Environmental Modeling: The Past, the Present, and the Future

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Abstract

The information age has ushered in a global awareness of complex environmental problems that do not respect political or physical boundaries: e.g., climatic change, ozone layer depletion, deforestation, desertification, and nonpoint source (NPS) pollution. The ability to simulate spatially and temporally variable environmental impacts, via mathematical modeling, is an important modern day necessity. Simulation provides the ability to ask and answer "what if" questions that can be used to guide decision-making strategies. Uncertainty in simulated assessments is unavoidable and sometimes even undetectable in environmental modeling. Quantification of accuracy and uncertainty in environmental modeling establishes the extent to which simulated results are reliable predictions of observed truth. Uncertainty can be due to model errors produced from simplification of process complexities described by the model. Uncertainty can also result from data error, i.e. the result of errors in the input data or the lack of information. Intrinsic model and data uncertainties have significant practical implications, either affirming or negating the use of predictive outputs from environmental models for guidance and action in a decision-making process. The development, the current utility, and the likely new roles of environmental modeling are discussed. The underlying focus of the paper is the characterization of accuracy and the impact of uncertainty in environmental modeling.

> "Everything must be made as simple as possible, but not simpler"
> Albert Einstein

1. Introduction

The foundation for hydrologic-response simulation, taken here as a surrogate for environmental modeling, was set in place at Stanford University, under the leadership of the late Professor Ray K. Linsley, serendipitously parallel to the advent of high-speed digital computers in the early 1960s. The operating algorithms that comprised the original Stanford Watershed Model (*Crawford and Linsley, 1966*) are illustrated in Figure 1. Crawford and Linsley captured the essence of hydrologic-response simulation with the following statement: *"The objective of the research is to develop a general system of quantitative analysis for hydrologic regimes. The most effective way for doing this has been to establish continuous mathematical relationships between elements of the hydrologic cycle. The operation of these mathematical relationships is observed and improved by using digital computers to carry the calculations forward in time... As mathematical relationships are developed, every attempt is made to realistically reproduce physical processes in the model. Experimental results and analytical studies are used wherever possible to assist in defining the necessary relationships."*

