Maine, there are hundreds of formal scientific models in active development and use. Some of the most relevant applications of these models come from SSI. Below, I provide a guided tour of a handful of SSI projects that make innovative use of scientific models in the search for improved economic, social and environmental quality of life in Maine.

Maine's Alternative Futures

Perhaps one of the largest challenges facing Maine is how to encourage economic development while maintaining the high-quality natural resources the state offers. Unfortunately, land-use decisions are often made with little information about the larger opportunities within Maine's landscape, putting development at odds with forestry, agriculture, and environmental conservation. At the policy level, land-use decisions occur within the context of broad, ideological arguments about the relative value of environmental conservation or economic development. These arguments often lack good data and science and as a result are likely missing effective compromises. Rob Lilieholm, a professor of forest policy at the University of Maine, is searching for those "win-win" solutions by combining advanced modeling techniques with the know-how and expert opinion of some of Maine's business leaders, resource managers, and citizens.

A prominent problem in land-use planning is that information on the value of land for different uses is patchy and only available for small areas. Imagine the following common scenario. Conservationists use habitat quality or biodiversity to identify a parcel as prime conservation land. Meanwhile developers use distance

STUDENT SPOTLIGHT

Spencer R. Meyer

Graduate Research Assistant, Sustainability Solutions Initiative; Ph.D. student, School of Forest Resources; Associate Scientist, Forest Stewardship, Center for Research on Sustainable Forests University of Maine

A New England native, Spencer Meyer has a passion for the natural world and an appreciation for the interconnections between people and the places where they live. He recently decided to combine his personal interests and professional expertise to pursue a Ph.D. through SSI. After working for years with large landowners on sustainable forest management in Maine, Meyer is examining the bigger picture of landscape conservation as a member of SSI's Alternative Futures Team. His work on land use models could help Maine communities make more sustainable choices amid pressures ranging from development to rising fuel prices.

What problem are you working to solve?

I'm helping to build stakeholder-driven models of land use in Maine. We want to know from conservationists, foresters, farmers, and developers what makes land best suited to their missions. Once we get a better understanding of needs and land-use suitability, we can begin to identify areas where land uses will likely overlap. For instance, where do forestry and conservation assets co-occur? What areas are most at risk for development and have high conservation value? We can then model multiple scenarios to estimate what might happen in the future.

What progress are you making toward solutions?

We've been working with a terrific group of business leaders, public servants, developers, scientists, and other citizens who want to see Maine plan for our state's future. We recently met with these partners to review our first project results: land-use-suitability maps for the Lower Penobscot River watershed, which includes Greater Bangor.

Our maps show areas where land uses are likely to compete and other areas where there are opportunities. For instance, our results reveal that most of the watershed is highly suitable for forestry, and we've identified other areas that have notable value for ecosystem services, biodiversity, and recreation. Forestry and conservation are highly compatible, so there are clear opportunities to expand conservation efforts.

We've also identified areas that are highly suitable for residential, commercial, or second-home development. We see some locations where this development, if it comes, is likely to have an impact on some of our natural resources.

Our models suggest that there's plenty of room to accommodate all land uses if Maine communities plan well. We're now fine-tuning these models based on partner feedback and then spreading the word. We hope to talk with communities, land trusts, state agencies, and landowners about how our maps might help them make decisions.

Now that we have a proof of concept for mapping the suitability of development, we're also planning to expand our work to southern Maine. We've partnered with SSI researchers including Dave Owen of the University of Maine Law School to look at how our models can help identify watersheds and forested areas that are most at risk of development. By identifying healthy urban streams that might be at risk of becoming impaired through development, we can help inform communities about the benefits of proactive planning to avoid potential expenses of water-quality mitigation required by environmental regulations.

How could your findings contribute to a more sustainable future in Maine and beyond?

As development pressures increase and Maine's demographic changes, land-use pressures shift. By investigating alternative future conditions under multiple land-use and demographic scenarios, we hope to help land-use planners to better match policy tools and economic incentives to the changing needs of Mainers.

—Kim Ridley

Judy Colby-George

STUDENT SPOTLIGHT

Graduate Research Assistant, Sustainability Solutions Initiative
Ph.D. Student, Ecology and Environmental Science, University of Maine

As the owner of a small geographic information systems (GIS) consulting business in Yarmouth, Judy Colby-George specializes in using geospatial tools to "empower citizens to become involved in decision making in their communities." She had long been considering returning to school, and SSI's philosophy and ideals appealed to her. Colby-George says she seeks an education that enables her to more deeply explore the work she's been doing for more than a decade and contribute to making a difference in her community and the state.

