MODELING FOR WATERSHED MANAGEMENT: A PRACTITIONER’S GUIDE

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Susanne M. Scheierling
and Grant Milne
TABLE OF CONTENTS

Acknowledgements .................................................................................................................. iv
Disclaimers ................................................................................................................................. iv
Contact Details ......................................................................................................................... iv
Acronyms and Abbreviations ................................................................................................. v
Executive Summary ................................................................................................................. vii

1. Introduction .............................................................................................................................. 1

2. Background on Modeling ..................................................................................................... 3
   2.1 Purposes of Modeling ......................................................................................................... 3
   2.2 What is a Model? ............................................................................................................... 4
   2.3 Organizing Modeling Efforts .......................................................................................... 4
   2.4 Model Selection and Use ............................................................................................... 5
   2.5 Further Issues .................................................................................................................. 5

3. Modeling for Watershed Management .............................................................................. 7
   3.1 Watershed Management Problems ............................................................................... 7
   3.2 Modeling Watershed Problems ..................................................................................... 8
   3.3 Approaches to Integrating Models ............................................................................... 12
   3.4 California's Central Valley as an Case Study ................................................................. 17

4. Conclusions and Practical Lessons .................................................................................... 19

References ................................................................................................................................ 21

Annex: Overview of Key Watershed Management Models and Developer Links .................. 25

Figures
   Figure 1. Computer Modeling as Extension and Organization of Thinking About Watershed Problems .......................................................................................................................... 2
   Figure 2. Watershed Management Problems and Activities ............................................... 7
   Figure 3. Spatial and Temporal Scales of Some Watershed Management Problems .......... 8
   Figure 4. Example Interactions Among Component Models ............................................... 9

Tables
   Table 1. Examples of Models of Various Watershed Management Components .................. 9
   Table 2. Examples of Models and Approaches to Integrated Modeling of Watershed Problems ................................................................. 13
   Table 3. California Central Valley Examples of Models and Approaches to Modeling Watershed ................................................................. 18
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## ACRONYMS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AquiVal</td>
<td>Graphic User Interface model for groundwater resources planning</td>
</tr>
<tr>
<td>AQUATOOL</td>
<td>A modeling suite for reservoir and aquifer systems, common in Spain</td>
</tr>
<tr>
<td>BASINS</td>
<td>Better Assessment Science for Integrating Point and Non-Point Sources</td>
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<tr>
<td>CALSIM</td>
<td>California Water Simulation model</td>
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<tr>
<td>CALVIN</td>
<td>California VAUe Integrated Network</td>
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<tr>
<td>DAMBRK</td>
<td>Hydraulic model for dam break analysis</td>
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<tr>
<td>DHI</td>
<td>International Engineering Consulting Firm (Hydrological modeling)</td>
</tr>
<tr>
<td>DWOPER</td>
<td>Operational Dynamic Wave Model for flow forecasting in natural rivers</td>
</tr>
<tr>
<td>EPANET</td>
<td>Model for piped water distribution (US Environmental Protection Agency)</td>
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<tr>
<td>ESSA</td>
<td>Environmental Science Service Administration</td>
</tr>
<tr>
<td>FLDWAV</td>
<td>Flood Wave model for flood forecasting (natural or dam breaks)</td>
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<tr>
<td>GAMS</td>
<td>General Algebraic Modeling System for mathematical programming</td>
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<td>GCM</td>
<td>Global Climate Models</td>
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<tr>
<td>GFDL</td>
<td>Geophysical Fluid Dynamics Laboratory (for model development)</td>
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<tr>
<td>GIS</td>
<td>Geographic Information System</td>
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<tr>
<td>HadCM</td>
<td>Hadley Climate Model</td>
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<td>HEC</td>
<td>Hydrologic Engineering Center, US Army Corp of Engineers</td>
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<tr>
<td>HEC-EFM</td>
<td>Hydrologic Engineering Center – Ecosystem Functions Model</td>
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<td>HEC EFT</td>
<td>Hydrologic Engineering Center – Ecosystem Flow Tool</td>
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<td>HEC-FDA</td>
<td>Hydrologic Engineering Center – Flood Damage Assessment</td>
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<td>HEC GeoRas</td>
<td>Hydrologic Engineering Center – Geographic River Analysis System</td>
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<td>HEC HMS</td>
<td>Hydrologic Engineering Center – Model for precipitation-runoff modeling</td>
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<td>HEC IFM</td>
<td>Hydrologic Engineering Center – Integrated flow model</td>
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<td>HEC PRM</td>
<td>Hydrologic Engineering Center – Prescriptive Reservoir Model</td>
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<td>HEC RAS</td>
<td>Hydrologic Engineering Center – River Analysis System</td>
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<td>HEC ResSim</td>
<td>Hydrologic Engineering Center – Reservoir Simulation Model</td>
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<tr>
<td>HEC RPT</td>
<td>Hydrologic Engineering Center – Regime Prescription Tool</td>
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<tr>
<td>HEC SSP</td>
<td>Hydrologic Engineering Center – Statistical Software Package</td>
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<tr>
<td>IGSM</td>
<td>Integrated Groundwater and Surface Water Model</td>
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<td>IWR-MAIN</td>
<td>Institute for Water Resources – Municipal and industrial water demand</td>
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<tr>
<td>MashWin</td>
<td>Streamflow generating models</td>
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<td>MIKE 11</td>
<td>General river modeling system</td>
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<td>MIKE 21</td>
<td>Integrated hydrodynamic model</td>
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<td>MIKE FLOOD</td>
<td>Integrated model for river flooding</td>
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<td>MIKE SHE</td>
<td>Integrated hydrological modeling system</td>
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<td>MODFLOW</td>
<td>Groundwater model (US Geological Survey)</td>
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<td>OptiWin</td>
<td>Optimization module of the water resources system management</td>
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<td>PCM</td>
<td>Parallel Climate Model</td>
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<td>SWAP</td>
<td>Statewide Agricultural Production model (California)</td>
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<td>SWMM</td>
<td>Storm Water Management Model (US Environmental Protection Agency)</td>
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<td>SimWin</td>
<td>Simulation model for water resources system management</td>
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<tr>
<td>TOPMODEL</td>
<td>A model for predicting catchment water discharge</td>
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<td>USEPA</td>
<td>US Environmental Protection Agency</td>
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<tr>
<td>WAS</td>
<td>Water Analysis System</td>
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<td>WEAP</td>
<td>Water Evaluation and Planning model</td>
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EXECUTIVE SUMMARY

Watershed management problems are usually quite diverse, and involve a wide range of biological, geological, chemical, and physical processes with complex human, social, and economic contexts. More complexity is added because watershed management also commonly involves land and water integration across spatial and temporal scales. Effectively addressing these wide-ranging factors often requires the application of suitable analytical tools. Practitioners and academics have worked on these kinds of problems for thousands of years using different approaches. Simple mathematical modeling of such problems began about 200 years ago. Computer modeling has been applied to specific water and watershed management problems for about 50 years. It continues to rapidly advance towards more detailed and extensive mathematical representations of watershed management issues, coupled with remote sensing and Geographic Information Systems (GIS).