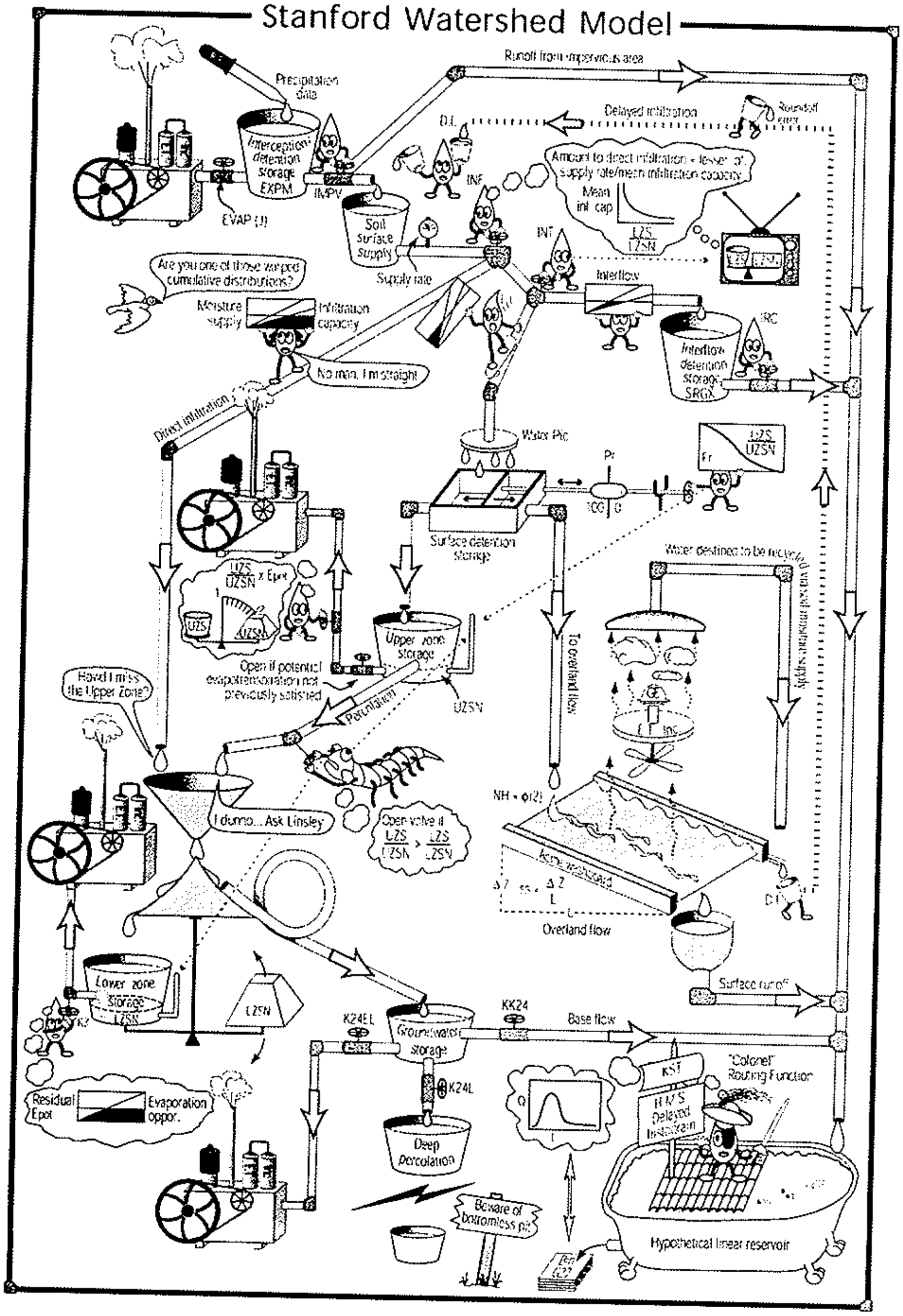

Figure 2, Flow diagram for the Stanford Watershed Model IV (Loague et al., 2000). The original cartoon was drawn by Steven Gorelick and David Stonestrom in 1977; the version shown here was drafted in 1997 by David Jones.

The spectrum of mathematical modeling problems, as perceived by Karplus in 1976, is illustrated in Figure 2. Today, it is well established that decisions related to environmental management usually involve risk, which is defined by uncertainty. In environmental modeling, the risk of not representing the system goes down when the operating algorithms are conceptual, based upon the coupled partial differential equations that characterize the dominant physical and/or chemical processes. Obviously, both the difficulty in obtaining a solution and the data requirements is greater with increasing model complexity.

The availability of geographic information system (GIS) software to those involved with landuse decisions in recent years has facilitated a new generation of models for targeting environmental problems in a risk assessment framework. The index/overlay method of *Aller et al. (1987)*, known as DRASTIC, was the first regional-scale assessment model for regional-scale groundwater vulnerability. Various leaching models have now been employed to make regional-scale assessments of near-surface leaching potential for agrochemicals. The elegant and ambitious effort of *Petach et al. (1991)* is an example of a process-based regional-scale groundwater vulnerability assessment. Our group has focused considerable effort on characterizing the uncertainty in NPS groundwater vulnerability assessments for the Hawaiian island of Oahu (e.g., *Loague et al., 1996*), the Canary island of Tenerife (*Diaz-Diaz et al., 1999, Diaz-Diaz and Loague, 2000*), and the San Joaquin Valley (SJV) at the southern end of California's Central Valley (*Blanke, 1999*). Currently working with the author: (i) Luis Ugalde is investigating the impact of correlated data in the characterization of uncertainty for pesticide leaching estimates for Oahu, Tenerife, and the SJV; and Melissa Mills is revising the Blanke vulnerability estimates for SJV with consideration for the spatial and temporal variability in recharge rates. We have also produced the first RIA (regional-integrated assessment) for pesticide leaching, based upon uncertainty and cost-benefit analyses, for Oahu (*Bernknopf et al., 1999, 2000*).

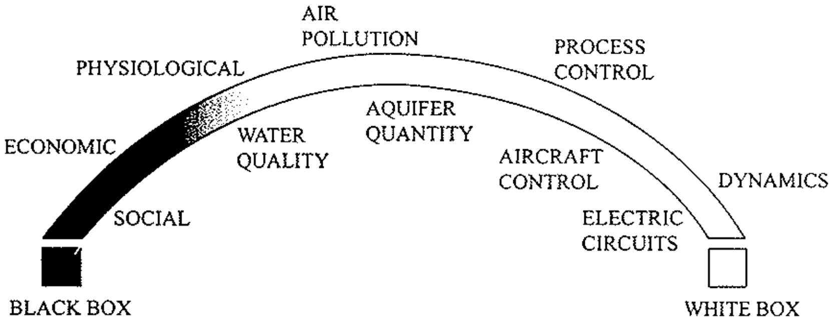

Figure 1, Spectrum of mathematical modeling problems as they arise in a variety of physical, life, and social science disciplines (after Karplus, 1976).

