Looking for Hydrologic Laws

JAMES C. I. DOOGE

Department of Engineering Hydrology, University College, Galway, Dublin, Ireland

The search for regularities in hydrologic relationships is discussed against the background of the general types of predictive models used in science. The various approaches to the study of water are compared and contrasted. The ideas discussed are illustrated by examples from the development of techniques in flood hydrology and by personal conclusions on the sources for new hypotheses in flood hydrology and the possibility of their verification.

1. Introduction

1.1. Relation of Hydrology to Science

Fifty years ago, there was only a handful of books and a handful of journals available to the hydrologist who wished to establish a sound scientific basis for his practical decisions. Today, there is an embarrassing abundance of books, monographs, journals and symposia proceedings clamouring for his or her attention. Is hydrology now an established science? Is hydrologic practice now firmly based on scientific principles?

This paper deals with the problems raised by the search for regularities and for laws in hydrology. In order to emphasize the challenge implicit in such a search, special attention will be paid to flood hydrology in which the enterprise is particularly difficult. It is proposed to discuss the subject within the context of predictive models and explanatory theories in science generally. Such an approach can be useful not only for the purpose of emphasizing the position of hydrology as one of the earth sciences but also because such an approach could lead to the suggestion of analogies which can be so fruitful in the construction of models and the development of theories [Polya, 1954].

Following an introductory section on the nature of scientific method, an outline is given of the contrasting approaches of analytical mechanics and statistical mechanics and the problems involved in dealing with systems of intermediate size. Attention is then turned to the various approaches to the study of water movement and the problem of parametrizing at a macroscale the effect of microscale processes that are not explicitly included in the macroscale model. Finally, the historical development of current methods of flood hydrology is reviewed against the background of the foregoing material. The purpose of the whole exercise is to provide the context for the formulation of a strategy for the development of a body of hydrologic knowledge that is both scientifically respectable and practically useful.

The term model is used to describe a system which is simpler than the prototype system and which can reproduce some but not all of the characteristics thereof. Accordingly, a model is related to those particular aspects of the behavior of the prototype for which understanding or prediction is required. It is important to realize that a model is not a theory and to distinguish between models that are constructed to provide a prediction of system behavior to some specific accuracy and scientific theories developed to provide insight into the nature of the system operation. Though their function is different, predictive models and explanatory theories can be closely related to one another. An hypothesis or a confirmed theory can be used as the basis for the construction of a predictive model and in turn some predictive models which reproduce a prototype behavior accurately can provide insight for the construction of explanatory theories.

For different scientific workers (or for the same scientific worker at different times) the level of interest in explanatory theories and predictive models may vary as shown schematically in Figure 1. A research scientist uses observations primarily as a basis of comparison between the predictions based on alternative hypotheses and combines confirmed hypotheses into a theoretical system enabling him or her to understand nature. An engineer uses observations as a check on the predictions he uses in his efforts "to control the materials and forces of nature for the use and benefit of man" (ICE Charter; see Dennis [1968]). Hydrology, as one of the earth sciences and as the basis of water resources development, is concerned with both of these functions. Understanding and prediction can aid the control of extreme flood events, but perfect understanding and perfect prediction would be small solace if failure to control resulted in a massive human tragedy.

1.2. Nature of Scientific Method

There seems at first sight to be all the difference in the world between the scientific method of the physical scientist and the efforts of the hydrologist to understand and predict extreme flood events or other hydrological phenomena. On closer examination, however, it becomes clear that while there are very significant differences, there are also similarities and analogies that may be helpful to the hydrologist in his task. It is clearly insufficient to define scientific method as "what scientists do," but it would be equally wrong to think that all scientists under all circumstances act in accordance with what is known as the scientific method.