Despite these advances in modeling, a recent review of World Bank-supported projects that aim to address watershed management problems indicated that modeling and other related tools have so far been applied only to a limited extent. This Working Note is part of the ongoing efforts to improve this situation. It aims to provide a brief guide on the usefulness of modeling, the role of models for watershed management, and an overview of various modeling approaches and modeling issues. The intended audience is academic practitioners, including Task Team Leaders of World Bank-supported projects, but also policy makers, sectoral planners and program managers involved in watershed management.

The Working Note seeks to show that computer modeling allows us to better organize, test, and refine our thinking about watershed management problems and potential solutions. Typically, following the flow of water leads modeling to be organized into the following areas: (i) precipitation and climate models; (ii) precipitation-runoff models; (iii) stream and aquifer models; (iv) infrastructure operations models; (v) economic, agronomic, social, environmental demand and performance models; and (vi) decision-making models. Selecting the right model to apply to specific problems requires that several factors be considered along with the objectives for modeling in the context of the field decision problem. Key factors include understandability, development and application time, resources required, transferability and maintenance.

Good modeling is common-sense and understanding reduced to calculation for the purposes of gaining insights into a real problem. Modeling should aid discussions, help thinking and provide insights to problems where individuals and interests struggle to understand the problem and struggle to work together to address a problem. To aid model development and the interpretation and communication of modeling and model results and insights, simplicity is a great virtue. While complex problems sometimes require complex models, shedding of unneeded complexity is important. Local and in-house expertise is preferred when developing and applying watershed models because of better familiarity with the problems assessed. Model integration is a growing trend but requires as much expertise and resources as development of any single model component.
1. INTRODUCTION

“All models are wrong, but some are useful.” Box (1979)

A watershed is a geographic area that supplies surface or subsurface water flows to a drainage system or body of water (Smyle et al., 2009). Watersheds can vary in size from a few hectares to a basin scale of thousands of square kilometers. Watershed management is the integrated use of land, vegetation, and water in a specified watershed to conserve land and hydrological services, and reduce downstream or underground impacts to be compatible with fundamental societal objectives. As watershed management became an accepted development approach in the 1970s, projects generally applied a soil and water conservation approach that emphasized engineering and civil works. However, by the end of the 1980s, it was clear that new approaches were needed. Since the 1990s, watershed management programs have tended to integrate broader livelihood improvements and poverty reduction objectives with more participatory soil and water conservation operations. Best-practice in watershed management now integrates land and water management, and for implementation at a micro-watershed scale in particular, works closely with local stakeholders.

Watershed management problems and programs tend to be quite complex and diverse, but have some common attributes. They all involve the flow of water tying the local hydrology to larger scale climate and they all involve some human problem, be it economic, social, or environmental involving the management of these water flows. Throughout history, every civilized people has managed water for their purposes at least at a local scale and often at a regional scale (Frontinus 97AD; Evenari et al. 1982; Mencius 1970). Beginning in the 1700s, with the French schools of engineering, mathematical representations of these problems began to be used to provide more precise insights into how to manage water problems (Ekelund and Hebert 1999). And in the last 50 years computer modeling has been employed to manage much more detailed and extensive mathematical representations of watershed problems (Loucks and van Beek 2005). Excellent insights into the application of computer modeling are available from Geoffrion (1976, 1997) and Gass (1983) generally, and into environmental and water modeling from Jakeman et al. (2006) and Beck (2002). Recent advances in modeling, coupled with more accessible remote sensing from a range of satellites and use of low-cost geographic information systems (GIS) can increase our understanding of the complex relationships between water, land, people, and proposed watershed management interventions.

Despite these developments, a recent review of fifteen years of World Bank supported projects involving watershed management indicated insufficient attention to basic hydrology and little application of modeling and other tools in many projects (Darghouth et al. 2008). This need not be the case. As this Working Note indicates, new advances in modeling, remote sensing and GIS, as well as improved data sets can help increase our understanding of the relationships between water, land, and proposed watershed management interventions. Analyses at the basin or sub-basin levels can now be conducted to support more effective watershed planning, for example by estimating the hydrological impacts of watershed management practices and technologies. Even broader environmental impacts can now be more easily quantified using available data and models, where time and resources permit. Modeling can also help address the demand for more transparency in decision making. But among watershed management practitioners, an overarching question is “what are these tools and models, and how can I decide on which ones to use”? To help address this problem, a number of Bank contributions have been made in the last couple of years to expand this knowledge base, including the preparation of briefing notes1 and the organization of technical seminars2 on the topic.

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1 For example, as part of a larger study on integrated river basin management, a briefing note was prepared on system modeling in river basin management (World Bank Institute, 2006).
2 During SDN Week 2008, hosted by the World Bank’s Sustainable Development Network in Washington DC, a workshop was
This Working Note is part of these ongoing efforts. It examines how to employ computer models to aid in managing watershed problems. Modeling should be closely tied to the conception of the management problem, the purpose of the modeling exercise (Figure 1). In some cases the modeling exercise will lead to fundamental or detailed changes in the conceptualization of the problem. In other cases, the modeling will merely confirm or help provide detail to the original conceptualization. Overall, computer modeling allows us to better organize, test, and refine our thinking about watershed management problems and potential solutions.

Chapter 2 provides a background of why modeling is useful, the conceptual basis, the selection and use of models, and some common issues that may arise. Chapter 3 reviews watershed management problems, and proceeds to discuss the roles of models for watershed management. Some approaches to employing and organizing modeling activities for watershed management are discussed, and several examples are presented. Chapter 4 provides conclusions and practical lessons. Readers who are interested in understanding the use of models in a general sense are referred to Chapter 2. Those who are searching for specific types of models to help them with analyzing particular watershed management issues may turn directly to Chapter 3 where the most relevant information is contained.

