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Lessons for successful participatory watershed modeling: A perspective from modeling practitioners

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ABSTRACT

Participatory modeling is the process of incorporating stakeholders, often including the public, and decision makers into an otherwise purely analytic modeling process to support decisions involving complex natural resources questions. Participatory modeling is particularly compatible with the rising focus on integrated water resources management, which incorporates systems theory and aims to protect and improve water resources while considering economic and social concerns in the community. In this article, we present a series of lessons based on experience working with stakeholder groups to develop watershed and water quality models to address water resource issues in Maryland, Vermont, Utah, and Virginia. We believe these lessons in participatory modeling, discussed from our perspective as scientists and modelers engaged in applied watershed issues, can help to achieve successful participatory modeling efforts elsewhere. The lessons relate to stakeholder engagement, modeling tools, model development and calibration, scenario testing, and applying results to management decisions.

Water and watershed management has been attracting modelers for several decades. Yuri Svirezhev's legacy in this field includes theoretical studies of aquatic environments (Voinov and Svirezhev, 1981; Voinov et al., 1984), several models of lakes that were built with his collaboration, including the models for Onega Lake (Voinov et al., 1981), Lake Balaton (Jolankai and Voinov, 1988), Lake Plesheyevo (Voinov, 1990), and others (Voinov, 1989). He has contributed to research on fishpond dynamics (Svirezhev et al., 1984). Moreover he was very active in application of his systems and analytical skills to real world problems. He was an active participant of the movement against the transfer of water from the Northern Rivers of Russia to the South—one of the first truly non-governmental, ground root efforts within academia that some call a harbinger of 'perestroika' since it was in stark opposition to the official governmental view on the issue. He was a member of many important commissions, such as the one appointed to study the ecological consequences of the Neva River estuary dam construction. He fought many battles and could very well appreciate how hard it may be to implement the findings from modeling exercises in real policies and decision making.

1. Introduction

In recent years, there has been a shift from top-down prescriptive management of water resources towards policy making and planning processes that require ongoing active engagement and collaboration between stakeholders, scientists and decision makers. Participatory modeling is the process of

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incorporating stakeholders, often including the public, and decision makers into an otherwise purely analytic modeling process to support decisions involving complex environmental questions. It is recognized as an important means by which non-scientists are engaged in the scientific process and is becoming an important part of watershed planning, restoration, and management. The modeling process itself, regardless of the results, leads to improved understanding of a system's interactions and behavior. It is this rich experience that led to the idea of incorporating the modeling process into decision making.

Previously science was often conducted outside of the policy making process, allowing scientists to develop models derived from analysis and observation of the natural world, thereby contributing an objective opinion to decisions without accounting for the values, knowledge or priorities of the human system that affects and is affected by the system being modeled. As a result, in our experience, models have frequently been rejected, especially when the scientific findings demonstrated a need for unpopular decisions related to human behavior. The shift towards more open and integrated planning processes is one way to avoiding potential conflict, misunderstanding and even litigation and has required the adaptation of the scientific modeling process to incorporate community knowledge, perspective and values.

Watershed management affects and is affected by society, especially when diffuse pollution is a primary issue (Korfmacher, 2001). Participatory modeling is particularly compatible with the rising focus on integrated water resources management which incorporates systems theory and aims to protect and improve water resources while considering economic and social concerns in the community. Integrated watershed management requires development of solutions for unique local situations, a task that is often best accomplished by engaging stakeholders and the public in the research process (Duram and Brown, 1999). Participatory modeling provides a platform for integrating scientific knowledge with local knowledge and when executed well provides an objective, value-neutral place for a diverse group of stakeholders to contribute information regarding water resource issues of interest. Recognition that effective watershed management requires input from both scientific and social processes is key to developing effective partnerships between scientists and stakeholders that live and work within a watershed (Rhoads et al., 1999). Participatory modeling supports democratic principles, is educational, integrates social and natural processes, can legitimate a local decision making process, and can lead participants to be instrumental in pushing forward an agreed agenda (Korfmacher, 2001). Modeling tools, appropriately applied, can empower stakeholders to move forward with concerted efforts to remediate an environmental problem (Argent and Grayson, 2003). The extent to which the public or representative stakeholder group can effectively participate in water resources research and management is determined by the methods employed in engaging stakeholders, inclusion of diverse groups, group size, incorporation of local knowledge and expertise, and the time available for the process to develop (Roberts, 2004).

Water resource issues are becoming more common and severe while the complexity of natural systems is further elevated by the complex human socio-economic systems built within them. Thus, decision-making processes will become more constrained by feasible options and time horizons, while consequences of wrong decisions will become more dramatic and affect larger geographic areas. Under such circumstances, standard scientific activities are inadequate and must be reinforced with local knowledge and iterative participatory interactions in order to derive solutions which are well understood, politically feasible, and scientifically sound.

2. Objective

In this article, we present a summary of our experience working with stakeholder groups to develop watershed and water quality models to address water resource issues in the states of Maryland, Vermont, Utah, and Virginia. Details on the watershed modeling studies from these groups are reported elsewhere (Voinov et al., 1999a,b; Costanza et al., 2002; RAN, 2005; Gaddis, 2007; Gaddis et al., 2007) and most of them are still in progress. A summary of each project is provided in the following section. In this article we report the lessons we have learned and found to be most effective in achieving successful participatory modeling. We present these findings from our perspective as scientists and modelers engaged in applied water resource issues.

3. Examples of participatory modeling exercises

3.1. *Solomons harbor watershed, Maryland*

Excessive nutrient loads to the Chesapeake Bay from surrounding cities and rural counties have led to eutrophication especially in small harbors and inlets (USEPA, 2002). The Maryland Tributary Strategies, Chesapeake Bay 2000 Agreement and Calvert County Comprehensive Plan (MDDNR, 2000), calls for reductions in nutrients entering the Bay in order to reduce impacts on aquatic natural resources. Though the goal set for phosphorous appears to be achievable, reductions in nitrogen lag well behind the target. Most sewage in rural residential areas of Maryland, such as Calvert County, is treated by onsite sewage disposal systems (septic systems). Almost all of the nitrogen pollution that enters local waters from Calvert County comes from non-point sources, of which the Maryland Department of Planning estimated 25% comes from septic systems. In this project we initiated a participatory modeling effort to focus on the most densely populated watershed in Calvert County that drains to Solomons harbor. Despite high population densities, only a small portion of the watershed is serviced by sewer. There are no major point sources of nitrogen in the watershed.