What problem are you working to solve?

I am looking at how and where GIS is most effective in communicating complex ideas to stakeholders and the public. I'm interested in the ways in which these new technologies can bring people to the table to better understand the choices they are asked to make on a regular basis. For example, on a personal level, people are making decisions about buying, selling, developing, and preserving land and housing. On a community level, municipalities are making choices about what they want to be and how they create policies and communities that reflect those choices. Specifically around land use, communities are deciding what types of development make sense for them and how will they provide jobs, housing, and community-based amenities that work for their town.

What progress are you making toward solutions?

I'm currently working with two SSI teams, the Sustainable Urban Regions project and ESCAPE (Ecological and Social Change: Adaptation, Place and Evaluation). I'll be surveying landowners in Greater Portland and Greater Bangor this spring to better understand their perceptions of landscape change and their role in it. Landscape change is difficult for many people to envision because it happens incrementally and often on a large scale. The research should illuminate the differences between various groups' understanding of landscape change and help communities to move toward consensus about the facts of this change even if values differ. A shared understanding of the facts will help communities to evaluate and implement policies intended to reach their shared goals.

How could your findings contribute to a more sustainable future in Maine and beyond?

I believe that the work we're doing can help to inform participatory decision making in Maine communities and the ways in which geospatial technology is used within those processes. In the end, our work will contribute to better ways or best practices for using this technology to empower people to understand problems, envision solutions, and implement effective policies and practices in their communities.

—Kim Ridley

to urban centers to screen sites for development. But, the two plots overlap. In this scenario, there is no win-win solution because with one parcel, someone always gets there first—it is always win-lose. If each land-use interest only considers their own primary indicator of land quality, as a whole, society will be unable to assess tradeoffs and will likely miss the best-mix solutions across the broader landscape. The problem is that developers pay no attention to conservation value or biodiversity, and conservationists do not pay heed to commercial or development value. The result is that individual choices and municipal policies can become myopic and miss strategic opportunities to satisfy multiple land-use needs simultaneously. Lilieholm's SSI team is exploring a way to address this problem, by broadening the spatial scale at which all land-use interests can prioritize parcels.

Lilieholm leads the "Alternative Futures" SSI research team. His team has created a *statistical model* that combines high-quality spatial, biophysical, and economic data with expert knowledge from developers, foresters, mill owners, farmers, ecologists, and others. Lilieholm's team uses a simple process to identify areas that are suitable for multiple land uses. First, stakeholder groups identify key aspects of land value for their purposes. Next, the researchers assemble all of the data needed to address land-use suitability for all three sectors. Finally, the team employs the expert land-valuation model to these data to predict which land parcels hold the highest value in each sector and to find both regions of likely conflict and tradeoff opportunities.

The team's central challenge is to get all of these divergent groups thinking about each other's needs. Their solution lies in creating a single set of land-use suitability maps that are valuable to developers, foresters, farmers, and conservationists. Each of these suitability maps is based on relevant biophysical and socioeconomic information for each land use. Therefore, while a map of soil quality is useful for agricultural operators, a map of distance to urban centers is valuable for developers, and a map of biodiversity is important for conservation organizations. All organizations benefit from seeing where their priorities are likely to conflict. To find win-win scenarios, the team identifies these areas of conflict and tradeoff opportunities so that the development of plans in each sector