Figure 1. Computer Modeling as Extension and Organization of Thinking About Watershed Problems

organized by the Water Anchor on “Pushing the Frontiers of Integrated Water Resources Management at River Basin Scales Using a Modeling Approach”. During the World Bank’s Water Week 2009, J.R. Lund, the lead author of this Working Note, was the key presenter in a seminar on “Modeling for Watershed Management” organized by the co-authors, G. Milne and S.M. Scheierling; and as part of a session on modeling tools for agricultural water management co-organized by the Water Anchor and the Agriculture and Rural Development Department, S.M. Scheierling gave a presentation on “Modeling Approaches Incorporating Hydrologic, Agronomic and Economic Aspects.” In 2010, several seminars were organized by the joint Water Resources and Watershed Management Thematic Group that focused on modeling issues in water management.
2. BACKGROUND ON MODELING

2.1 Purposes of Modeling

“The purpose of computing is insights, not numbers.”
Hamming (1962)

Computer modeling integrates and explicitly represents knowledge in a level of detail, extent, and complexity and with a computational speed which would be impossible for the unaided human mind or the unaided minds of any group of individuals. As with all scientific knowledge, the knowledge embodied in a computer model must have empirical and deductive origins. Much of the value of computer modeling lies in using model development to formally state and integrate relevant knowledge in the context of a particular problem.

More generally, computer modeling can have the following uses:

- Integrate empirical and deductive knowledge
- Create a complex testable hypothesis
- Improve and test intuitive understanding (education)
- Identify gaps in understanding
- Explore and compare solutions to problems
- Avoid costly trial and error in the field
- Reduce uncertainty and provide assurances

For more applied problems, this list can be simplified to the use of models to:

1. Improve understanding of the problem. Often the work of developing computer models helps formalize and improve our thinking and understanding about a problem in ways that improve the discussions and outcomes regarding solutions to the problem. Often, this improvement provides benefits even if numerical results from the model itself are not employed. This educational value applies especially to professionals new to the problem.

2. Explore and compare solutions without costly trial and error. Development of solutions by field experimentation alone is very time consuming and costly. The hard to control nature of most field experiments also raises questions of the scientific validity of their outcomes and interpretation. While computer modeling has limitations, its use before field experimentation and application can make field experiments more likely to provide greater insight and improve the likelihood of success in field applications.

3. Improve communications, negotiations. Real problems often involve negotiations and compromise, which requires communications among parties. Computer models can be employed as part of a negotiations setting where solutions and their implications for each party’s interests can be explored rapidly.

4. Ultimately, modeling and other technical studies should provide decision makers with greater confidence in solutions to problems. For practical reasons, many solutions cannot be field tested before they are adopted. Having modeling and other technical studies estimate the likely field performance of various solutions provides a more scientific basis for selecting a particular solution than comparative evaluations based on intuition, past experience, or political assessments alone. Ideally, the technical aspects of computer modeling provide “strong invincible arguments” (Disco and van der Ende 2003) to aid in moving policy discussions towards more promising solutions.

5. More cynically, sometimes computer modeling is undertaken because models require time to develop, test, and apply (especially complex models). The delay in decision-making required by extensive technical studies, modeling, and data collection provides respite for those interested in continuing the status quo or avoiding controversy while seeming to address a controversial issue. For individuals and interests, protracted modeling can provide an opportunity to delay decision-making.
Overall, computer modeling should be undertaken to develop, test, support, and communicate convincing insights into a problem and its solutions.

2.2 What is a Model?

“Probability theory is nothing but common sense reduced to calculation.” Laplace (1819)

Computer models should represent organized human reasoning. This reasoning can have only two scientific bases, deductive and empirical. A deductive base involves the use of logic to derive implications from established knowledge (which might ultimately be empirical). Empirical knowledge is based on systematic and consistent observation (ranging from physical laws—conservation of mass, energy, and momentum—to patterns observed from regressions, econometrics, or other generalizations from data). All modeling steps should have such a formal foundation, using the computer to help organize this reasoning and make it explicit. The modeling, in the end, is to reduce extensive application of common sense to calculation.

The model itself then has three parts:

- **Theory and Computer Software.** This is usually the named model or computer code. There is some underlying theory or conceptualization of the problem or part of the problem, which is implemented by the computer code. Simplifications and numerical representations and calculations are often needed to implement this conceptualization into the form of computer software. Modeling software can range from highly specialized scientific codes to spreadsheets.
- **Data.** Data are the form of model inputs and parameter values, as well as any user-specified options for how the computer code is to be run, such as which numerical solution method should be used for solving a set of equations. Data involve field data, data estimated outside the model from field data or outputs from other models or calculations, or expert judgments. Often field data alone have substantial errors. Model results can be erroneous because of errors in data used in the model, as well as errors in other aspects of the model.
- **Expertise of Modeler.** All models are simplifications of reality, so it is important for the model developer and user to artfully and carefully employ the model and data, and make interpretations of model results with these simplifications and potential errors in mind, as well as keeping in mind the problem being addressed. Two good and careful modelers using the same model and field data sets are likely to have model results which are at least somewhat different. To some degree these differences represent the limitations we have on our understanding and representation of the problem. Sometimes these differences will be unimportant for decision-making. Sometimes these differences will represent opportunities for controversy. There is often a gap between the understanding of a watershed management problem needed for problem-solving, versus the understanding of a watershed often pursued by a research scientist. Good science is not always good problem-solving; this sometimes requires different types of modeling expertise.

Model development and use often pose a dilemma. Is a sophisticated model by a less expert modeler better than a simple model by a great modeler? In general the better modeler will employ data, methods, and theory more usefully to a particular problem than a sophisticated specialized scientific modeler using a specialized model. This returns us to the importance of how one organizes modeling efforts for a particular problem.

2.3 Organizing Modeling Efforts

An important aspect of modeling is to have and keep a focus around a well-defined problem. Often the first contribution of a modeling effort is to lead to a better definition of the problem. All modeling should fit and be interpreted in the context of this problem.

The definition of the problem is not merely technical. The institutional context is equally important in establishing the decision framework for the application of models to practical land and water use issues, or policy challenges. It is important to develop a sound process for stakeholder participation to identify the key issues and questions that
modeling can help address. In other words, the results and insights of both model users, and the users of model results must be involved. Further, planning must also ensure that modeling results will be understood and convincing and insightful to the users of the results and decision-makers. The decision making and institutional context are both important considerations in how modeling efforts are organized and presented. Presentation of modeling to decision-makers in purely technical terms, divorced from the problem-solving context, can be unhelpful.

Component technical efforts need to be organized into an integrated framework for problem-solving which includes a strategy for bringing the technical efforts to bear in decision-making. It is important to invest significant resources and expertise into developing this link between the modeling efforts and decision-makers, and it is important to invest much effort in integrating component modeling efforts to be coherent technically and comprehensible for decision-making (Jakeman and Letcher 2003; Jakeman et al. 2006). This will be further discussed below.

