

#1071

United States
Department of
Agriculture

Agricultural
Research
Service

1994-5

October 1994

Proceedings of the ARS Conference on Hydrology

Denver, Colorado
September 13-15, 1993

Spatial and Temporal Variabilities of Landscapes

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Summary

The task of characterizing spatially and temporally varying landscapes is a large one. Scientists have made progress in the past 20 years: first in recognizing that spatial variability must be incorporated into hydrologic models, and second in quantifying variability associated with input parameters for these models. To better model variable landscapes we must first understand the role played by heterogeneity.

"We can have no hope of understanding determinate heterogeneous systems unless we first understand homogeneous ones, and to take this further, we shall have no hope of understanding stochastic heterogeneous systems without first understanding determinate ones." (Philip 1980)

Our current ability to predict how geophysical properties vary over space and time is very limited. A related issue concerns our current inability to control or quantify errors associated with measurement techniques themselves. This document represents an attempt to address these issues and set a research agenda for the future. The current research status was evaluated, gaps and problems were identified, and promising areas were defined. Scientific challenges identified include:

- 1) determining the scale at which current research should be focussed;
- 2) developing better methods for incorporating spatial variability into models and their estimates;
- 3) establishing better methods for extrapolating between the scale at which parameters were evaluated and the scale at which they are applied; and,
- 4) developing better methods for characterizing spatial variability.

Associated research opportunities established were:

- 1) relating hydraulic properties to vegetation type and other methods of indirect parameter estimation;

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- 2) evaluating the significance of temporal variability in hydrologic processes;
- 3) expanding applications of remote sensing;
- 4) improving methods for analyzing large data sets; and,
- 5) planning more integrated research projects.

It is important to understand soil-physical processes including spatial variability so that appropriate theory is used in hydrologic models. We must continue our efforts to elucidate the complications which form the gap between what is found in the field and what our simplified mathematical models are capable of representing.

Introduction

Geophysical variability is apparent both on the land surface and the subsurface. Tectonic, sedimentary, and cultural processes produce the landscapes in which we currently do our hydrologic research. Sedimentation associated with streams and lakes is a dynamic process. Sediments are deposited and eroded over time, leaving behind a vast array of particle arrangements. Tectonic forces shift deposited sediments and bring to the surface subsurface materials. Overlain on this are soil formation processes which affect the surface geologic material in which we have traditionally confined our research. Cultural processes associated with agriculture also has a significant effect on the landscape.

Although interesting from a scientific perspective, the primary reason for studying geophysical variability is to establish order and predictability. The first step in developing a model which mimics a natural system is establishing a conceptual understanding. This is based upon an understanding of how the system reacts to variability and how components interact. Once we understand these interactions, mathematical relationships can be formulated, following rules and requiring inputs. It is in establishing these inputs that variability must be quantified.

"At its present level of development, soil-water physics provides quantitative physical theory and quantitative measurement techniques which enable useful quantitative predictions about the equilibrium and movement of soil-water, and of material in solution in soil-water, under certain circumstances. These circumstances are those of controlled experimentation on laboratory systems which are not too complicated and of simple field situations. Difficulties frequently arise, however, when attempts are made to apply quantitative soil-water physics over areas of any size in the field." (Philip 1980)

In the 13 years following this statement, some progress has been made in evaluating field and watershed scale phenomena. However, our models are still not and may never be absolute predictors of hydrologic responses. The dominant reason for our inability to jump from the controlled laboratory settings to "real" field conditions is variability of landscapes, both in time and space.

Variability poses special problems in the collection of data to be used as input for or the testing of physically based models. Measurement techniques assume soils to be uniform in the region of measurement. If heterogeneity is present, the measurement gives some equivalent value appropriate

for the measured area. This equivalent value may not be relevant for modelling the field situation for which the measurement is taken.

All porous materials are inherently heterogeneous when viewed at a small enough scale. Also, in the case of simple porous systems of uniformly packed particles, heterogeneity gives way to an apparent homogeneity so far as physical properties are concerned as the scale of viewing increases. This scale is referred to as the representative elementary volume (REV). It is on the basis of this apparent homogeneity at a large enough scale that soil physical "constants" are defined.