In his notable work The Logic of Scientific Discovery, Popper [1959] proposed falsifiability as the criterion of demarcation of empirical science. He requires of any scientific system that 'it must be possible for an empirical scientific system to be refuted by experience.' Popper goes on to develop such principles and rules as will ensure the testability, i.e., the falsifiability of scientific statements.
Platt [1964] describes the steps in such an empirical method as follows:

Strong inference consists of applying the following steps to a problem in Science formally and explicitly and regularly: (1) devising alternative hypotheses; (2) devising a crucial experiment (or several of them) with alternative possible outcomes each of which will, as nearly as possible, exclude one or more of the hypotheses; (3) carrying out the experiments so as to get a clear result; and (4) recycling the above procedure, making sub-hypotheses or sequential hypotheses to define the possibilities that remain, and so on.

It is clear that in catchment hydrology we cannot carry out fully controlled experiments, let alone critical experiments designed to discriminate between alternative hypotheses. However, this circumstance should not lead us either to despair of discovering the nature of the regularities in hydrological behavior or to a denial that such regularities exist.

It is perhaps consoling for hydrologists to realize that even the most strongly established of scientific laws cease to hold under certain conditions. This is illustrated in Figure 2, which depicts the development of Physics as a staircase [Wheeler, 1980]. Each of the steps in the staircase represents the discovery of each new law and each riser marks the attainment of conditions so extreme that the law is transcended. Thus the physical concept of density and the law of hydrostatics cease to have any meaning under conditions of extremely high pressure and the fundamental chemical concept of valency and the law of chemical combination cease to have any meaning under conditions of high temperature.

2. METHODS OF PREDICTION

2.1. The Study of Mechanisms

The classical approach of analytical mechanics is to use a set of ordinary differential equations and a set of initial conditions to predict the future behavior of a system of particles. An outstanding historical success using this approach was Newton’s Law of Universal Gravitation. This achievement of Newton was facilitated both by the careful observations and analysis of those who had preceded him and by the fact the solar system could be analyzed by reduction to the superposition of a number of two-body problems. The synthesis of Newton (1642–1726) was preceded by the formulation of the heliocentric hypothesis by Copernicus (1473–1543), the vast amount of observational data compiled by Tycho Brahe (1546–1601), and the painstaking analysis of these data by Kepler (1571–1630).

After 4 years of analysis, Kepler formulated his theory of planetary motion in the form of three laws as follows.

1. The planets describe ellipses with the sun at one focus.
2. Equal areas are swept in equal times by the radius vector drawn from the sun to a planet.
3. The squares of the orbital periods are proportional to the cubes of the major axes of the orbits.

It can be shown [Lin and Segel, 1974] that these three laws can without further assumption be combined to give the kinematic form of the inverse square law. Newton’s law of universal gravitation requires the addition to the kinematic inverse square law of two further factors: (1) the definition of force as proportional to mass and to acceleration and (2) the application of the principle of superposition to the planets of the solar system. The latter use of reductionism to enable an analytical solution to be found was a key factor in Newton’s success.

To retrace the path from the dynamic form of the inverse square law through the kinematic form to predict a planetary orbit involves the solution of a second-order linear differential equation. When Newtonian mechanics is modified to take account of the general theory of relativity, the basic equation which has to be integrated contains in addition a small term involving the square of the dependent variable which makes the equation nonlinear. It can be shown by the use of perturbation theory that the orbit is still very close to an ellipse but that there is in each orbital period an advance of the point of closest approach to the sun. The observation of this advance was one of the crucial empirical tests of the general theory of relativity.

There are echoes of the development of planetary theory to be found in the domain of hydrology. Kuhn [1962] argues in his influential work on The Structure of Scientific Revolutions that in the 16th-century astronomy was ready for the Copernican Hypothesis (anticipated by Aristarchus in the 3rd century B.C.) because ‘A man looking at the net result of the normal research efforts of many astronomers could observe that astronomy’s complexity was increasing far more rapidly than its accuracy and that a discrepancy corrected in one place was likely to show up in another’. On this criterion, there are grounds for believing that the subject
of catchment hydrology is ripe for a similar revolution. Hydrologists may need (1) hypotheses as radical and as conceptually simple as that of Copernicus; (2) comprehensive observations capable of falsifying or confirming such hypotheses; and (3) skill and patience in analysis to bring hydrology to the position represented by Kepler's laws. To advance to the stage of the Newtonian synthesis might be too much to hope for but hydrology could contribute to a biogeophysical synthesis on a regional or global scale.