2.4 Model Selection and Use

Which models and approach to integration and use should be selected? Several factors and objectives for modeling should be considered in the context of the field decision problem. These include:

- **Understandability.** For each audience, as well as for those undertaking and explaining the modeling, communication of the modeling and its results is needed (Geoffrion 1997). If modeling and results cannot be understood and communicated, then there is likely to be less confidence in them, and the modeling will be less effective. Good documentation of the model and model runs are important aspects of understandability, which are usually insufficient alone.

- **Development and Application Time and Resources.** The time and resources available for the development and employment of modeling tools is usually important. Integrating and making sense of modeling results also requires expertise, time, and resources. New model development and integration also entails risks depend-

ing on how well the effort is managed. Guidance for the development of models is summarized in Jakeman et al. (2006), Gass (1983), and Harou et al. (2009).

- **Transferability.** Model ownership, proprietary software, required expertise, data, resources, etc. can limit or encourage the ability to transfer a model among organizations. This is important particularly when several organizations will be involved in the work or decisions, or if the project envisions transferring the modeling capability to others.

- **Maintainability.** Data, expertise, and resources are needed to continue any modeling effort and maintain modeling capability. The lifetime of the model can be quite short if it requires the expertise of one person or external organization. Modeling and data management efforts should be designed to be maintained and ultimately replaced.

For many model developers and users the “best” model is often the model they know best. This is a natural human condition reflecting the greater ability of an experienced user of a particular model to work around normal model limitations and to be comfortable doing so, the lesser amount of time needed for someone to develop a model in already-familiar software, and sometimes the financial and professional interest of the modeler.

2.5 Further Issues

A few additional common modeling issues should be touched on.

**Data and Models.** Which comes first, the model or the data? Should modeling occur only after “enough” data has been gathered? Or, should data collection be guided by the use of preliminary models to assess which data would be the most important and useful? Clearly data and model development should go together with neither being completely subservient to the other. Modeling should represent the larger conceptual framework for collecting data, and field testing model results. Such a modeling framework is not entirely empirical and data-driven, but begins with the logic and physics of the problem, which involves theory which exists beyond and before data.
For many applications there is often an uncalled-for confidence in field data. Data can sometimes be of poor quality, and overconfidence in field data can lead a good model to be over-questioned. (For technical and scientific quality control, one should always question a model, or any other form of knowledge.) By using a model to organize and motivate data collection, where systematic motivation is often needed, models can lead to better and more useful data and more targeted data development efforts. You will never have enough data, but you might have sufficient data for a decision. Modeling can tell you if you are likely to already have sufficient data.

In cases where agencies or groups who have data feel threatened by a model or other data development efforts, sometimes a new model and an opportunity to become involved or embarrassment at not being involved can lead to greater cooperation.

Model Calibration and Testing. Model calibration is the setting of parameter values to represent what you know, including reasonable fitting of parameter values to field data. Models are frequently said to be “validated” as well, when they are tested against an independent set of field data. Alas, models cannot be validated or proven to be valid (Konikow and Bredehoeft 1992). Models can only be invalidated by such comparisons to field data. Where field data are inaccurate, even a good model can be carelessly invalidated. Models can be tested more broadly against common sense, expert judgment, field data, more complex models, using sensitivity analysis, tests of individual model component, and tests of software code and numerical solution methods (Gass 1983; Beck 2002).

Decision Support Systems. Decision support systems are intended to tailor model interfaces and results for direct use by decision-makers or their staffs. As such, there are two sides of a decision support system: (i) the model analysis and display of information, and (ii) the human decision-makers. The software, model analysis, and information display is doable and is the easy part of developing a decision support system. However, organizing human decision-makers to use a “decision-support” system is a major accomplishment. The institutions and individuals involved in decision-making actively employ the software for this purpose. This implies that the human decision-making process is configured to employ and seek out the use of such model-derived information and that the modeling and software have been configured to provide information and exploration in a form valued by decision-makers. A set of software can hardly be called a decision support system if it is not used by decision-makers in decision-making. Decision support systems are more easily designed and employed for routine operational decision-making and tend to be more successful if designed in collaboration with decision-makers and supported by higher-level management.

Why Analysis Fails. Applied modeling and analysis fails when it does not provide insights into real problems. In some cases, this is due to stakeholders failing to ask the right questions about why modeling is required and what specific land/water or policy issues need to be addressed. Insights can be in the form of improved understanding and thinking about a problem merely from clearer problem conceptualization and organization as part of model development, even if no model results are used. More conventionally, the model can stimulate insights based on comparison of model results for different conditions. Models also can produce insights through the education of new professionals who use and apply the model.

However, modeling analysis often fails to develop insights to real problems. This can be due to a lack of focus on real problems and a lack of focus on improving human thinking about the problem. Sometimes academic modeling of real problems becomes diverted towards issues of academic rather than practical or policy interest. Sometimes modeling deteriorates into a quest for unrealistic or unproductive rigor, so-called “rigor mortis.” Even when the analysis is done well for the problem, analysts often have trouble communicating their results to policy-makers. Just as often, policy makers have trouble listening to or understanding the results of modeling analysis, sometimes due to a lack of time, patience, or technical skills and sometimes due to a lack of political interest. At the most cynical level, a request for “more detailed modeling” can just be a tactic for delaying or steering controversial decisions.
3. MODELING FOR WATERSHED MANAGEMENT

3.1 Watershed Management Problems

Watershed management problems are diverse and often inter-related. Figure 2 illustrates the variety of problems that can be involved in watershed management. These problems can range from the design of a micro-catchment to gather and retain rainwater for agricultural intensification and groundwater recharge in an arid region, to the integrated management of land use at a basin level involving reservoirs, aquifers and levees, urban land use for regional flooding, and regional water supply problems.

Even for the micro-catchment, important physical, biological, and economic processes must be understood and perhaps manipulated. The probability distribution of annual rainfall, the ability and preparation of the local soils and embankments to retain, absorb, and not lose this rainfall, the probability that rainfall will be insufficient so that water must be imported or the tree’s death endured, the economic costs and benefits of these water and agricultural management activities, and the political economy of the people who would undertake these activities are all important. For larger-scale watershed problems, many more physical, biological, economic, and human processes will become important. One aspect of watershed management problems is that complex physical, chemical, biological, and socio-economic processes are occurring simultaneously. Typically many more things are going on than an individual mind can keep track of with any precision, so mathematical and computer models have become common-place for these problems.