2. Why and how we should model

In general, there are two idealized reasons for environmental modeling. The first use is in the prediction of future events and impacts based upon a calibrated and validated model. The second use is the development of concepts for the design of future experiments to improve our understanding of processes. Improvements to prediction and concept developments simulation efforts can benefit from (i) performance standards based on both statistical criteria and graphical displays (*Loague and Green, 1991*), and (ii) uncertainty analysis designed to uncover information shortfalls and process misrepresentation (*Loague and Corwn, 1996*).

A model is a good representation of reality only if it can be used to predict, within a calibrated and validated range, an observable phenomenon with acceptable accuracy and precision. Of course, no environmental model can ever be detailed enough to be valid for all situations. Therefore, upon selecting what processes are to be modeled, a modeler must set a level of desired accuracy and precision for model validation. A model's performance is judged acceptable if it is not possible to reject the hypothesis of no difference between observed and predicted values. Two types of error are possible: (i) type-I error is a risk to the model builder and corresponds to rejecting a true hypothesis, (ii) type-II error is a risk to the model user and corresponds to accepting a false hypothesis. Currently, Edzer Pebesma (Universiteit Utrecht), Paul Switzer (Stanford University), and the author are developing a statistics-based protocol for evaluating model performance.

There are three sources of error inherent to environmental modeling that can be easily identified: (i) model error, (ii) input error, and (iii) parameter error (*Loague and Freeze, 1985*). The aggregation of model error, input error, and parameter error is the total (or simulation) error. For multiple-process models, simulation error is complicated further by the propagation of error between model components. The different methods that have been used to evaluate uncertainty in environmental modeling efforts fall into two distinct categories: (i) uncertainty analysis, where the causes of simulation uncertainty are the focus of concern; and (ii) sensitivity analysis, where the primary concern is assessing the propagation of error between model components. Uncertainty analysis considers the inherent uncertainty in model input and parameter information, and the subsequent effect this uncertainty has upon simulation results. Uncertainty analysis can be carefully designed to uncover information shortfalls and process misrepresentation. Uncertainty analysis methods for estimating data uncertainty fall into two general categories: (i) first-order variance propagation, and (ii) Monte Carlo methods. Sensitivity analysis, on the other hand, makes no use of information related to the sources or ranges of uncertainty in the model input; i.e., only considering the sensitivity of the model outputs to slight changes in an input variable/parameter.

3. Two Examples

3.1 Groundwater vulnerability

The simulation effort known as the Fresno case study (*Loague et al., 1998a,b*) was designed to determine if label-recommended NPS applications were the principal source of DBCP groundwater contamination in east-central Fresno County in the SJV. The Fresno case study simulations, for an area of 2,184 km^2, characterize the non-intuitive interplay between climate, soil type, landuse, and chemical properties as related to long-term leaching. The near-surface results for the 35-year simulated DBCP leaching history for the Fresno case study suggested that the pesticide had migrated from the surface to the water table in detectable concentrations and at some locations these concentrations exceed the maximum contaminate level (MCL). The leaching simulations also suggested that future DBCP loading at the water table, resulting from past applications, would be below the detectable limit. The saturated subsurface simulations (with recharge and pumping) of regional-scale groundwater flow, as related to the long-term fate and transport of DBCP, suggested that NPS applications of DBCP were not responsible for the observed hot spots in the study area. Of the Fresno case study, *Fogg et al. (1999)* wrote "*This unprecedented study used process-based models for both estimating rates of transport and transformation in the vadose zone and for simulating transport in groundwater. They were able to elucidate timing and mechanisms by which the contaminants migrated through the subsurface and made important inferences about DBCP application rates.*" The bottom line from the Fresno case study is that process-based simulations of NPS regional-scale groundwater vulnerability will be prohibitive, for some time, due to the exhaustive data demands and computational effort.

The Fresno case study has spun off in several directions. *Loague and Abrams (1999)* used the Fresno case study as the foundation for reverse flow path and forward solute transport simulations designed to determine if the isolated, high DBCP concentrations in the Fresno study area were likely to be the result of NPS applications. *Soutter and Loague* (*2000*) reported on the impact of upscaling spatially variable soil and crop-cover information for the Fresno case study near-surface simulations. *Stewart and Loague* (*1999*) developed non-parametric 'type' transfer functions (TTFs) to obtain quantitative, regional-scale estimates of groundwater contamination for the Fresno study area. The effort by Stewart and Loague clearly demonstrated that one can make quantitative regional-scale assessments with a TTF approach and is the basis of an ongoing study (see *Stewart and Loague, this volume*).