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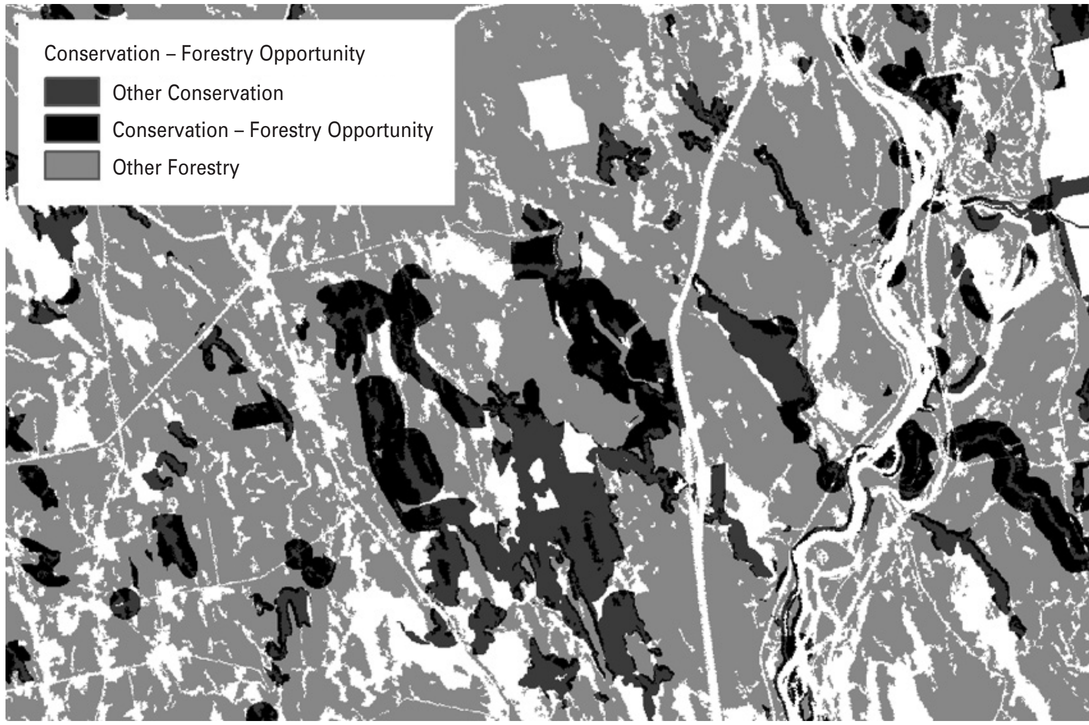
FIGURE 1: **Bayesian Belief Network (BBN) Model**



does not happen in isolation from those in other sectors.

At the heart of this effort is a scientifically valid, transparent, and trustworthy process for stakeholders in each sector. To build that trust, Lilieholm's team works with stakeholders to create an advanced statistical model, which produces these specialized maps. The model is called a Bayesian belief network, or BBN, named for probability theorist Thomas Bayes. A BBN accumulates the expert judgment on various aspects of the land and then makes spatial predictions about the areas most suitable for each land-use type. If the model accurately represents expert opinion, then experts recognize that the model successfully identifies land that is valuable to them. Naturally, stakeholders would have no reason to trust such a model if they had not already contributed to its construction.

The team's BBN model, illustrated in Figure 1, combines detailed spatial data with expert opinion from stakeholders in different sectors to predict land value for different uses. The model also identifies conflicts and synergies between different land uses. In the example shown in Figure 1, the BBN model identified overlapping areas valuable for both forestry and conservation, and presenting a unique opportunity for a mixed land-use type.

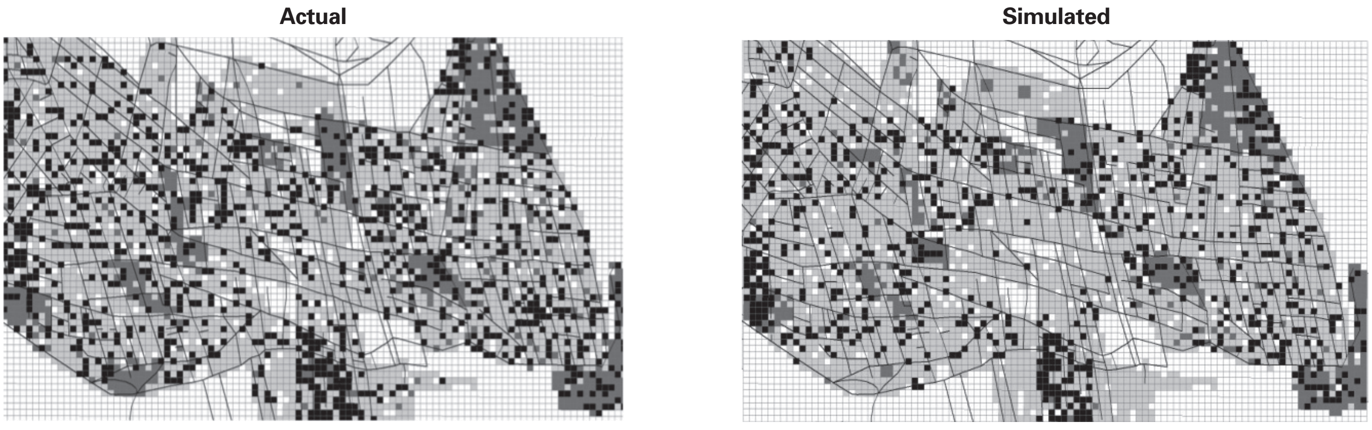
In this way the Alternative Futures team gives us a clear example of how scientific models can serve as powerful collaboration tools, even across divergent interest groups. An important milestone for the Alternative Futures team came at a meeting in late fall of 2011, during which experts and stakeholders agreed that preliminary maps generated by this BBN model are indeed valuable for their uses. The work of the Alternative Futures research team demonstrates how the application of scientific modeling to stakeholder needs is valuable, no matter how you value land. (For more information, see McCloskey et al. [2011])