Watershed management problems also often involve conflicting purposes, particularly for larger watersheds. At a basin level, millions of people are typically involved in watershed management problems and their outcomes. Each person has different interests in the resolution of the problem. Indeed, watershed management solutions often involve considerable long-term infrastructure investments and long-term institutional commitments or precedence, so several generations of people, even those unborn, are likely to be affected by the management of a watershed. These issues give rise to commonly-observed conflicts involving water and watershed management. For these reasons, watershed management decision-making often involves many people and interests, ranging from local individuals to high levels of government. Such decision-making often involves professional technical studies to help provide convincing or external assurances to those involved regarding the facts of the matter to aid in discussions or negotiations. Computer modeling often has an important role in such technical studies. These technical studies are more effective if they are organized to provide such information and assurances within the larger context of decision-making, problem exploration, and problem solving. Harou et al. (2009) review the development and application of hydro-economic modeling involving spatially explicit representation of problems and management.

Watershed management problems also commonly involve integrating across spatial and temporal scales. One example is the spatial effects of management of sub-watersheds on larger watersheds, and vice versa. In terms of temporal scale, the use of reservoir, aquifer, or soil moisture storage affects
how and if annual precipitation is available for a particular irrigation application during the dry season. Watershed problems often occur at a variety of spatial and temporal scales simultaneously, which complicates policy development and implementation, as well as modeling. These problems of scale are further complicated by the interaction of water management aspects with non-water issues, such as larger urban land use, economic, social, and environmental policies and processes. This complexity can become conceptually and practically overwhelming; this provides a strong rationale for modeling. However, it is never possible to model all aspects of any major watershed management problem. In some sense, we will never understand it all, and therefore we can never model it all. (Interests favoring the status quo will sometimes insist on a high level of detail of modeling and analysis for this reason.) Modeling cannot be used not to represent everything. Instead, modeling is best used to leverage and test our intuition and concerns as policy and management discussions of the problem progress. In practical terms, models can help identify priority sites for investments in soil and water conservation measures; help set the scale of operations and phasing; provide information to guide development of operational policies and regulations for land/water use in priority watersheds, etc. Sometimes, a large integrated modeling framework will be needed; at other times a series of smaller limited modeling applications will be better with more of the integration being conceptual in the minds of those pondering the problem and making decisions.

3.2 Modeling Watershed Problems

Computer modeling for watershed management problems is very common. Indeed, the sheer number of models, often competing for attention, sometimes distracts from the purposes and artful employment of models to aid in solving problems. The organization of modeling for watershed management is one of the first important technical issues to be resolved. It is usually best to organize modeling to follow the water through the system, using the physics of the hydrologic cycle to support the logic of modeling. Perhaps more importantly, since it follows the flow of water, this approach is also relatively easy for decision-makers and others to understand.

Table 1 provides a necessarily incomplete summary of a few of the hundreds of models developed for these processes. Importantly, the set of available models is always changing as new models are developed, and older models fall into disuse or go unmaintained. Relevant references for these models can be found on the links provided at the end of this paper or using an internet search engine. Wurbs (1994) provides a nice review of models existing at that time. Below the different modeling areas are discussed in more detail.

Figure 4 presents examples of flows of information that are common between these types of model components. Of course, the arrangement and presence of these components varies with the specific problem. For example, in some cases, the agronomic system (model) might be sup-
Table 1. Examples of Models of Various Watershed Management Components

<table>
<thead>
<tr>
<th>Model area</th>
<th>Examples*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation and climate</td>
<td>GFDL, PCM, HadCM, local weather forecasting</td>
</tr>
<tr>
<td>Precipitation-runoff</td>
<td>HEC-HMS, WEAP, SWAT, SWAP, SWMM, TOPMODEL, MIKE, local flood forecasting</td>
</tr>
<tr>
<td>Stream</td>
<td>HEC-RAS, DWOPER, FLDWAV, DAMBRK, MIKE 11, MIKE 21</td>
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<tr>
<td>Aquifer</td>
<td>MODFLOW, MIKE SHE, IGSM, many others</td>
</tr>
<tr>
<td>Infrastructure operations</td>
<td>HEC-ResSim, CALSIM, local system models</td>
</tr>
<tr>
<td>Economic, agronomic, social, environmental</td>
<td>IWR-MAIN, HEC-FDA, various local and academic models</td>
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<tr>
<td>demand and performance</td>
<td></td>
</tr>
<tr>
<td>Decision-making</td>
<td>ESSA, Shared Vision Modeling, HEC-RPT, various hydro-economic models</td>
</tr>
</tbody>
</table>

*Web links to these and other models are provided in the Annex.
Source: Authors.

Figure 4. Example Interactions Among Component Models

Source: Authors.
plied directly by precipitation, without stream, aquifer, or infrastructure.

Precipitation and climate models represent the original source of water to the watershed. Such models can include General Circulation Models (GCMs), which represent the entire world’s climate (albeit simplified) with indications for what might happen in a regional watershed or, more likely, what might happen in the part of the globe where the watershed is located. Downscaling of GCM precipitation, temperature, and other results is usually needed for the watershed scale. Alternatively, field records of climate can be used to develop empirical models of precipitation, temperature, etc. To represent climate change, it is often more convenient and comprehensible to adjust historical data for changed conditions than to rely on downscaled GCM results directly. GCM results often provide a basis for adjusting historical data. Adjusting historical data based on GCM and other information on potential climate changes can be done with less specialized expertise. Alternatively, for many areas, regional numerical weather forecasting models are often available and used over short time scales and might be more suitable for some short-term operations problems. (Giorgi and Mears 1991; Wilby, R.L. and T.M.L. Wigley 1997)

Precipitation-runoff models can range from highly disaggregated representations of detailed flow physics on hill-slopes and groundwater to simple regression equations based on field data, and a wide variety of methods that mix empirical and physically-based approaches. Hundreds of precipitation-runoff models have been developed and applied since the 1970s, supported by widespread technology and expertise. Considerable debate exists over the relative merits and problems of so-called physics-based versus empirical precipitation-runoff models (Loague and Vander Kwaak 2004). While many precipitation-runoff models are quite complex, rather simple models calibrated on the historical record often can be quite effective (Jakeman and Hornerbrger 1993). Because these problems involve local geology and climate, it is often useful to have local engineers or hydrologists involved in developing these models. HEC-HMS is an example of such a model; but many such models exist, often based on local and university software. Existing local models of runoff from precipitation often can be found. Where the type of runoff problem is similar to that of an existing trusted model, use of the existing model can be cost-effective. In other cases, a new model might be needed.

Modeling of flows into streams and into aquifers is usually undertaken separately, but recent years have seen greater use of combined modeling of these processes where stream-aquifer interactions might be important. For flooding problems, aquifers are usually not important. Stream and aquifer modeling is quite common professionally, with a wide range of expertise available from government agencies, consulting firms, and universities. One problem is that these models are often constructed for one purpose and then re-applied for different purposes. For example, a stream model developed for flood flows might be less accurate for low flows encountered for water supply applications. Aquifer models developed for water quality applications might need to be revisited or expanded spatially before being applied to water supply problems. Again, it is important that the model be tailored or interpreted for the problem at hand. The US Geological Survey’s MODFLOW model is (primarily) an example of an aquifer model, while HEC-RAS is an example of a stream hydraulics model.