Two different modeling tools were used to analyze and visualize the fate of nitrogen from three anthropogenic sources: septic tanks, atmospheric deposition, and fertilizer. The first was a simple dynamic model of a septic tank and leachfield system using STELLA™ software, which allows the user to evaluate alternative septic technologies. The second modeling tool was the spatially explicit landscape modeling framework (LMF) developed by the Gund Institute for

Ecological Economics. The LMF can be used to estimate the relative impact of different nutrient sources on waters throughout a watershed (Costanza and Voinov, 2004).

Participation in the study was solicited from community stakeholders who were instrumental in understanding how models could be applied to local decision making, in making appropriate model assumptions, and in developing politically feasible scenarios. The model results found that septic tanks may be a less significant contributor to surface water nitrogen pollution in the short-term, whereas fertilizer used at the home scale is a more significant source than previously thought. Stakeholders used the model results to develop recommendations for the Calvert County Board of Commissioners. Recommendations included mandating nitrogen removal septic tanks for some homes, but primarily focused on intensive citizen education about fertilizer usage, local regulation of fertilizer sales, reduction in automobile traffic, and cooperation with regional regulatory agencies working to reduce regional NO_x emissions.

3.2. St. Albans Bay watershed, Vermont

Lake Champlain has received excess nutrient runoff for the past 50 years (VTANR and NYDEC, 2002) due to changes in agricultural practices and rapid development of open space for residential uses (Hyde et al., 1994). The effect of excess nutrients has been most dramatically witnessed in bays such as St. Albans Bay, which exhibit eutrophic algal blooms every August (Hyde et al., 1994). The watershed feeding St. Albans Bay is dominated by agriculture at the same time that the urban area is growing. In the 1980s, urban point sources of pollution were reduced by upgrading the St. Alban's sewage treatment plant. At the same time, agricultural non-point sources were addressed through implementation of 'best management practices' (BMPs) on 60% of the farms in the watershed at a cost of $2.2 million (USDA, 1991). Despite the considerable amount of money and attention paid to phosphorus loading in St. Albans Bay, it remains a problem today. The focus has remained primarily on agricultural sources in the watershed, and as a result has caused considerable tension between farmers, city dwellers, and landowners with lake front property.

Recently, the Lake Champlain phosphorus total maximum daily load (TMDL) allocated a phosphorus load to the St. Albans Bay watershed that would require a 33% reduction of total phosphorus to the bay (VTANR and NYDEC, 2002). We initiated a participatory modeling effort to apportion the total load of phosphorus among all sources, including diffuse transport pathways, and identify the most cost-effective interventions to achieve target reductions.

A group of stakeholders was invited to participate in the 2-year research process and were engaged in the research at multiple levels including water quality monitoring, soil phosphorus sampling, model development, scenario analysis, and future policy development. Statistical, mass balance, and dynamic landscape simulation models were used to assess the state of the watershed, the long-term accumulation of phosphorus in the watershed, and to describe the distribution of the average annual phosphorus load to streams in terms of space, time, and transport process. Watershed interventions, matched to the most significant phosphorus sources and transport processes, were identified with stakeholders input and evaluated with the landscape model.

Modeling results suggest that the St. Albans Bay watershed accumulates phosphorus over the long-term, primarily in agricultural soils. Dissolved phosphorus in surface runoff from the agricultural landscape, driven by high soil phosphorus concentrations, accounts for 41% of the total load to watershed streams. Direct discharge from farmsteads and stormwater loads, primarily from road sand washoff, were also found to be significant sources.

The participatory modeling approach employed in this study led to the identification of different solutions than stakeholders had previously assumed would be required to reduce the phosphorus load to receiving waters. The approach led to greater community acceptance and utility of model results as evidenced by local decision makers now moving forward to implement some of the solutions identified to be most cost-effective.

3.3. Redesigning the American neighborhood, South Burlington, VT

Urban sprawl and its associated, often poorly treated stormwater, have a large impact on water quality and quantity in Vermont. Converting agricultural and forested land to residential and commercial use has significantly changed the capacity of the watersheds to retain water and assimilate nutrients and other materials. Currently, storm discharges may be 200–400 times greater than the historical levels (Apfelbaum, 1995).

Redesigning the American neighborhood (RAN) is a project conducted by the University of Vermont to find cost-effective solutions to the existing residential stormwater problems at the scale of small high-density residential neighborhoods (RAN, 2005). The project is focusing on a case study of the Butler Farms/Oak Creek Village communities in South Burlington, VT, to identify and prioritize implementation of BMPs on residential property. The idea was to engage local homeowners in a participatory study that would show them how they contribute to the stormwater problem and introduce them to existing alternative methods of stormwater mitigation through low-impact distributed structural and non-structural techniques.

The project had a slow start because only a few homeowners were willing to participate in the process. However, soon the neighborhood learned that their homes were subject to long-expired State stormwater discharge permits, and that their neighborhood's stormwater system did not meet stringent new standards. As is often the case, problems with home sales, localized flooding, and confusion about the relationship between the City's stormwater utility and the State permit impasse led to frustration and even outright anger on the part of residents. The tension increased after the homeowners realized that in order for the City to take over the existing detention ponds and other stormwater structures they have to be upgraded to currently active 2002 standards. Since then the interest and involvement of residents in Stormwater Study Group has been heightened, but stakeholder meetings have become forums for conflict between homeowners and local municipalities.