Sustainable Cities for Maine

The Sustainable Urban Regions Project, led by Charles Colgan at the University of Southern Maine's Muskie School of Public Service in Portland, has a similar goal to that of the Alternative Futures team, but Colgan's research team is targeting the complex interactions and tradeoffs in cities. Because the interactions of residents, laws, economics, infrastructure, and the built environment of cities are exceedingly complex, plans and policies tend to miss important connections among the many different systems that make up an urban region.

Colgan's approach to addressing this problem is to build *simulation models*, similar to the Everglades Landscape Model, to help cities make the best choices about how they develop over time. Focusing on the Portland and Bangor metropolitan areas, the simulation

FIGURE 2: A Comparison of Actual and Simulated Distribution of Three Household Types on the Portland Peninsula in 2000



Note: Simulations such as the one that produced the output to the right can be calibrated based on their match to real data. Note the similarity between the two images. Simulations of this sort can be used to experiment with different zoning and planning options.

models under development combine multiple approaches to modeling, from econometrics to artificial intelligence, to capture the richness of sustainability challenges in urban areas. Current projects include detailed spatial simulations that integrate housing, economic activity, and land use, transportation simulations that track vehicle movements on each road, and energy systems simulations that link land use, transportation, and climate impacts. Social simulations of this magnitude are many times more complex than models of physical, chemical, or biological systems. This complexity comes with added challenges and benefits.

The challenge of complex simulations of entire cities is that a small amount of error or uncertainty in one assumption or piece of input data can spread through a simulation and make results unrealistic. This problem is overcome through the processes of *model validation*. Dr. Colgan's UrbanSim team uses three types of validation. First, the team collects the data they need to initialize the simulation. Data at the individual parcel level are needed for nearly 90 Maine towns. Colgan's team has gathered large amounts of accurate spatial, social, and economic data on Portland and Bangor areas. These *initialization data* ground the simulations of virtual social interactions in a realistic context. Next, simulations are subjected to rounds of *robustness*, *sensitivity*, and *uncertainty analyses* to determine if any assumptions, parameters, and model procedures might have undue, unusable, or unrealistic influence on model dynamics. These analyses require running the model a great many times to accumulate statistics about how it works under different conditions. After improving the model based on these results, the simulation is finally calibrated so that it matches the real-world conditions of each city.

Model calibration often uses a second set of data that the model has not been initialized with, and has never "seen," as a test of predictive accuracy. Calibration is successful when model simulations reliably predict real-world test data. Among the calibration techniques to be used are "back casting" approaches—testing the model by asking it to replay actual history. This final step is a strong signal of model quality because if the model can correctly predict real-world outcomes beyond the range of data on which it was "trained," it may well be able to identify subtle but important issues influencing the future.

Throughout this process of model validation are important opportunities for stakeholder input and trust building. Like Lilieholm's team, Colgan and his research team are working with stakeholders from the business and environmental communities, real estate development and conservation groups, and regional and local officials in each of the two metropolitan areas to make sure that the model is understood, trusted to make reliable output, and directed toward useful and challenging questions. For example for their work in Portland, Colgan's team is working with the Maine Department of Transportation, the Greater Portland Council of Governments, the Maine Turnpike Authority, and Southern Maine Regional Planning, among other groups. Early development of the models has focused in particular on energy and climate issues along with the changing demographics of the regions based on input from stakeholders.

The benefit of these procedures, applied well, is a city simulation that can accurately respond to complex urban scenarios, which real cities have not yet had to face directly. Once the design, testing and calibration of the simulation is complete, Colgan's team will work with stakeholders to identify a number of different policy scenarios to examine. Each carefully chosen scenario will represent relevant policy choices facing Maine's two largest urban regions in the coming years.