3.2 Rainfall-runoff

For more than three decades, the R-5 catchment located near Chickasha, Oklahoma has hosted field studies and simulation efforts designed to characterize near-surface hydrologic response. There has been a concerted effort by the author and others to simulate observed R-5 rainfall-runoff events with Horton-type models of overland flow (e.g., *Loague and Kyriakidis, 1997*). These simulation efforts have not been successful, as the Dunne mechanism is now known to be an important streamflow generation mechanism for R-5 rainfall-runoff events. The paper by *Loague and Freeze* (*1985*), which reported poor model performance for R-5 events with a quasi-physically-based rainfall-runoff model, generated a fair amount of commentary. Almost fifteen years after the paper by Loague and Freeze, *VanderKwaak and Loague* (*2000*) have shown with physics-based I*n*HM simulations that a complete hydrologic-response analysis of both unsaturated and saturated subsurface fluid flow is needed to capture the dynamics of the Horton and Dunne mechanisms as they contribute to streamflow generation during relatively simple R-5 rainfall-runoff events. I*n*HM was designed (*VanderKwaak, 1999*) to quantitatively simulate, in a fully coupled approach, water flow and solute transport (i) within a spatially variable porous medium (with or without fractures and/or macropores) and (ii) across the land surface above and adjacent to the subsurface in (i). I*n*HM is capable of simultaneously simulating each of the four streamflow generation mechanisms (i.e., Horton and Dunne overland flow, subsurface stormflow, and groundwater discharge). Figure 3 shows the first of their kind I*n*HM simulation results for R-5 rainfall-runoff event number 68 (i.e., soil-water contents, surface water depths, surface water velocities) of the type needed to drive spatially- and temporally-variable sediment transport simulations.

Future plans for I*n*HM and the R-5 data set include continuous rainfall-runoff and erosion simulations, requiring that evapotranspiration and sediment transport algorithms be added to the current version of I*n*HM. Continuous (versus event-based) simulation of R-5 rainfall-runoff response will make it possible to take advantage of the extensive soil-water content data set for the catchment and further the critical evaluation of I*n*HM. It should be pointed out that by 1970s standards, related to comprehensive physics-based rainfall-runoff simulation, the R-5 data set is a marvelous collection of information for a relatively small and uncomplicated catchment. By the standards of the new millennium, the R-5 data set is severely limited. Our ongoing I*n*HM simulations are for the three week-long sprinkler experiments at the Coos Bay experimental catchment (see *Anderson et al., 1997a, b; Montgomery et al., 1997; Torres et al., 1998*). The Coos Bay data sets facilitate model performance testing of I*n*HM well beyond what has been reported for the R-5 rainfall-runoff events. In contrast to the R-5 application of I*n*HM, the Coos Bay application of I*n*HM is: (i) dominated by subsurface fluid flow and solute transport processes, and (ii) includes consideration for fractures/macropores and hysteresis.

4. Conclusions

Twenty years ago, when the focus was at the hillslope scale, data and computers (i.e., storage and speed) were the limitations associated with process-based simulation. Today, with the focus of many environmental problems being at regional scales (e.g., NPS impacts such as agrochemicals and erosion), the limitations of process-based simulation are still data and computers. The InHM simulations reported by *VanderKwaak and Loague* (*2000*) for R-5 rainfall-runoff events clearly illustrate, as prognosticated by *Freeze and Harlan* (*1969*), that it is possible at the catchment scale to effectively simulate rainfall-runoff events with a comprehensive physics-based hydrologic-response model. An important question, relative to simulations of the type reported by VanderKwaak and Loague for R-5 rainfall-runoff events, was raised by J.R. Philip twenty years ago (*Philip, 1980*), "*Can it be that the vast labor of characterizing these systems, combined with the vast labor of analyzing them, once they are adequately characterized, is wholly disproportionate to the benefits that could conceivably follow?*" Related to the development of new concepts and/or refining the current understanding of rainfall-runoff processes, the answer to Philip's question is yes; related to operational hydrology, the answer is most likely (depending upon the problem) no.