Field measurements are best made with the application in mind. For example, if the objective is to predict runoff from a field sized area using the field as the computational unit size, then one would desire to know the set of inputs which best represent the field as a whole and not individual locations on the field. However, traditional field methods have been technique driven rather than application driven. The area over which the measurements are taken often depends more on available techniques than on how the data will eventually be used.

Soil heterogeneity may be deterministic in that it is known and can be measured, or stochastic in that it varies randomly. However, spatial variability is, in general, not purely random. If measurements are made at two different locations, the closer the measurement points are to each other, the closer the measured values will generally be. Normally, there is correlation in the spatial distribution of measured data.

Some classical methods which have been used to evaluate variability are statistical, geostatistical, and stochastic. Classical statistical methods involve estimation of a mean, a variance, and a distribution. We assume the estimate we obtain through sampling accurately reflects the population. However, we rarely collect enough data to establish precise estimates. Geostatistical methods also yield estimates of the mean, variance, and distribution, but in addition they evaluate correlation over time and/or space. The stochastic method assumes parameters associated with specific points in the system are random variables which can be characterized by statistical parameters (i.e., mean, variance, correlation lengths). Because of this definition, the stochastic method associates error estimates with predicted values. Difficulties with the stochastic method include evaluating the statistical parameters associated with inputs, determining how the results relate to the actual system, determining at what discretization level the parameters are to be applied, and the large number of samples necessary to evaluate the required input characteristics.

Scientific Challenges

Matching Measurement Scale to Problem Defined

The first challenge facing researchers and society alike is defining the scale of the problems being addressed. Philip (1980) raised this question:

"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?"

To avoid wasted effort we must clearly evaluate our goals and objectives, and use these to define relevant research related to variability.

Solving problems at the field scale requires different knowledge of variability than does solving problems at the watershed scale. The nature of current issues requires research at various scales. For example, the importance of hydraulic conductivity determined using a 20 cm² core becomes lost at the watershed scale. What is needed is a representation of hydraulic conductivity at the computational scale being used. In order to apply measurements taken on scales smaller than those at which they are applied, we need to better examine scaling relationships and model sensitivity.

There are many surface and subsurface models currently available. Each of these models has strengths and weaknesses. Each of these models was developed for application at a specific scale. We as modelers must take care not to overextend the intended use of these models. A better effort must also be made to ensure that regulatory and action agencies do likewise.

Distributed deterministic models require estimates of inputs at different scales. It makes little sense to be concerned with spatial variability measured within 1 m² plots when the model is using 10 ha grids. Examination of the sensitivity of the model to input variation becomes a very important issue in evaluating the importance of spatial and temporal variability of geophysical data.

Modeling

Several methods exist for incorporating variability into models. Models can be classified based upon the character of the results they produce. If any of the variables in the model are random having distributions in probability and are treated as such within the model framework, then the model is stochastic. If all of the variables are treated as constants, then the model is deterministic.

Some models incorporate characteristics of both of these methods in an attempt to combine some of the advantages of both approaches into one model. In this approach, the physically-based governing equations for a problem are simplified and one or several of the key parameters are treated as stochastic variables (Entekhabi and Eagleson 1989). However, as with other approaches, difficulties associated with scale and parameter development remain.

The most common modeling method is deterministic. Deterministic models assume a level of homogeneity. To a certain extent the system is assumed to be spatially and temporally homogeneous such that it can be described by a single set of constant inputs. Distributed models assume homogeneity over a defined computational scale. Traditionally, modelers have used mean estimates as model parameter inputs. However, in some situations use of the mean parameters may not yield reliable results.

A typical model validation involves taking numerous field measurements in order to get input parameter estimates. In conjunction with this, measurements are made to compare to model predictions such as runoff, soil-moisture, and chemical concentration. A judgement must be made on how to use the parameter estimates and how to compare model estimates to observed values. Do we use the arithmetic mean of observed values and compare it to the model output based upon estimates obtained using arithmetic mean values of the input parameters? Do we compare individual point observations to model estimates made using point measurements of the input parameters?