The modeling tool selected for this projected was spatial analysis using the ESRI ArcGIS 9.2 capabilities for hydrologic modeling. As high-resolution LIDAR data became available, it became possible to generate clear visualization and substantial understanding about the movement of water through the neighborhoods and to develop new approaches to resolve the stormwater management conundrum. The micro-stormwater network has helped to visualize rain flowpaths at a scale where residents have been able to make the connection with processes in their backyard (RAN, 2005). The micro-stormwater drainage density (MSDD) index was instrumental in optimizing the location of BMPs of small- and mid-scale management practices and had an important educational and trust building value.

At present the homeowners seem to prefer decentralized medium and small-scale interventions (such as rain gardens) to centralized alternatives such as large detention ponds.

3.4. *Cutler reservoir TMDL process, Utah*

Cutler reservoir, in the Cache Valley of Northern Utah, has impounded the Bear, Logan, and Little Bear Rivers since 1927. Cutler Dam is operated by PacifiCorp-Utah power and light to provide water for agricultural use and power generation. Cutler reservoir supports recreational uses and a warm water fishery while providing habitat for waterfowl and a water supply for agricultural uses. Cutler reservoir has been identified as water quality limited due to low dissolved oxygen and excess phosphorus loading. The Utah Division of Water Quality initiated the process of developing a total maximum daily load for Cutler reservoir in 2004 with the goal of restoring and maintaining water quality to a level that protects the beneficial uses described above.

Participation from local stakeholders is encouraged throughout the TMDL process and has been formalized in the development of the Bear River/Cutler Reservoir Advisory Committee, which has representation from all the major sectors and interests of the local community. The Advisory Committee has been meeting monthly since August 2005 and has informed the TMDL process by contributing data, knowledge of physical and social processes in the watershed, and identifying solutions to help reduce pollution sources.

Watershed loading models and a reservoir response model, BATHTUB (USACOE, 2007a), are in preliminary development stages at the time of this writing and will benefit from feedback from the advisory committee. It is expected that committee members will continue to provide feedback to the TMDL process while working with their respective constituents to provide direction to the Utah Division of Environmental Quality in developing and implementing a watershed management plan. They will also be helpful in identifying funding needs and sources of support for specific projects that may be implemented.

3.5. *James River shared vision planning, Virginia*

The James river in Virginia will potentially face significant water supply development pressures over the next several years due to growing population and development pressure. The Corps' Norfolk District has already received one application for a Clean Water Act Section 404 permit for Cobb Creek reservoir, and initial inquiries by the Virginia Department of Environmental Quality indicate the potential for more applications in the near future. USEPA Region III has formally requested that the Norfolk District prepare a basin-wide assessment that considers all the proposed water supply projects on the James River and make permitting decisions based on a cumulative impacts analysis.

These factors pointed to the need for a comprehensive planning process, involving all the key agencies and stakeholders, in order to identify broadly acceptable and sustainable solutions for water management within the basin. Due to historic water conflicts in the state the shared vision planning process (USACOE, 2007b) has been proposed as the method for conducting this comprehensive process. The Corps has pioneered participatory decision making since the 1970s (Wagner and Ortolando, 1975, 1976). The shared vision planning process is a participatory modeling approach in which stakeholders are involved in creating a model of a system that can be used to run scenarios and find optimal solutions to a problem. Shared vision planning relies on a structured planning process firmly rooted in the federal Principles and Guidelines, and in the circles of influence approach to structuring participation (Palmer et al., 2008).

The James River Study (JRS) began with a general workshop in the winter of 2005–2006 entitled "Finding and Creating Common Ground in Water Management". The purpose of this open meeting was to start a continuing dialogue among the various stakeholders involved, including those with divergent interests. A major objective of the workshop was to describe and introduce the use of collaborative modeling to facilitate learning and decision making across various governmental and non-governmental groups. While there was good participation in the workshop the process stalled when working groups were to be formed. Only a few stakeholders signed up to continue with the participatory modeling effort, and during the subsequent months the process almost stopped. It took some time to realize that in fact, the project got stuck amidst some major controversy between two key stakeholders. In addition, there was some internal opposition to the project within the Army Corps. Under these conditions, not surprisingly, stakeholders who knew about these conflicts were skeptical about the project and reluctant to participate. At the time of this writing a consensus seems to be emerging between the stakeholders regarding the goals of the project and a fresh start is planned in the near future.

4. Lessons learned

4.1. *Identify a clear problem and lead stakeholders*

Although most watershed management decisions benefit from stakeholder input and involvement, some issues might not have raised the interest of a wide group of stakeholders. If the problem is not understood or considered to be important by stakeholders, then it will be very difficult to solicit involvement in a participatory exercise. For example, the Virginia project had a very difficult startup because there was clear disagreement between stakeholders on the importance of the study. While it was quite clear to all that there will be future water supply problems in the area, the current situation did not look bad enough for local people to really get involved, while agencies had their own agendas and did not completely understand the purposes of the study.

Education of the community about water resource issues and the impact of decisions on the community is often a good first step. This can be accomplished through the media, town hall meetings, or volunteer and community oriented programs.

In some cases it is helpful when there is a strong governmental lead in the process. The Calvert group sprouted from an open meeting where all citizens residing in the watershed were invited to comment on proposed regulation of septic systems by the County Planning and Zoning Commission. The possibility of new regulation caught the attention of the public and interested parties were willing to participate in the study. In other cases, interest from some stakeholders may only arise after a policy change that directly impacts them. The RAN project started with several stakeholder workshops, where homeowners were addressed about the looming problems associated with untreated stormwater. The reception was lukewarm with very low attendance. Things changed quite dramatically when the city of South Burlington approved legislation that created a stormwater utility, which would take over stormwater treatment from the homeowners, but only after they brought their runoff up to certain standards. Meanwhile their property titles were about to become invalid since stormwater permits have expired. The interest to the RAN project immediately jumped, but even then the involvement of university researchers was seen as an impediment for some homeowners.

Never underestimate the “luck factor”. Since you are working with people just one or two stakeholders that choose to take an obstructionist position can damage the process. Likewise, several committed and active stakeholders can significantly enhance the effort.