The principle of superposition was one of the keys to Newton's success in developing his theory of universal gravitation. In hydrologic theory the major successes in both the deterministic and the stochastic approaches have been in the development of the linear analysis of hydrologic systems. Once we attempt to advance to the nonlinear, serious difficulties are encountered as in all fields of science. The classification in Tables 1 and 2 is based on Franks [1967], who assessed the ease of solution of different types of mathematical problems by linear and nonlinear analytical methods. It will be noted that of the nine linear cases, one is classed as trivial, two as easy, two as difficult, and four as impossible or essentially impossible. However, of nine cases of mathematical problems involving nonlinear equations given in Table 2, three are classed as very difficult and the remaining cases as impossible. The developments of the past 20 years in mathematical power do not essentially affect this contrast. Our ability to obtain closed form solutions of nonlinear problems of any size or complexity is severely limited. Still more limited is our ability to analyze nonlinear problems in such a way as to gain insight into the fundamental behavior of the systems being examined.

2.2. The Study of Large Aggregates

The limitations involved in analytical mechanics have restricted its scope to certain types of problems. In a number of problems in the physical sciences and in most problems in the biological sciences and the earth sciences, alternative approaches must be explored. There are not only analogies between the dilemmas of the hydrologist and biologist but analogies between the types of system they study, both being adaptive.

Statistical mechanics attempts to overcome the limitations in analytical mechanics by jumping from treating a very small number of objects to treating a very large number of objects. This strategy was successful in a number of areas because of the operation of the so-called law of large numbers, according to which we are more likely to observe values close to the predicted average values as the size of the system increases. Systems for which the number of particles is large, so that prediction of some properties can be made with adequate precision, form the subject matter of statistical mechanics.

The basis of the latter approach is to assume a highly simplified model of the microscale behavior of a large number of particles and to concentrate on a small number of average properties on the macroscale. The derivation of macrobehavior in this way involves both simplified laws of interaction on the microscale and hypothetical probability estimates. As Popper [1959] said,

Statistical methods, or frequency statements, can never be derived simply from laws of a deterministic kind for the reason that in order to deduce any prediction from such laws, initial conditions are needed. In their place, assumptions about the statistical distribution of initial conditions—that is to say specific statistical laws are obtained from micro-assumptions of a deterministic or precise character.

In this approach the macrosystem containing a large number of molecules is assumed to be sufficiently unorganized as to show regular statistical behavior. Thus Weinberg [1975] writes 'Intuitively, randomness is the property that makes statistical calculations come out right. Although this definition is patently circular, it does help us to understand the scope of statistical methods.' It is perhaps a salutary reflection for hydrologists that the techniques of statistical mechanics work well in the kinetic theory of gases where the molecular motion is highly random but are much less straightforward in the case of the kinetic theory of liquids because the latter are loosely structured, being intermediate between the unstructured gases and the highly structured solids.

The foundations of the kinetic theory of gases and of statistical mechanics were laid by Maxwell (1831-1879), Boltzmann (1844-1906), and Gibbs (1839-1903), who introduced such concepts as the probability of a particular molecular state, the relation between the entropy and the probability of a macrostate, the equipartition of energy among degrees of freedom, and the ergodic hypothesis [Brush, 1983]. The approaches and assumptions of statistical mechanics would appear to offer some guidance in dealing with the key problem of quantitative geomorphology. Examples of counterparts to the concepts in statistical mechanics are found in catchment hydrology in such concepts as the role of entropy in landscape formation [Leopold and Langbein, 1962] and the equal chance hypothesis of topologically distinct drainage networks [Shreve, 1966]. There is, however, a great contrast between statistical physics and statistical hydrology in regard to the sizes of the aggregates involved and in the fact that the hydrological phenomena of major interest involve transient rather than equilibrium behavior.