Hydrologic modelers must begin to include the variability of input parameters in their simulations. This will help to quantify model uncertainty associated with inputs versus uncertainty associated with the model itself. One method for doing this is Monte Carlo simulation. Monte Carlo simulation requires random samples from a distribution of input parameters, and generates a distribution of outputs. Statistical properties of the outputs are tabulated as desired.

Stochastic modeling places emphasis on the statistical characteristics of hydrologic processes. Stochastic methods can be used to incorporate the uncertainty of input parameters into model output. Purely stochastic models have been developed for simulation of saturated (Freeze 1975) and unsaturated groundwater flow (Yeh et al. 1985), for ground-water quality modeling (Duffy and Gelhar 1985), and surface water flow and transport. However, stochastic models have inherent problems. In order to establish a stochastic model of a complex hydrologic system many simplifying assumptions have to be made concerning the statistical characteristics of the input parameters. These assumptions decrease model accuracy. Second, data sets for establishing the statistical characteristics for the input are incomplete. Most available data sets are from too short a time period to establish a probability distribution with any degree of confidence. Each of these problems must be overcome in order for stochastic methods to offer more utility in general hydrologic modeling.

New Approaches for Measuring/Characterizing Variability

If we are to incorporate spatial and temporal variability into our modeling efforts, we must strive for consistency in our data bases. This means establishing standard techniques for measuring physical characteristics as well as developing new methods for obtaining data. This will allow us to more accurately compare data sets.

In addition to a standardization of techniques we must report sources and estimates of measurement error. It is critical to know the error associated with measurement, recording, processing techniques and the variability of the reported data in order to attempt to separate model error, parameter variability, and measurement error.

An opportunity exists for developing better estimates of surface characteristics based upon remotely sensed data. Scale and resolution of this data are continually improving. The speed at which data can be collected and the scales over which it can be applied make it a tool which will help us quantify spatially variable properties. Some promising areas for application of remote sensing are in the evaluation of surface texture, surface moisture, land use, and land slope. Coleman et al. (1993) found significant correlation among spectral radiance data and sand, silt, clay, organic matter, and iron oxide content of surface soils. However, the amount of variance explained was quite low. Coleman et al. (1993) attributed this to the coarse spatial resolution (30 m) of the available data.

Research Opportunities

Data Collection

Work has shown that the variability in surface soil properties which influence infiltration, runoff, etc. are strongly correlated with variations in vegetation life form (Blackburn et al. 1992). Perennial vegetation can modify surface soil conditions and thereby control hydrology. Infiltration under shrubs can be 3 to 10 times that in the interspace between shrubs (Blackburn 1975). Therefore, opportunity exists to use vegetation to stratify variability in surface soil properties (Pierson et al. 1993). This could improve sampling efficiency and aid in data interpretation. More work needs to be done on scaling such information to field or watershed levels. Evidence also shows that plant community type may be a way to stratify soil and hydrologic variables on a larger scale, but little data is available to test this theory.

Some evidence has been presented which indicates that on some rangelands temporal variability is more important than spatial variability (Blackburn et al. 1992). Erosion is generally low on most rangelands, but conditions exist where extreme erosion can take place (Blackburn et al. 1990).

Little information is available to predict such temporal responses since its collection is much more difficult than spatial data.

Remotely sensed observations have the potential to provide fundamentally new parameters which can be derived from areally-integrated observations at various spatial scales. One exciting new challenge in the remote sensing area is to develop techniques for deriving new models and their associated parameters.

More work needs to be conducted on interpretations of remotely sensed data and on the development of new remote sensing techniques which are useful at a variety of scales. Approaches are being developed which are more accurate and provide data at smaller scales. Remote sensing is useful for model parameterization, but not necessarily for model validation or calibration. Therefore, field techniques for collecting data at appropriate scales to validate and calibrate models still need to be developed.