Infrastructure operations models represent operational and infrastructure planning decisions involved in watershed management. Operational decisions include reservoir releases, irrigation diversions, operations of flood bypass gates, and aquifer pumping and recharge quantities. For urban water supply and hydropower, such modeling is especially common. For other applications, infrastructure operations modeling expertise is less widespread, although most large water systems have their own models and in-house modeling expertise. The US Army Corps of Engineers’ HEC ResSim model is moderately general simulation software for larger watershed reservoir systems.

Economic, agronomic, social, environmental demand and performance models represent aspects of the managed and unmanaged flow of water that are important for operational, planning, and policy decisions. Agronomic models might indicate how water deliveries would affect the growth, maturity, and yields of crops. Economic models might be employed to indicate the economic benefits of urban, agricultural, or hydropower uses of water, the economic damages of flooding, or the costs of pumping, treatment,
3. Modeling for Watershed Management

or construction (Ward and Pulido 2008). Social performance modeling might indicate changes in employment or flood evacuation with water management. Environmental performance models might address how water management affects fish populations or water quality. The US Army Corps of Engineers model for flood damage reduction analysis (HEC-FDA) is one common example for flood management. Their Ecosystem Functions Model (HEC-EFM) is applied to various environmental flow management problems. IWRMAIN is a model of urban water demands.

**Decision-making models** try to integrate some of the above types of models into a software and institutional setting where decisions are made. For routine operational decisions, this might take the form of a decision support system tailored to a particular water management project and problem, with local users trained in the use of such software on a daily basis. This is common for the integrated use of hydraulic network modeling and field monitoring for urban water system operations and for the operations of many hydropower systems and a few large irrigation systems. For planning and policy-making problems, often special interface software is made to organize and manage the use of models in a particular planning or policy decision-making setting. For planning and policy purposes, such software is usually tailor-made for specific problems (ESSA, Shared Vision Modeling). More general software has been developed for some common types of problems, such as the US Army Corps of Engineers’ Regime Prescription Tool (HEC-RPT).

These models are commonly simulation models, which allow users to investigate the likely implications and performance of specified alternatives. Sometimes optimization models are employed which manipulate a simulation representation of the system to automatically suggest better solutions (defined as a mathematical objective function, commonly based on cost, net benefits, or water deliveries). Optimization methods are particularly common in hydropower systems (Jacobs et al. 1995), where operating objectives are most strictly economic, and have also found use for scoping integrated solutions in the early phases of planning and policy studies (HEC-PRM, CALVIN – see Annex).

An important group of decision-making models is hydro-economic models which link economic and hydrologic aspects of water resources systems at a regional scale. These models have emerged as a privileged tool for conducting integrated water resources management. An overview of the concepts and designs as well as the wide applications of hydro-economic models is provided in Harou et al. (2009). In hydro-economic models, water allocation is driven or evaluated by the economic values it generates. All major spatially distributed hydrologic and engineering parts of the system are represented, including water balance components such as river flows, evaporation from surface water bodies, natural groundwater recharge and discharge, and return flows. Relevant water supply infrastructure and operations may include canals, reservoirs, desalination plants, water and waste-water treatment plants, groundwater or pipeline pumping stations, artificial recharge basins and other groundwater banking infrastructure. These hydrologic and engineering features are included in a node-link network, where economic demands have locations (nodes) and costs (or benefits) are incurred on links. The network accommodates both physical and economic spatially distributed systems, and integrates all major hydro-economic elements. Hydro-economic models are applied to study instream and offstream intersectoral allocation and use; water supply, engineering infrastructure and capacity expansion; conjunctive use of groundwater and surface water; institutions, water markets and pricing; conflict resolution, transboundary management and sustainability; land-use management, including floods and water quality; and adjustments to drought and climate change. Most hydro-economic models are custom-built, often using commercial optimization software.

The above taxonomy of modeling efforts does not imply that each modeling areas can be “outsourced” to a different group and then conveniently assembled into a more comprehensive and comprehensible understanding of the problem. Model integration involves many problems. These involve technical issues of passing information coherently and consistently between model functions and across temporal and spatial scales. The existence of feedbacks between these model functions also poses technical challenges. Model integration usually requires as much talent and resources

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1 Refer to the web links in the Annex to find more information about each model and specific institutions that could provide further assistance.
as each individual model, perhaps more. Expertise for such modeling is often available in government agencies, some universities, and some specialized consulting forms.

3.3 Approaches to Integrating Models

Several approaches are available for integrating modeling efforts to address a specific watershed management problem. Each of these is available and suitable to different degrees for different problems and locations, and the approaches are often hybridized. These approaches are summarized in Table 2.
Table 2. Examples of Models and Approaches to Integrated Modeling of Watershed Problems

<table>
<thead>
<tr>
<th>Model(s)</th>
<th>Precipitation and climate</th>
<th>Precipitation-runoff</th>
<th>Stream</th>
<th>Aquifer</th>
<th>Infrastructure operations</th>
<th>Economic, agronomic, social, and/or environmental performance</th>
<th>Decision-making</th>
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<tbody>
<tr>
<td><strong>Mega-models</strong></td>
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<td>WEAP</td>
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<td>CALVIN/ HEC-PRM</td>
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<td>WAS – Jordan</td>
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<td>Stella, Excel, GAMS, etc.</td>
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<td><strong>Modeling suites</strong></td>
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<td>HEC and IWR</td>
<td>HEC-HMS</td>
<td>HEC-RAS</td>
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<td>RES-SIM</td>
<td>HEC-IFM, IWR-MAIN</td>
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<td>Aquatool</td>
<td>MashWin</td>
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<td>AquiVal</td>
<td>SimWin</td>
<td>OptiWin Equalizador</td>
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<td>DHI</td>
<td>MIKE-FLOOD</td>
<td>MIKE 11, MIKE 21</td>
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<td>MIKE SHE</td>
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<td>PG&amp;E Hydropower</td>
<td>Field data</td>
<td>Basin regressions</td>
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<td>Excel basin optimizations</td>
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<td><strong>Home-grown integration</strong></td>
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<td>Energy and service prices</td>
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<td>GIS</td>
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<td>Excel basin optimizations</td>
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<td>Spreadsheets</td>
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<td>HydroPlatform</td>
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<td>Other</td>
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<tr>
<th>Model(s)</th>
<th>Precipitation and climate</th>
<th>Precipitation-runoff</th>
<th>Stream</th>
<th>Aquifer</th>
<th>Infrastructure operations</th>
<th>Economic, agronomic, social, and/or environmental performance</th>
<th>Decision-making</th>
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<tr>
<td>MODFLOW</td>
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<td>GAMS-econ</td>
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<td>Regression</td>
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Source: Authors.
Mega-Integrated Model. Many models of watershed management problems are formulated to include a broad range of human, physical, and management processes in one model. These mega-models, sometimes called “holistic” (Cai et al. 2003), are often relatively integrated and inclusive, but they can never be complete. No model or modeling framework can address all aspects of most problems. Each mega-model will tend to have its strengths and weaknesses, reflecting the expertise of the model developers and the kinds of problems the model has been applied to over time. Some examples of models taking this approach include CALVIN (based on HEC-PRM) (Draper et al. 2003; Medellin et al. 2007), WEAP (Yates 2005a, 2005b), WAS (Fisher et al. 2005; Rosenberg et al. 2008), and various problem and location-specific systems dynamics models (Palmer et al. 1999), or optimization formulations (Cai et al. 2003; Cai 2008).