4.2. *Engage stakeholders as early and often as possible*

A key to success with any participatory approach, is that the community participating in the research be consulted from the initiation of the project and help to set the goals for the project and specific issues to be studied (Beirele and Cayford, 2002). Stakeholder participants engage in the decision making process in the form of model selection and development, data collection and integration, scenario development, interpretation of results, and development of policy alternatives. It is generally recognized that engaging participants in as many of these phases as possible and as early as possible, beginning with setting the goals for the project, drastically improves the value of the resulting model in terms of its usefulness to decision makers, its educational potential for the public, and its credibility within the community (Korfmacher, 2001).

Establishment of a community-based monitoring effort can be a particularly effective entry point to a community that is ready to ‘act’ on a perceived problem and is not satisfied with more meetings and discussion. Monitoring by citizens, in particular, provides other benefits to the research process. In many cases, they live close to monitoring sites or have access to private property such that more frequent and/or more complete monitoring can take place at significantly less cost than researchers could complete independently. Citizens also gain benefits by becoming more familiar with their watershed, an educational opportunity that may be shared with other community members. When stakeholders see how samples are taken, or, ideally, take part in some of the monitoring programs, they bond with the researchers and become better partners in future research and decision support efforts.

In the St. Albans Bay watershed, there was a lack of recent data regarding the general state of the watershed including water quality, discharge, and soil phosphorus concentrations. At the same time, there was a highly motivated group of citizens organized through the St. Albans Area Watershed Association eager to begin “doing” something in the watershed immediately. In partnership with this group and the Vermont Agency of Natural Resources a citizen’s volunteer monitoring program was established with 25 monitoring sites around the St. Albans Bay watershed. Most of the 500+ water quality samples and stage height data were collected by a group of fifteen volunteers drawn from the community over 2 years. The resulting data would not have been available otherwise, and the process engaged a group of local citizens in a critical phase of research. This early engagement proved valuable during the latter stages of the project when a stakeholder group was assembled for the participatory modeling exercise. The partnership that grew from the monitoring effort also built trust between the researchers and watershed advocates working in the community.

4.3. *Create an appropriately representative working group*

Participatory modeling may be initiated by local decision makers, governmental bodies, citizen activists, or scientific researchers. In the United States, most participatory modeling activities are initiated by governmental bodies (Duram and Brown, 1999). Depending upon the type of participatory modeling and the goals and time restrictions of the project, stakeholders may be enlisted to participate in a variety of ways. In some projects stakeholders are sought out for their known ‘stake’ in a problem or decision and invited to join a working group. In other cases involvement in the working group may be open to any member of the public.

Regardless of the method used to solicit stakeholder involvement, every attempt should be made to involve a diverse group of stakeholders that represent a variety of interests regarding the question at hand. This adds to the public acceptance and respect of the results of the analysis. If a process is perceived to be exclusive, model results may be rejected by key members of the stakeholder and decision-making community. When less well-organized stakeholder groups do not actively participate, watershed managers can obtain information about their opinions through other means such as public meetings, education, or surveys (Korfmacher, 2001).

During the establishment of the Bear River/Cutler Reservoir Advisory Committee the Division of Water Quality took special care to find representatives from all groups affected by the TMDL process. Since Cache Valley is a small community, most committee members represented more than one interest. A matrix was developed to acknowledge this diverse representation and ensure that the committee was balanced and did not favor any particular stakeholder group.

In this sense, the St. Albans Bay watershed modeling process may have failed somewhat in that the stakeholder group formed rather organically from those that currently work on issues or are directly affected by watershed management including local, state, and federal natural resources, planning, and agricultural agencies as well as farmers and watershed activists. A deliberate attempt was made to involve members of the business and residential community without success (Harp, 2006), due to a lack of interest in the process perhaps, because they perceived themselves to have no stake in the outcome.

4.4. *Gain trust and establish neutrality as a scientist*

Although participatory modeling incorporates values, the scientific components of the model must adhere to standard scientific practice and objectivity. This criterion is essential in order for the model to maintain credibility among decision makers, scientists, stakeholders, and the public. Thus, while participants may determine the questions that the model should answer and may supply key model parameters and processes, the structure of the model must be scientifically sound and defensible.

Furthermore, facilitators of a participatory modeling exercise must be trusted by the stakeholder community as being objective and impartial, and therefore should not themselves be direct stakeholders. In this regard, facilitation by university researchers or outside consultants, if established as a neutral party, can reduce the incorporation of stakeholder biases into the scientific components of the model. On the other hand it is essential that stakeholders trust the facilitators and scientists, and a certain track record in the local area and perhaps even recognition of researchers by the local stakeholders based on past research or involvement can be helpful.

The models developed for use in the St. Albans Bay and Solomons Harbor watersheds have been peer-reviewed and accepted by the scientific community (Gaddis, 2007; Gaddis et al., 2007). Model development is still underway for the James River and Cutler reservoir.

4.5. *Know your stakeholders and acknowledge conflict*

In some cases, stakeholders may have historical disagreements with one another. One purpose of the participatory modeling method is to provide a neutral platform upon which disputing parties can contribute and gain information. However, it is important to watch for such historic conflicts and external issues that may overshadow the whole process. In addition, we have found that when the outcome of a modeling exercise is binding, such as in the development of a TMDL, parties may be more engaged but also defensive if they perceive that the process will result in a negative impact on them or their constituents. For example, point source polluters may look for ways to hold up a TMDL process in order to delay a load reduction decision. These sources of contention may be masked as scientific dissent when they are actually political. When conflict within the group becomes unmanageable, it is important to setout rules for discussion and in some cases involve a professional facilitator.

In the James River project there was a long history of tension between some stakeholders on issues of water planning. The shared vision planning process got caught in this controversy and could move nowhere further until some consensus was reached between stakeholders. In theory the modeling process was supposed to be open to all stakeholders, should be truly democratic and transparent, and should not depend upon local misunderstanding between some stakeholders. In practice, the historic network of connections, both professional and personal, between stakeholders is evident and can come to dominate the participatory process.