There is no doubt that the current generation of, potentially useful, environmental models are laced with both model and data errors. It is the belief of this author that environmental models will not reach their potential in the decision management arena until (i) rigorous nonsubjective model performance criteria are established, and (ii) uncertainty impacts, related to both model and data errors, are incorporated into simulation protocols. *Dunne* (*1983*), in an important 1983 paper, called for closer cooperation between the scientists working on field studies and those interested in modeling. Dunne's original suggestions for cooperative work between the Cains and Abels of hydrology are generally still valid today.

Acknowledgements

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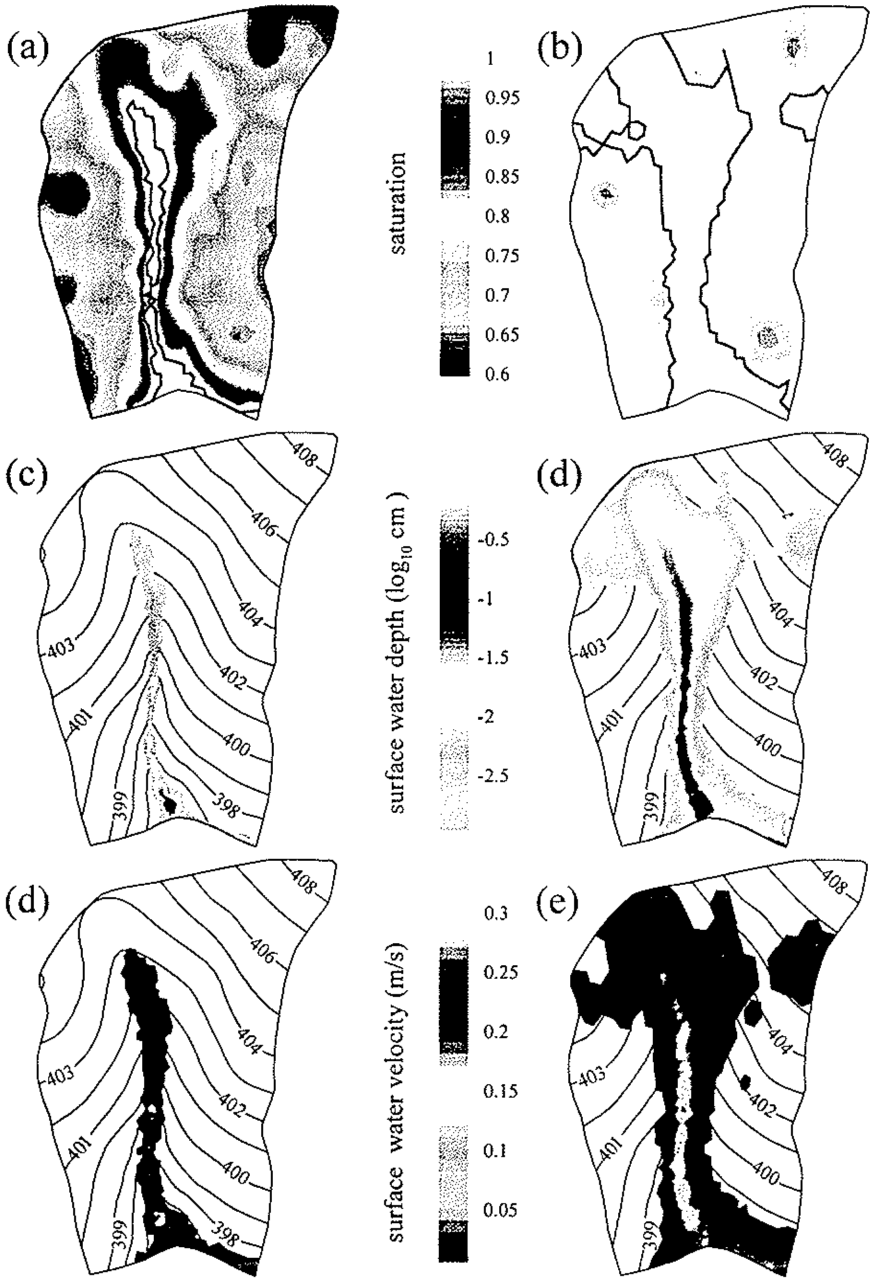

Figure 3, Plan view plots across the R-5 catchment of the InHM simulated soil-water contents at the surface [(a) and (b)], surface water depths [(c) and (d)], and surface water velocities [(e) and (f)] for event number 68 (after VanderKwaak and Loague, 2000); (a), (c), and (e) are the initial conditions, (b), (d), and (f) are at the time of peak streamflow. The solid lines in (a) and (b) outline the areas of surface saturation.

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