When carefully constructed, initialized, and validated, simulation models such as Colgan's urban simulation provide planners with a special power to examine critical issues. What are the implications of an aging society that no longer needs large suburban houses? What are the prospects for development of empty big box stores? When can denser development be most effective at conserving forests and wildlife habitat? These sorts of questions are only accessible through a simulation of an entire city.

Portland's Water Source: Sebago Lake

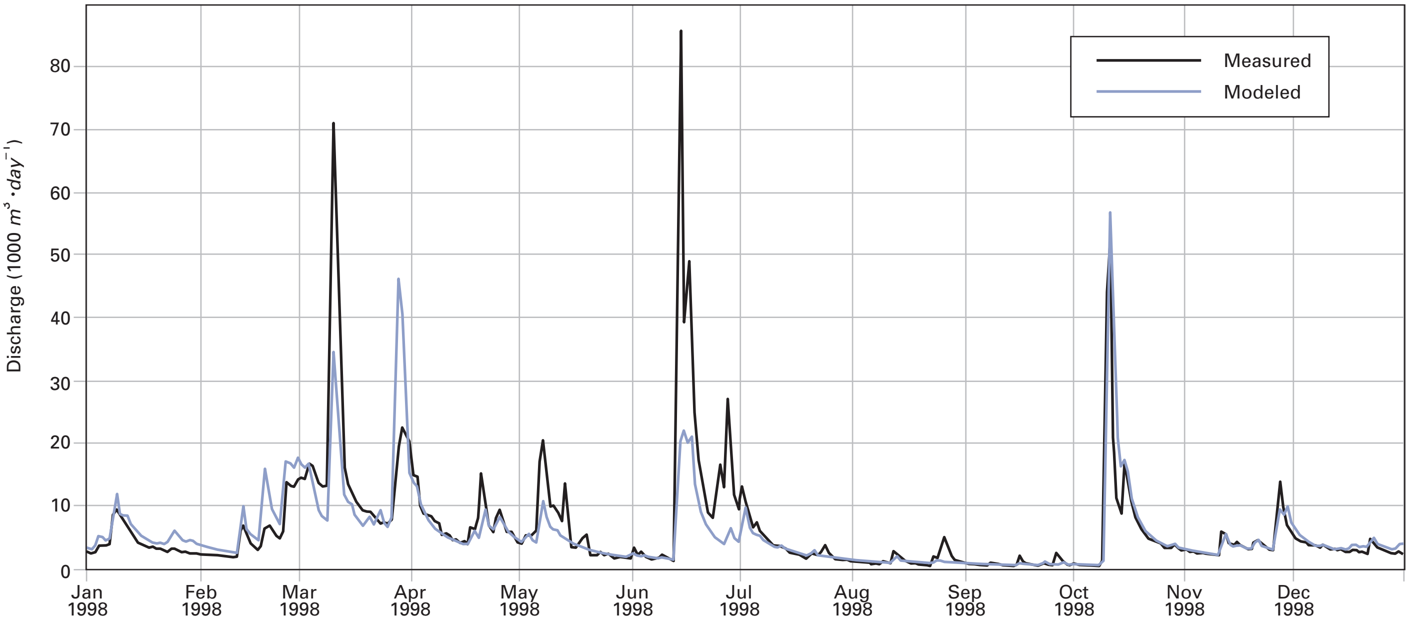
Sebago Lake is many things to many people. Sebago provides drinking water to the 200,000 residents of the greater Portland area; it is an important recreational destination and a source of hydroelectricity for local factories; and the lake is a diverse aquatic ecosystem cherished by residents and visitors alike. However, much like the challenge of managing the Everglades for multiple uses, just managing the level of Sebago Lake has proven controversial due to these multiple interests and uses. The wickedness of this problem lies in disagreement about the optimal lake level and lake-level variability throughout each year and between multiple years, driven by seasonal inputs from rainfall and melting snowpack. This lake-level variability influences the various lake uses and influences how lake outflows, controlled by a dam, are managed. How low should the lake be drawn down in the summer? How high should we allow it to fill in the spring? How often should it be high and low? Should down-river interests have a say in the management of Sebago Lake? The Eel Weir Dam, near the outflow to Sebago Lake, is currently being relicensed by the Federal Energy Regulatory Commission (FERC), and groups with different viewpoint are voicing their opinions to regulators in an effort to shape future lake-level management.