4.6. *Select appropriate modeling tools to answer questions that are clearly identified*

A critical step, early in the participatory modeling process, is the development of research questions and goals of the process. The questions identified should be answerable given the time and funding available to the process. In addition, it is important that all stakeholders agree on the goals of the process such that a clear research direction is embraced by the entire group before detailed modeling begins.

Selecting the correct modeling tool is one of the most important phases of any modeling exercise. Model selection should be determined based on the goals of the participants, the availability of data, the project deadlines and funding limitations rather than being determined by scientists' preferred modeling platform and methodology. Some models are used to formalize concepts of watershed, stream, and receiving water processes and as such explore existing dynamics and characteristics. Models can also be predictive or used to compare proposed management plans and explore their effects on other processes. Modeling tools can be especially useful in communicating complex processes, spatial patterns, and data in a visual format that is clear and compelling and, when appropriately applied, can empower stakeholders to move forward with concerted efforts to address an ecological problem.

It is important to maintain 'model neutrality'. It is common for modelers to turn to models and modeling platforms that are most familiar to them. It is important however, to always survey the available tools and select one that is most appropriate to the questions of interest to the stakeholders. The Solomons harbor watershed project was initially geared towards a fairly sophisticated spatial modeling effort based on our experience in integrating dynamic spatial models. While this modeling was still performed, the project focus turned to some fairly simple balance calculations that helped to move the decision making process in the right direction.

The literature includes watershed models that can be described as indices (Birr and Mulla, 2001), statistical (Ramsey and Schafer, 2002), spatial, process (temporal), lumped dynamic, and distributed dynamic models (Table 1). Models range in complexity, spatial and temporal scale, and parameter assumptions and thus have different applications in watershed management (Westervelt, 2001; BASINS, 2004; Costanza and Voinov, 2004; DHSVM, 2004; RHESSys, 2004; USGS, 2004; Voinov et al., 2004; USACOE, 2007a).

Table 1 – Modeling paradigms used in watershed management

Model characteristic	Indices	Spatial models	Process models	Vector-based spatial models	Raster-based spatial models
Software examples	Spreadsheet (Excel)	Geographic Information System	Stella, Simile, C++	Hydrologic Simulation Program—Fortran (HSPF), C++	Spatial modeling environment (SME), C++
Model examples	Phosphorus index	Map of landuse change	Stella-based plant growth	BASINS, RHESSys	LMF, DHSVM
Spatial scale	Field	Vector or grid	Not spatially explicit	Hydrologic Response Unit (HRU)	Grid-based (scale depends on wshed size)
Time scale	Year	Snap-shot	Seconds–years	Seconds–days	Seconds–days
Output format	Coefficients	Spatial layers (maps)	Time series	Vector maps. Point time-series	Raster maps. Point time-series.
Application	Rank and prioritize	Calculate and compare spatial data.	Mass balance of local (vertical) processes.	Prediction of stream flow and nutrient transport	Simulation of processes over space and time
Major advantages	Fast and simple	Spatially distributed	Dynamic	Run-time, automated data preparation and input	Ability to capture both temporal and spatial dynamics.
Major limitations	Simplistic	No temporal dimension.	No spatial dimension	Aggregated HRU. No neighborhood relationships	Complexity. Run-time. Data availability and preparation

To be useful in a participatory framework models need to be transparent and flexible enough to change in response to the needs of the group. In some cases tools as simple as MS Excel can be the right choice. One major benefit of MS Excel is that it is readily available in most cases and many stakeholders are already familiar with it. Simulation (process) models help to determine the mechanisms and underlying driving forces of patterns otherwise described statistically; however, they are not practical for exploring the role of the spatial structure of an ecosystem. Alternatively, geographic information systems (GIS) explicitly model the spatial connectivity and landscape patterns present in a watershed, but are weak in their ability to simulate a system's behavior over time (Westervelt, 2001). Model complexity must be dictated by the questions posed by the stakeholder group as well as available data and information. Models that are too simple are less precise and explanatory, however, a model that is too complex can lose transparency among the stakeholder group. In many cases a simple model that can be well communicated and explained is more useful than a complex model that has narrow applicability, high costs of data, and more uncertainty. In summary, successful participatory modeling requires appropriate modeling tools and paradigms. In addition, selection of a complex model for which there is little data for model development and calibration may not be scientifically sound.

In addition to a STELLA^{TM} implementation of the simple TR-55 routing model, the RAN project used GIS analysis. The spatial visualization of streamflows in the fine scale that was allowed by the LIDAR data was a turning point in the discussions because stakeholders could actually see how their local decisions could make a difference.

4.7. *Incorporate all forms of stakeholder knowledge*

The knowledge, data, and priorities of stakeholders should have a real, not just cursory, impact on model development both in terms of selecting a modeling platform and in setting model assumptions and parameters. Stakeholders often contribute existing data to a research process or actively participate in the collection of new data. Some stakeholders, particularly from governmental agencies, may have access to data that is otherwise unavailable to the public due to privacy restrictions or confidentiality agreements. This data can often be provided to researchers if it is aggregated to protect privacy concerns or if permission is granted from private citizens. In addition, some stakeholders are aware of data sources that are more specific to the watershed such as locally collected climatic data.

The participatory modeling approach is based on the assumption that those who live and work in a system may be well informed about its processes and may have observed phenomena that would not be captured by scientists. Stakeholders can also be very helpful in identifying whether there are hydrologic, ecological or human-dominated processes that have been neglected in the model structure. Stakeholders can also verify basic assumptions about the dynamics, history, and patterns of both the natural and socio-economic system. Farmers and homeowners possess important local knowledge about the biophysical and socio-economic system being researched. Anecdotal evidence may be the only source of assumptions about human behavior in a watershed, many of which are important inputs to a simulation model (i.e. frequency of fertilizer application). This type of knowledge when combined with technical knowledge of watershed processes is key to identifying new and more appropriate solutions to environmental problems (Webler and Tuler, 1999; Gough and Darier, 2003).