While the concept of a mega-model implies that all aspects of the problem are represented, the depth and flexibility of how each aspect is represented is often quite variable. Some models include more detailed precipitation-runoff modeling capability (WEAP), while others take time series of hydrologic inflows as given (CALVIN) or merely single annual inflows or probability distributions of inflows (WAS). Some models have more complete representations of household and farm water management decisions (WAS), a summarized economic water demand schedules (CALVIN), or merely prioritized delivery targets (WEAP). Models similarly vary in their abilities to represent internal operational decisions and uncertainties.

While mega-model software is often convenient, for well-focused idiosyncratic problems it is common to have tailor-made mega-models implemented in common systems dynamics software (such as Stella, Extend, or Goldsim) or spreadsheet software (such as Excel). Such models can be well-tailored to the specifics and idiosyncrasies of a problem. However, many applications of systems dynamics software seem to have difficulty in being maintained over a long time, perhaps due to the more proprietary nature of the software platform and the expertise needed for continued use and development of such models. WAS (written in GAMS) is quite flexible, but requires GAMS modeling expertise. It seems more common for spreadsheet-based models to have longer longevity and use by a broader range of interests.

Integrated Suite of Models. For some routine problems, water resource software developers have found it useful to develop a suite of models which are designed to be easily integrated for a specific class of problems. Perhaps the most widespread example is software developed by the US Army Corps of Engineers’ Hydrologic Engineering Center (HEC). This software was designed mostly for flood control and navigation problems commonly encountered by the US Army Corps of Engineers. It includes component models HEC-HMS (rainfall runoff), HEC-SSP (for estimating flood frequencies), HEC-RAS (river hydraulics), HEC-GeoRAS (GIS display of HEC-RAS results), HEC-ResSim (reservoir operations simulation), HEC-FDA (flood damage estimation), and HEC-EFT (environmental flow performance). These models, with their modeling practices and documentation, developed to be assembled for flood problems allow modeling of these problems to be pursued in a fairly efficient way and integrated more easily than most other models. Many modeling integration issues have been addressed in the design and documentation of the models.

Other organizations (such as Valencia Politecnic University, DHI, Wallingford, Delft, and various hydropower software and system firms) have developed suites of models for various problems. AQUATOOL (Andreu et al. 1996) is widely used throughout Spain for water supply and management problems. In California, the Pacific Gas and Electric Corporation runs dozens of hydropower reservoirs which require operational decisions for short and long time horizons. They have developed a suite of spreadsheet and programming-language based software to support these decisions, which includes hydrologic, operations, and economic models (Jacobs et al. 1995). Flood warning system suites also are common (David Ford and Associates, see Annex). Many specialized suites of models are proprietary overall or in their components. A group of Australian partners is currently developing several suites of models for urban, rural, ecosystem, and river management problems (eWater, see Annex).

One advantage of integrated suites of models over mega-models is that they allow a greater degree of modularization for local conditions and expertise. If a different precipitation-runoff or flood damage model is desired, it is relatively easy to swap out the suite-designed model for the other model, providing the spatial and temporal resolution
of the new component model can be made compatible. Alternatively, each component of the suite can be used independently of the suite and integrated in a more novel way with other models or model components.

**Home-Grown Integration.** It is common for “integrated” modeling to consist of a stitched-together set of sequential model runs, with each component model’s outputs post-processed or adapted to provide input data for the next model in the sequence. Where several component models have been developed independently without the benefits of a formal integrated development process, this might be the only option available in the short term, especially for one-off problems.

In the longer term, such stitched together modeling can provide a basis (and motivation) for prototyping more integrated suites or mega-models. Since any model of an evolving problem might be useful for only a decade, using home-grown integration for prototyping should be a promising direction. Otherwise, the maintenance of disintegrated models and their periodic stitching together requires an unusual amount of expertise and resources to maintain and upgrade. That said, such homegrown integration is best done at home; it is even more difficult for outsiders to understand the component models and integrate them. Several groups are working to make it easier to integrate models in an ad hoc or homegrown way. HydroPlatform is seeking to develop a common data platform for a variety of models to be compared and employed without the traditional awkwardness of multi-component modeling. OpenMI is another research effort to help modular component models communicate with less re-programming or new interfaces.

Somewhat to the contrary, GIS often provides an organizing or integrating framework for modeling activities. GIS is especially good at providing an explicit spatial framework for both managing and displaying information and data and integrating land use, spatial processes, and water. However, GIS integration might not always be as easy as it is promising. While some modeling capability is available within GIS software, processes will most likely require additional simplification. Maidment (2002) and Maidment and Djokic (2000) demonstrate a wide range of capability for the use of GIS. Many other modeling efforts (including the HEC suite) are often designed to interface well with GIS. For problems which are highly spatial, GIS might be a promising software framework for integrated model development.

**System Component Models.** Software packages sometimes are available for specific system components of a watershed problem. Such packages are often developed by research organizations, governments, or universities for scientific purposes and then become applied. MODFLOW (originally by the US Geologic Survey for groundwater problems) and EPANET (by the US Environmental Protection Agency for pipe network hydraulics) are two such models. Packaged models can provide nice, often detailed models of system components. Where local models already exist in such packaged software, they might be usefully adapted for larger modeling integration or provide a basis for calibrating more simplified components of larger system models. Sometimes local packaged models can be stitched together into a suite or with other models, as home-grown integration, usually for one-off applications.