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### Table 1. Mathematical Problems Involving Linear Equations

<table>
<thead>
<tr>
<th>Type of Equation</th>
<th>One</th>
<th>Several</th>
<th>Many</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algebraic</td>
<td>trivial</td>
<td>easy</td>
<td>essentially impossible</td>
</tr>
<tr>
<td>Ordinary differential</td>
<td>easy</td>
<td>difficult</td>
<td>essentially impossible</td>
</tr>
<tr>
<td>Partial differential</td>
<td>difficult</td>
<td>essentially impossible</td>
<td></td>
</tr>
</tbody>
</table>
2.3. The Study of Intermediate Systems

Unfortunately, in many fields of enquiry the key problems do not fall within the scope either of analytical mechanics or of statistical mechanics. A schematic representation of the areas of application of these two approaches due to Weinberg [1975] is shown as Figure 3. For a low degree of randomness and for a relatively simple mechanism, the approach of classical analytical mechanics will yield models capable of providing predictions of an acceptable accuracy. This approach has been discussed in section 2.1 above, and the limitations to it in the face of increasing complexity and of nonlinear behavior are indicated in Tables 1 and 2. For a sufficient degree of randomness, prediction of average behavior is possible through the methods of statistical mechanics discussed in section 2.2 above.

In the intermediate region, where there is both a relatively high degree of complexity and some degree of organization, neither of these approaches will provide an accurate basis for prediction. It is in connection with problems of this type that the various varieties of systems theory have been developed. Most problems arising in catchment hydrology fall in the category of complex systems with some degree of organization. Hydrologic processes can be analyzed on the basis of the equations of hydraulics and soil physics, but the high degree of spatial variability in a catchment of any size poses serious problems of parameter specification. Similarly, average properties of drainage networks such as the bifurcation ratio can be predicted asymptotically for very large topologically random networks [Shreve, 1966; Gupta and Waymire, 1983]. However, the study of the properties of random networks of finite size still depends on numerical experimentation. The indications are that a study of the use of the systems approach in other disciplines could provide a useful supplement to the work accomplished in systems hydrology over the past 25 years.

The nature of the general systems theory approach is described in such works as those by Bertalanffy [1968], Klir [1972], and Wymore [1967]. These three books are listed not only in alphabetical order but also in the order of increasing mathematical complexity. Bertinski [1976] has written an extended essay which is critical of the exaggerated claims sometimes made for general systems theory and for the ability of mathematics to predict the behavior of complex systems. One of the main difficulties of the systems approach is the tendency of its practitioners to become absorbed with the details of their models and to neglect the need for objective testing of the model's predictive power. Many systems modelers seem to follow in this modern age the example of Pygmalion, the sculptor of Cyprus, who carved a statue so beautiful that he fell deeply in love with his own creation. It is to be feared that a number of hydrologists fall in love with the models they create. In hydrology, as in many other fields, the proliferation of models has not been matched by the development of criteria for the evaluation of their effectiveness in reproducing the relevant properties of the prototype.

General systems theory is intellectually opposite to the classical approach based on reductionism which breaks down complex problems into solvable subproblems and then synthesises the individual solutions. Recently, there has emerged a new attempt to construct a theory of complexity based on the concept of reality as intermediate between determinism and randomness in which changing patterns of stability and instability contribute to the self-organization of systems [Prigogine and Stenges, 1984; Prigogine, 1980, United Nations University (UNU), [1984]. As far as the author is aware, this approach has not yet been applied in hydrology.