The modeling process should be flexible and adjustable to accommodate new knowledge and understanding that comes from the stakeholder workshops. This requires that models be modular, robust and hierarchical to make sure that changes in components do not crash the whole system. In many cases a simple model that can be well communicated and explained is more useful than a complex model that has narrow applicability, high costs of data, and more uncertainty.

4.8. *Gain acceptance of modeling methodology before presenting model results*

Giving stakeholders the opportunity to contribute and challenge model assumptions before results are reported also creates a sense of ownership of the process that makes results more difficult to reject in the future. This can only occur, however, if the models developed are transparent and well understood by the public or stakeholder group (Korfmacher, 2001). In some cases, it can reduce conflict between stakeholders in the watershed, since model assumptions are often less controversial than model results.

Transparency is not only critical to gaining trust among stakeholders and establishing model credibility with decision makers, but is also key to the educational goals often associated with participatory modeling. The model developed should be relatively easy to use and update after the researchers have moved on. This requires excellent documentation and a good user interface. If non-scientists cannot understand or use the model, it will not be applied by local decision makers to solve real problems.

The development of the modeling tools used in the St. Albans Bay and Solomons harbor watersheds was very transparent. Stakeholders were repeatedly given the opportunity to comment on model assumptions, parameters selected, and even consulted on alternative modeling frameworks when appropriate. However, the models are complex and not "user-friendly" due to the architecture of the landscape modeling framework.

4.9. *Engage stakeholders in discussions regarding uncertainty*

Many ecological questions, especially those that incorporate socio-economic processes, require analysis of complex systems. As problem complexity increases, model results become less certain. Understanding scientific uncertainty is critically linked to the expectations of real world results associated with decisions made as a result of the modeling process. This issue is best communicated through direct participation in the modeling process itself.

Stakeholders that participated in all the stages of the model building activities develop trust in the model and are less likely to question the reliability of the results. Primarily that is because they know all the model assumptions, know the extent of model reliability and know that the model incorporated the best available knowledge and data, and understand that there will always be some uncertainty in the model results.

4.10. *Develop scenarios that are both politically feasible and most effective*

Stakeholders are best placed to pose solution scenarios to a problem. Many of them have decision making power and/or influence in the community and understand the relative feasibility and cost-effectiveness of proposed solutions. In addition, engaging local decision makers in the scenario modeling stage of the research process can lead to development of more innovative solutions (Carr and Halvorsen, 2001).

In the Solomons Harbor watershed, Maryland an interesting question emerged from the discussion of scenarios that could reduce nitrogen to Solomons Harbor. Given limited resources for modeling, is it better to focus on scenarios which we, the research team, suspect will have the greatest impact on water quality or those scenarios which are most easily and therefore likely to be implemented politically? Scenarios were very different for each perspective. A consensus was reached through discussion to test both sets of scenarios. By testing politically feasible scenarios, we understood the boundaries of what might reasonably be achieved in the short-term given current funding and political realities. Meanwhile, the most environmentally effective scenarios pushed stakeholders to think beyond conventional solutions and to recognize the boundaries and time lag involved with what they aimed to accomplish. Besides, yet another most cost efficient and productive scenario emerged from the participatory fact finding exercise, that is, to focus on reduction of residential fertilizer application and other airborne sources of nitrogen in the area.

4.11. *Interpret results in conjunction with stakeholder group: facilitate development of new policy and management ideas, engage stakeholders in reporting results*

A primary goal of a participatory modeling exercise is to resolve the difference between perceived and actual sources of a water resources problem and use the model to affect real management decisions (Korfmacher, 2001). Whereas stakeholders may have proposed scenarios based on their perception of the problem, they may be particularly well adept at proposing new policy alternatives following initial model results from a scenario modeling exercise (Carr and Halvorsen, 2001). The participatory modeling process can further facilitate development of new policies through development of a collaborative network of stakeholders throughout the research process (Beirele and Cayford, 2002). Stakeholders are important communication agents to deliver the findings and the decision alternatives to the decision makers in the federal, state or local governments. They are often more likely to be listened to than the scientists who may be perceived as foreign to the problem or the locality.

In the St. Albans Bay watershed, many of the modeling results were unexpected by the stakeholder group. Some of most important sources and pathways of phosphorus movement to receiving waters (dissolved phosphorus from agricultural fields, road sand washoff, and tile drainage) were not addressed by most of the proposed scenarios. Some processes had previously been considered significant by the stakeholder group. However, several stakeholders have indicated that they intend to use the information gleaned from the project to direct existing funding sources and adapt policies for the most significant phosphorus transport processes and sources in the watershed. The municipalities in the watershed have agreed to investigate alternatives to road sand for winter deicing of roads. Staff at the NRCS are moving forward with plans to improve treatment of farmstead discharge in the watershed (Hakey, K., personal communication, Spring 2006). Finally, model results will contribute to the basin plan under development for the St. Albans Bay watershed by the Agency of Natural Resources (Bates, K., personal communication, Spring 2006).

The TMDL process, currently underway for Cutler reservoir, Utah, requires that the results of the participatory modeling study be included in the TMDL document submitted for approval to the USEPA. These decisions include required nutrient load reductions according to load allocations for various point and non-point sources throughout the watershed, as well as a project implementation plan designed to achieve these reductions.