Andrew Reeve, a University of Maine professor of earth science specializing in hydrogeology, is beginning a project to simulate lake level within Sebago Lake. The goal of this modeling effort is to provide a virtual environment that allows interested parties to experiment with different climate, development, and lake-management scenarios to forecast how lake level will respond. The team hopes that this model will inform stakeholder groups about the processes that influence lake level and identify management strategies that strike a balance between groups advocating for different management plans. The lake-level model being developed will be used to predict lake-level responses to a variety of alternative scenarios.

> When carefully constructed, initialized, and validated, simulation models... provide planners with a special power to examine critical issues.

A watershed is all of the land that drains into a water body. The Sebago watershed model is composed of sub-models that simulate the water flow into Sebago Lake from different streams and rivers. These sub-watershed models are each calibrated individually with stream data being collected from the major rivers discharging into Sebago Lake, including nearly continuous stream-water-level measurements and periodic stream-flow measurements. The simulated outflows of these calibrated sub-watershed models, driven entirely

FIGURE 3: A Sub-watershed Model Prediction for Sebago Lake, Calibrated with Data from 1997 and Made to Predict Water Discharge for 1998



Note: The more similar the two lines the more accurately the model predicted measured outflows.

by weather-related data, are then combined with discharge at the outflow to predict the changing level of Sebago Lake over time. Although the complete model is still in the construction phase, the sub-watershed models have been calibrated and produce accurate predictions (Figure 3).

Reeve and his team are assembling a web-based interface for the computer model to allow access to this simple model by user groups, stakeholders, and decision makers. This lake-level model cannot resolve disputes, but it can provide a transparent and objective framework different groups can use to assess how changes within the Sebago Lake watershed will influence lake levels.

THE VALUE OF SCIENTIFIC MODELS FOR SOUND POLICY IN MAINE

Carefully constructed, tested, and calibrated scientific models are powerful tools for management and planning. Such models provide the best possible meeting ground for diverse and competing interests in the quest to solve society's wicked problems. Fundamentally, scientific models are valuable because they provide objective and transparent tools for planning, predicting, and understanding the hardest challenges Maine will face in the coming decades.

No model is perfect, of course, and until tested, calibrated, validated, and verified, preferably with representatives of all relevant stakeholders, no model will be useful. Building high-quality reliable models of complex social-economic-environmental issues requires a great deal of expertise and advanced training. Traditionally, these sorts of models are developed within the confines of a single business, academic institution, or government agency. That narrow approach limits the applicability of the model and reduces its ability to help multiple constituencies and can aggravate conflicts between economic sectors, resource user groups, or political ideologies, making wicked problems worse. In the three examples above, we see the opposite—models being used to unite divergent interests around a way to envision, and plan for, a common future. These SSI projects employ different types of models to different challenges in a similar way. Four characteristics that these projects share transform traditional, narrow scientific models into wicked tools. They are (1) a focus on a policy-relevant issue, (2) the inclusion of stakeholders and multiple interests in the design and calibration, (3) the integration of social, economic, or environmental dynamics, and (4) robust and reliable scientific design, testing, validation, and calibration. With these additional characteristics, scientific models can become wicked tools. Scientific models applied in the traditional narrow fashion do not address wicked problems. However, if scientific models are designed to focus on a policy-relevant issue, are made to include input from relevant stakeholders, to integrate social, economic, and environmental dynamics, and are well-built, tested, validated, and calibrated, they can become wicked tools, and help society around its biggest challenges (Table 1).

Maine needs powerful new tools to tackle its wicked problems. The SSI modeling efforts detailed above, and others like them, present a new way of applying scientific modeling, and an innovative new opportunity for our state. The question remains: what wicked problems should we address next?

TABLE 1: **Wicked Problems Require Wicked Tools**

Wicked Problems:	*Wicked Tools (or Good Models):*
have no single definition	are clearly defined
have no best solutions	produce measures of solution quality
have no stopping rule	are clearly bounded
have no ultimate test of a solution	can test many alternative solutions
have no enumerable set of solutions	can evaluate a set of alternative solutions
are always unique	are always unique
have one-shot solutions	allow you to pick better solutions the first time
may be symptoms of other problems	make complex interconnections explicit
contain multiple relevant, potentially contradictory, perspectives	are objective, and can facilitate communication across perspectives
are too important not to solve	are too powerful not to use

ACKNOWLEDGMENTS

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