2.4. Weinberg's "Laws" of Complex Systems

A most readable work on systems theory is the book of Weinberg entitled An Approach to General Systems Thinking [Weinberg, 1975]. His approach will be closely followed in this brief account of the subject. Weinberg [1975] presents a number of "laws" as a guide to the nature of the systems approach. He points out that our ability to apply the approach founded on analytical mechanics is limited by what he calls the "Square Law of Computation" expressed as follows: 'Experience has shown that unless some simplification can be made the amount of computation involved increases at least as fast as the square of the number of equations'. This gives a rough quantitative form to the qualitative classifications of Table 1 and Table 2 in section 2.1. If all but a few interactions between the components of the system can be neglected, then this approach can be fruitful indeed as discussed in section 2.1 above for the example of planetary orbits.

In contrast, for purely random systems we have the "Law of Large Numbers," which states that the larger the population involved the more likely we are to observe values that are close to the predicted average values. This law can also be given rough quantitative form as the square root law described by Schrodinger [1945].

Weinberg suggests that for the intermediate region of organized complexity we can postulate a third law which he calls the "Law of Medium Numbers" and expressed it in the form 'For medium number systems, we can expect that large fluctuations, irregularities and discrepancies with any theory will occur more or less regularly.' Weinberg emphasizes that the importance of this law of medium numbers is not in its predictive power but in the number of systems to which it applies. The Law of Medium Numbers is often quoted in every day life in the form "anything that can happen will happen," and known as "Murphy's Law." Science has achieved a good deal of success by confining itself to
TABLE 3. Significant Length and Time Scales

<table>
<thead>
<tr>
<th>Discipline</th>
<th>Subject of Study</th>
<th>Length, m</th>
<th>Time, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical chemistry</td>
<td>water molecule</td>
<td>$10^{-10}$</td>
<td>$10^{-13}$</td>
</tr>
<tr>
<td></td>
<td>water cluster</td>
<td>$10^{-8}$</td>
<td>$10^{-11}$</td>
</tr>
<tr>
<td>Continuum mechanics</td>
<td>continuum point</td>
<td>$10^{-3}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Hydraulics</td>
<td>turbulent flow</td>
<td>$10^{-2}$</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Hydrology</td>
<td>experimental plot</td>
<td>$10^{10}$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td></td>
<td>basin module</td>
<td>$10^{2}$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td></td>
<td>Subbasin</td>
<td>$10^{4}$</td>
<td>$10^{4}$</td>
</tr>
<tr>
<td>Climate studies</td>
<td>basin</td>
<td>$10^{-6}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>general atmospheric circulation</td>
<td>$10^{2}$</td>
<td>$10^{6}$</td>
</tr>
</tbody>
</table>

problems to which the Law of Medium Numbers does not apply. The hydrologist like other applied scientists suffers from the grave disadvantage that most of his problems lie within the region in which the relevance of this law is only too evident.

Generally, systems theory attempts to produce laws that provide insight rather than specific answers. These laws inevitably are less precise, less directly applicable than the universal laws of analytical mechanics or statistical mechanics. However, even the universal laws of science are not immutable. Throughout the history of the development of science the fundamental law of the conservation of energy has undergone many changes. It still stands as a law today because every time an instance was found which contradicted the law as enunciated at the time, the concept of energy was redefined. Weinberg [1975] cites this as an example of what he calls “The Law of Conservation of Laws”: ‘When the facts contradict the law, reject the facts or change the definitions, but never throw away the law.’ In this way a law can be kept alive but increasingly becomes more sterile as the elaboration of definition reduces its scope from that of a general law of broad predictive power to a more and more particular statement of behavior.

Weinberg emphasizes that we should not lose our way in making laws so general that they cease to be of any use. He advocates the “Law of Happy Particularities”: ‘Any general law must have at least two specific applications.’ He warns equally against the danger of undergeneralizing as an impediment to progress and balances the Law of Happy Particularities given above the “Law of Unhappy Particularities”: ‘Any general law is bound to have at least two exceptions.’ The latter law is already known to us in its popular form ‘If you never say anything wrong, you never say anything.’ The latter version is probably easier to remember in its negative form, since we expect laws to be prohibitive.