In the Solomons harbor watershed, Maryland unexpected results led the working group to adapt management goals and policies for Calvert County. Fertilizer and atmospheric deposition were found to have a significantly larger effect (more than the community thought) on nitrogen loads in Solomons harbor, whereas none of the proposed septic management scenarios are likely to have a real effect on the trophic status of the harbor, in the short-term. Nonetheless, upgrading septic tanks were still valued as a good environmental decision since it would improve groundwater quality and, in the long-term, affect surface water quality. Furthermore, it is the only regulation that can be easily and immediately implemented at the local level. The model results were first presented to the smaller working group over two meetings and were a severe test of participant confidence, since our results were somewhat contrary to previous estimates (Wood et al., 1998). The working group took a very positive and constructive approach. While acknowledging the inherent uncertainties in the modeling process, they began to explore new solutions and policy recommendations. Rather than abandoning the proposed policies to reduce nitrogen from septic tanks, the working group chose to expand its policy recommendations to include all sources of nitrogen to the watershed. The research team found this to be a distinctly positive outcome of the participatory modeling exercise. The working group came up with the following conclusions about the types of policy options that are realistic and available to the Solomons harbor community. Atmospheric deposition cannot be directly influenced by local citizens, except through reduction of local traffic and lobbying regional officials to reduce NO_x emissions from coal-fired power plants. Fertilizer usage could be most easily influenced through educational initiatives since policy changes would require involvement of other governmental and citizen groups beyond the Department of Planning and Zoning, which is currently leading the initiative to reduce nitrogen to the harbor.

An important final step in the participatory modeling method is dissemination of results and conclusions to the wider community. Presentations to larger stakeholder groups, decision makers, and the press should be made by a member of the stakeholder working group. This solidifies the acceptance of the model results and cooperation between stakeholders that were established during the participatory modeling exercise. In addition, members of the community are often more respected and have a better handle on the impact of policy decisions on local community's issues.

In the Solmons harbor watershed, two members of the working group presented their recommendations to the larger stakeholder group following a presentation of the modeling results by one member of our research team. During this meeting the Director of Planning and Zoning for Calvert County solicited feedback on proposed policy recommendations and later refined them for a presentation to the Calvert County Board of Commissioners. We emphasize that the role of the research team in this process was to support the discussion rather than to recommend our own policy ideas.

In the St. Albans Bay watershed, several stakeholders participated in the presentation of model results to the local press and general public in May 2006. Several interagency partnerships appear to have been strengthened and trust developed through previously opposing groups as a result of the participatory modeling exercises (Harp, 2006).

4.12. *Treat the model as a process*

There are always concerns about the future of participatory efforts. What happens when the researchers go away? If we look at how collaborative model projects are developed, there is a clear similarity with the open source paradigm in computer science, when software is a product of joint efforts of a distributed group of players. Ideally the process should live on the web and continue beyond a particular project. It is a valuable asset for future decision making and conflict resolution. It can stay alive with incremental funding or even donations, with stakeholders able to chip in their expertise and knowledge to keep it going between peaks of activity when bigger projects surface. Unfortunately the web and modeling tools that would provide this kind of functionality and interoperability are still quite rudimentary, although, there have recently been some promising efforts in this direction. Regardless of whether or not the model lives on beyond a project, it is important to value the process of developing a model in collaboration with a stakeholder group as much as the model results themselves. The modeling process offers many benefits beyond deriving results including identifying data gaps, gaining an improved understanding of the system, and incorporating multiple perspectives into the understanding of a system.

5. Conclusions

Participatory modeling is a valuable research approach that incorporates policy and values into models to solve complex and challenging water resource questions. The approach has successfully resolved challenges in agricultural and urban watershed management as well as TMDL development. Modeling tools implemented with the approach vary with application and range from simple statistical models to spatially explicit dynamic models. Participation from stakeholders and decision makers may range from model development to data integration and development of policy scenarios. The primary benefit of participatory modeling is that the models developed are often more useful in informing decision makers, though the approach is also widely recognized for its educational benefits and achievements in building consensus among diverse stakeholders.

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REFERENCES

Apfelbaum, S.I., 1995. Role of landscapes in stormwater management. In: National Conference on Urban Runoff Management: Enhancing Urban Watershed Management at the Local, County, and State Levels, Chicago, IL, EPA/625/R-95/003.

Argent, R.M., Grayson, R.B., 2003. A modelling shell for participatory assessment and management of natural resources. Environ. Model. Software 18, 541–551.

BASINS, 2004. Better Assessment Science Integrating Point and Nonpoint Sources. USEPA. http://www.epa.gov/waterscience/BASINS/.

Beirele, T.C., Cayford, J., 2002. Democracy in practice: public participation in environmental decisions. Resources for the Future. Washington, DC.

Birr, A.S., Mulla, D.J., 2001. Evaluation of the phosphorus index in watersheds at the regional scale. J. Environ. Qual. 30 (6), 2018–2025.

Carr, D.S., Halvorsen, K., 2001. An evaluation of three democratic, community-based approaches to citizen participation: surveys, conservations with community groups, and community dinners. Soc. Nat. Resour. 14, 107–126.

Costanza, R., Voinov, A. (Eds.), 2004. Landscape Simulation Modeling: A Spatially Explicit Dynamic Approach. Springer-Verlag, New York.

Costanza, R., Voinov, A., Boumans, R., Maxwell, T., Villa, F., Voinov, H., Wainger, L., 2002. Integrated ecological economic modeling of the Patuxent River watershed, Maryland. Ecol. Monogr. 72 (2), 203–231.

DHSVM, 2004. Distributed Hydrology Soil Vegetation Model. University of Washington. http://www.hydro.washington.edu/Lettenmaier/Models/DHSVM/.

Duram, L.A., Brown, K.G., 1999. Assessing public participation in U.S. watershed initiatives. Soc. Nat. Resour. 12, 455–467.

Gaddis, E.J.B., 2007. Landscape modeling and spatial optimization of watershed interventions to reduce phosphorus load to surface waters using a process-oriented and participatory research approach: a case study in the St. Albans Bay watershed, Vermont. Ph.D. Dissertation. Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington.

Gaddis, E.J.B., Vladich, H., Voinov, A., 2007. Participatory modeling and the dilemma of diffuse nitrogen management in a residential watershed. Environ. Model. Software 22 (5), 619–629.

Gough, C.E., Darier, 2003. Contexts of citizen participation. In: Kasemir, B., Jaeger, C.C., Jager, J., Gardener, M.T. (Eds.), Public Participation in Sustainability Science. Cambridge University Press, Cambridge.

Harp, H., 2006. Stakeholder involvement in computer based planning in St. Albans, Vermont. Masters Thesis. Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington.