Data Analysis

One of the biggest limitations in analyzing spatial and temporal data is data management and manipulation. Handling and processing large data sets can be difficult and time consuming. ARS has many data sets, some of which are long term, which are virtually untapped because they are not well organized, error checked and/or available for a variety of scientists to use. In the future remote sensing data may run the same risk if we are not equipped to process and assimilate large data sets. GIS systems are being employed to aid in this area, but additional tools and approaches are needed. Many database management tools are already available and the discipline of information management is growing rapidly. ARS needs to stay abreast of new developments in these fields and put more emphasis on and provide more credit for data collection and management efforts. Without good data the field of hydrology will make little progress in the future.

Some geophysical characteristics are more difficult to measure than are others. For example, basic textural characteristics of soils are relatively easy and inexpensive to measure. However, hydraulic conductivity is difficult to measure because it is hard to collect a good quality undisturbed sample, and it is difficult to obtain a good estimate through lab or field measurement. Deterministic or stochastic models may be able to estimate those parameters which are more difficult to measure with a reasonable amount of accuracy. Past efforts to do this have met with some success, but additional time and effort must be put into this area.

Integrated Research

The hydrology of even a small watershed is very complex and difficult to quantify. Many processes interact to produce an overall watershed response which spans plant, soil and hydrologic disciplines. Therefore, to attack even the smallest hydrologic problems, requires a multidisciplinary approach. Few groups of scientists in the world are as broad-based as the one found within the ARS hydrology effort. ARS scientists need to work together at all levels to address future problems in hydrology. However, the current structure of the ARS does not adequately promote and reward cooperative projects. Therefore, identifying future integrated research projects is hindered until the ARS designs a better way of accomplishing multidisciplinary objectives.

Several multi-disciplinary field experiments have been carried out in recent years which provide the unique opportunity to study the application of remotely sensed data to the derivation of fundamental new parameters and variables observed at different spatial scales (MONSOON '90, Walnut Gulch

'92, Washita '92, and HAPEX-Sahel). These efforts attest to the success that can be made through cooperative efforts involving scientists from several different backgrounds.

Modeling

Our ability to parameterize models is far behind our model development and data collection efforts. This is due primarily to an inability to quantify spatial and temporal variability at the scale of interest. More research and model development effort is needed on model parameterization techniques. This includes field data collection procedures that action agencies can use to collect data for model parameterization, calibration, and validation. We need better algorithms for estimating difficult parameters which incorporate spatial and temporal variability. We need to expand our research on artificial intelligence and employ new approaches to model parameterization and to modeling itself. Such things as knowledge bases, case-based and rule-based decision making and multi-objective decision making techniques along with the more familiar mathematical models, graphic user interfaces and GIS systems could all be quite useful in this area. The ARS needs to examine the systems approach to defining problems and then design, build and implement solutions based on a variety of technologies.

Conclusion

This report addresses some of the key research issues related to spatial and temporal variability. Because it is a central issue in the physical sciences, it is of great interest to many different disciplines. Great effort has gone, and will continue to go, into research on this topic. Progress has been made. However, critical research gaps still exist. Some of these gaps were identified in this report:

- 1) our inability to control or quantify errors associated with measurement techniques;
- 2) a failure to incorporate spatial variability into models and their estimates;
- 3) the need to establishing better methods for extrapolating between the scale at which parameters were evaluated and the scale at which they are applied; and,
- 4) a lack of good methods for characterizing spatial variability.

These scientific gaps create research opportunities. Some of these opportunities were identified in this report:

- 1) relating hydraulic properties to vegetation type and other methods of indirect parameter estimation;
- 2) evaluating the significance of temporal variability in hydrologic processes;
- 3) expanding applications of remote sensing;
- 4) improving methods for analyzing large data sets; and,
- 5) planning more integrated research projects.

We must understand spatial variability in order to develop appropriate theory in hydrologic models. Efforts to elucidate the complications which form the gap between what is found in the field and what our simplified mathematical models are capable of representing must forge ahead.

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