Successful modeling packages sometimes evolve or broaden to become more like suites of models or mega-models, as applications drive expansion of the model. Both MODFLOW and EPANET have expanded over time and can be considered as a suite of models built around a central software or mega-models for some applications. The MODFLOW farm package, for example, brings in farm processes into the MODFLOW groundwater model for irrigation system applications. EPANET now includes various water quality modeling capabilities. WEAP began as a regional water balance model, but now includes a precipitation-runoff and other modeling capabilities.

**Human Integration.** Ultimately, all effective integration and organization of modeling, no matter the technical process and procedures, is human and must be comprehensible to be effective. Modeling allows us to work with far larger and more complex problems than we can work with individually or as a group. However, to be useful for decision-making the model has to be done and communicated in such a way that it sustains confidence that the work was well done technically and aids human comprehension of the problem and development and evaluation of solutions.
Almost every major river system in the developed world has a set of simulation models to aid in water supply and flood planning and operations. Simulation models are also typically available for almost every large urban water supply system in the developed world. These models require a systematic effort at data collection, organization, distillation, quality control, and storage. The models also must be integrated into operational, planning, and policy decision-making institutions. For river basins, it is common to have several models, for different time and spatial scales, for different basin problems and management decisions, such as flood control, hydropower, and water supply. Data and institutional activities typically require greater resources than the modeling efforts themselves. Many basins employ widely-available commercial or public software for modeling, and many basins develop their own.

California’s Central Valley is a rather large and intensive case study of how models are applied to watershed problems by the wide variety of institutions responsible for managing water. A wide variety of national, state, local, private, NGO, and scientific institutions are involved in modeling different aspects of this watershed. Indeed, for our purposes, the basin is so large and complex that examples of most elements of Table 2 can be found there, as illustrated in Table 3.

In essence, in a system where water management affects millions of water users and thousands of professional water managers requires a wide variety of technical information which can be provided using models. Each user of model-derived information has different topical and geographic interests. So over time, many local, state, and federal agencies have developed their own models, and have developed means to represent the interface of their local or regional models with other parts of the larger Central Valley system.

The resulting multiplicity of modeling efforts has resulted in some advantages, and some difficulties. Advantages have included the presence in many agencies and consulting firms of technically knowledgeable and skilled individuals, able to represent local technical aspects and concerns to higher-level technical and policy discussions and technical efforts. A wide range of modeling and data technologies also have been employed within the regional water management community. Difficulties also have arisen from this diversity, in terms of technical and policy disagreements over technical direction, data, representation of different system components, and technical cooperation and integration. The variety of models and data also can impede more systematic studies, as a coherent technical representation over the broad system must overcome locally and topically fragmented representations of the system (Jenkins et al. 2001).

It is clear that water users have benefited tremendously from the responsiveness of decentralized management and technical work, but have also suffered from the lack of basin-wide technical coherence.
### Table 3. California Central Valley Examples of Models and Approaches to Modeling Watershed Problems

<table>
<thead>
<tr>
<th>Model(s)</th>
<th>Precipitation and climate</th>
<th>Precipitation-runoff</th>
<th>Stream</th>
<th>Aquifer</th>
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<th>Decision-making</th>
<th>Developer</th>
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<tr>
<td><strong>Mega-models</strong></td>
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Source: Authors.
4. CONCLUSIONS AND PRACTICAL LESSONS

To conclude, the following practical lessons should be kept in mind when considering the modeling of watershed management issues:

• Good modeling is common-sense and understanding reduced to calculation for the purposes of gaining insights into a real problem. Modeling is likely to be more than common sense can manage, but each step in the modeling process should be supported by common sense in the form of empirical and deductive logic.

• As such, modeling should aid discussions, help thinking and provide insights to problems where individuals and interests struggle to understand the problem and struggle to work together to address a problem. To do so, the modeling should follow the problem, usually based on the physics and economics of the problem.

• To aid model development and the interpretation and communication of modeling and model results and insights, simplicity is a great virtue. Complex problems sometimes require complex models, but the identification and shedding of unneeded complexity is an important part of insight development (Medellin et al. 2009).

• Many modeling options exist. The option and approach taken to modeling should reflect the problem being addressed and the human context in which model results must be understood.

• Identification and use of expertise is important to the development and use of models. Local and in-house expertise is preferred, as this expertise is often closest to the problem under study.

• Model integration is a major problem which requires as much expertise and resources as development of any model component. The chain of data custody between model components requires someone who is conversant in both model components, diligent in quality control, and cognizant of the problem and purpose motivating the investigation.
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Driven Water Planning Model: Part 1, Model Charac-

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International* 30:501–12.
ANNEX: OVERVIEW OF KEY WATERSHED MANAGEMENT MODELS AND DEVELOPER LINKS

AQUATOOL: http://www.upv.es/aquatool/index_E.htm  

BASINS: http://www.epa.gov/waterscience/basins  
MODFLOW: http://water.usgs.gov/software/lists/ground_water  

CALVIN: http://cee.engr.ucdavis.edu/CALVIN  
OpenMI: http://www.openmi.org  

DAMBRK: http://www.bossintl.com/products/download/item/DAMBRK  
OptiWin: http://www.upv.es/aquatool  

PCM: http://www.cgd.ucar.edu/pcm  

eWater: http://www.ewatercrc.com.au  
SWAP: http://www.swap.aterra.nl  

EPANET: http://www.epa.gov/nrmrl/wswrd/dw/epanet.html  
SWMM: http://www.epa.gov/ednnrmrl/models/swmm  

ESSA Technologies Ltd.: http://www.essa.com  
SimWin: http://www.upv.es/aquatool  

FLDWAV: http://www.fema.gov/plan/prevent/fhm/dl_fdwv.shtm  
TOPMODEL: http://www.epa.gov/nrmrl/pubs/600r05149/600r05149topmodel.pdf  

GAMS: http://www.gams.com  
WAS: http://www.wallingfordsoftware.com  

GCM: Global Circulation Model (type of model)  
WEAP: http://www.weap21.org  

GFDL: http://www.gfdl.noaa.gov  
Miscellaneous Web Links  

HadCM: http://www.metoffice.gov.uk/climatechange/science/hadleycentre  
Charles Howard and Associates: http://cddhoward.com  

David Ford and Associates: http://www.ford-consulting.com  

HydroPlatform: http://www.hydroplatform.org  
Delft Hydraulics: http://www.wldelft.nl/soft/intro/index.html  

IGSM: http://hydrologicmodels.tamu.edu/PDF/Precipitation-runoff/General/CVGSM.pdf (Largely replaced by IWFM – http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM)  
DHI: http://www.dhigroup.com  

MashWin: http://www.upv.es/aquatool/manuales/ManMashwinEsp.pdf  