Hyde, K., Kamman, N., Smeltzer, E., 1994. History of phosphorus loading to St. Albans Bay, 1850–1990. Lake Champlain Basin Program. Technical Report No. 7B.

Jolankai, G., Voinov, A.A., 1988. Eutrophication model of Lake Balaton (Hungary). In: Patten, B. (Ed.), Wetlands and Shallow Water Bodies, vol. 2. Academic Publishing, The Hague.

Korfmacher, K.S., 2001. The politics of participation in watershed modeling. Environ. Manage. 27 (2), 161–176.

MDDNR, 2000. Maryland Tributary Strategies, Chesapeake Bay 2000 Agreement and Calvert County Comprehensive Plan. Maryland Department of Natural Resources. http://www.dnr.state.md.us/bay/tribstrat/patuxent/patuxent.html.

Palmer, R.A., Cardwell, H.E., Lorie, M.A., Werick, W., 2008. Disciplined planning, structured participation, and collaborative modeling – applying shared vision planning to water resources decision making, ASCE J Water Resour. Manage. Plan., in press.

Ramsey, F.L., Schafer, D.W., 2002. The Statistical Sleuth: A Course in Methods of Data Analysis. Duxbury Press, Belmont, CA.

RAN, 2005. Redesigning the American Neighborhood, Rubenstein School of Environment and Natural Resources, University of Vermont. http://www.uvm.edu/~ran/ran/.

RHESSys, 2004. Regional Hydro-Ecological Simulation System. http://typhoon.sdsu.edu/Research/Projects/RHESSYS/index.html.

Rhoads, B.L., Wilson, D., Others, P., 1999. Interaction between scientists and nonscientists in community-based watershed management: emergence of the concept of stream naturalization. Environ. Manage. 24 (3), 297–308.

Roberts, N., 2004. Public deliberation in an age of direct citizen participation. Am. Rev. Public Admin. 34 (4), 315–353.

Svirezhev, Y.M., Krysanova, V.P., Voinov, A.A., 1984. Mathematical modelling of a fish pond ecosystem. Ecol. Model. 21, 315–337.

USACOE, 2007a. FLUX, PROFILE and BATHTUB: Simplified Procedures for Eutrophication Assessment and Prediction, Environmental Laboratory. U.S. Army Engineer Waterways Experiment Station. http://www.wes.army.mil/el/elmodels/emiinfo.html.

USACOE, 2007b. The Shared Vision Planning Website, Institute for Water Resources. US Army Corps of Engineers. http://www.svp.iwr.usace.army.mil/.
USDA, 1991. St. Albans Bay Rural Clean Water Program. United States Department of Agriculture, Vermont Water Resources Research Center.
USEPA, 2002. The State of Chesapeake Bay: a report to the citizens of the Bay region. Chesapeake Bay Program Office, United States Environmental Protection Agency, EPA 903-R-02-002.
USGS, 2004. USGS Surface Water Software, United States Geologic Survey. http://water.usgs.gov/software/surface_water.html.
Voinov, A.A., Voronkova, O.V., Lukyanov, N.K., Svirezhev, Yu.M., 1981. Modeling of lake ecosystems. In: Problems of Ecological Monitoring and Ecosystem Modeling. Gidrometeoizdat, Leningrad. vol. 4, pp. 204–234 (in Russian).
Voinov, A.A., Svirezhev, Yu.M., 1981. Stability in a simple model of an aquatic ecosystem. J. Gen. Biol. 42 (N6), 936–940 (in Russian).
Voinov, A.A., Svirezhev, Yu.M., 1984. A minimal model of eutrophication in freshwater ecosystems. Ecol. Model. 23, 277–292.
Voinov, A.A., 1989. Simulation modeling in ecology: lakes, ponds, reservoirs. In: Samarsky, A.A., Moiseev, N.N., Petrov, A.A. (Eds.), Mathematical Modeling: Methods of Description and Investigation of Complex Systems. Nauka, Moscow, pp. 99–120 (in Russian).
Voinov, A.A., 1990. Ecosystem modelling of Lake Plesheyevo. In: Henderson-Sellers, B. (Ed.), Water Quality Modelling. vol. 4. Applications to Lakes and Reservoirs. CRC Press, pp. 115–151.
Voinov, A., Costanza, R., Boumans, R., Maxwell, T., Voinov, H., 1999a. Patuxent Landscape Model. Gund Institute for Ecological Economics, University of Vermont. http://www.uvm.edu/giee/PLM.
Voinov, A., Costanza, R., Wainger, L., Boumans, R., Villa, F., Maxwell, T., Voinov, H., 1999b. Patuxent landscape model: integrated ecological economic modeling of a watershed. Environ. Model. Software 14, 473–491.
Voinov, A., Fitz, C., Boumans, R., Costanza, R., 2004. Modular ecosystem modeling. Environ. Model. Software 19, 285–304.
VTANR, NYDEC, 2002. Lake Champlain Phosphorus Total Maximum Daily Load (TMDL). Vermont Agency of Natural Resources and New York State Department of Environmental Conservation.
Wagner, T.P., Ortolando, L., 1975. Analysis of new techniques for public involvement in water planning. Water Resour. Bull. 11 (2), 329–344.
Wagner, T.P., Ortolando, L., 1976. Testing an iterative, open process for water resources planning. US Army Engineer Institute for Water Resources, Contract Report No. 76-2.
Webler, T., Tuler, S., 1999. Integrating technical analysis with deliberation in regional watershed management planning: applying the national research council approach. Policy Stud. J. 27 (3), 530–543.
Westervelt, J., 2001. Simulation Modeling for Watershed Management. Springer-Verlag, New York, p. 190.
Wood, K.V., Boyton, W.R., Kaumeyer, N.L., Keefe, C.W., Zimmerman, C.F., Roxey, D.T., 1998. Solomons Harbor Study: Water quality monitoring and long-term trends. University of Maryland Center for Environmental Science, Chesapeake Biological Laboratory. Prepared for the Calvert County Board of County Commissioners, [UMCES] CBL 98-063.