3. APPROACHES TO THE STUDY OF WATER

3.1. Importance of Scale

Having discussed the three general approaches used in scientific analysis, let us now look in more detail at the study of the occurrence and movement of water which by definition is the subject matter of hydrology. In a previous publication [Dooge, 1983] the author attempted to answer the question “What does water mean in a scientific context?” There is no single simple answer to this question because scientists of different disciplines, and often scientists within a discipline, give varying answers to it. To the social scientist, “water” is an important factor in a number of significant types of group action and is defined at various times as either a means of subsistence or a method of transportation or as a technological input or as an important element in religious ritual. To the economist, water is a scarce resource to be allocated in some optimal fashion between different users of different economic need in different places and at different times. To the biologist, water is of prime importance as a necessity of life and a shaper of the various forms which living organisms take. To the botanist, water is of particular importance as the means by which plant nutrient is taken up and distributed. To the zoologist, the potassium-rich water of the cell is important for the diffusion of chemical substances while the sodium-rich extracellular water provides an environment for the cells that is thermostatically controlled. Within the physical sciences and the earth sciences there is and can be no universal model for water movement. The significant length and time scales appropriate to different models of water are approximately as summarized on Table 3 [Dooge, 1983].

The values of a number of the properties of water are anomalously high: melting point, boiling point, latent heat of vaporization, specific heat, thermal conductivity, surface tension, and dielectric constant. The physical chemist is able to explain these anomalously high values by modeling water as a highly polar (i.e., nonsotropic) molecule which through hydrogen bonding continually forms clusters which break down and reform again on a time scale of about $10^{-11}$ s. The anomalously high values of these water properties are of hydrological significance since they affect such phenomena as the occurrence of water on earth in all three phases, the energy balance of land surfaces, the retention of soil moisture, and the transport of solutes.

In contrast with the nonsotropic model of the physical chemist, the study of the deformation and movement of water based on continuum mechanics uses a model incorporating a fluid which is assumed to be completely isotropic. This single assumption is sufficient to reduce from 36 to 2 the number of material parameters required to describe the behavior of a Newtonian fluid [Dooge, 1983]. The contrasting nature of the fundamental assumptions at the molecular scale and the continuum scale is a warning to hydrologists to question their preconceptions that derive from hydraulics before applying them on a hydrologic scale. To predict catchment behavior reliably we must either solve extremely complex physically based models which take full account of the spatial variability of various parameters or else derive realistic models on the catchment scale in which the global effect of these spatially variable properties is parameterized in some way. The former approach requires extremely sophisticated models and exceedingly expensive computers to have any hope of success. The latter approach requires the discovery of hydrologic laws at the catchment scale that represent more than mere data fitting. This is, indeed, a daunting research task.

As is indicated in Table 3, there are scales beyond the hydrologic. Those interested in the problems of climate require from the hydrologist models capable of representing land surface processes by a few parameters on a grid square of $400 \times 400$ km in a general circulation model of the earth’s atmosphere [Eagleson, 1982a]. Already, a hydrologic-atmospheric pilot experiment (HAPEX) is being planned on a scale of $100 \times 100$ km to assist in this task [World Climate Research Programme, 1983, 1985]. The hydrologic time
scales in Table 3 are those appropriate to direct catchment response; for glaciers and for groundwater and for geomorphological processes, much longer time scales are involved [Schumm and Lichty, 1965; Gregory and Walling, 1973; Martinec, 1985]. The relationship between space and time scales is also important for climatic studies at these longer time scales [Clark, 1984].

The history of science suggests that progress is not made by a continuous progression from one scale to another. Klemes [1983] points out that science in antiquity was largely concerned with observation on a human scale and emphasis the point that the subsequent development of science did not progress uniformly from this human scale through larger and larger scales in one direction and through smaller and smaller scales in the other. He points to the fact that in the one direction the key problems of the scale of the solar system were solved before those of the global scale and in the other direction problems involving interaction between atoms were solved before problems involving interaction between molecules. In each of these cases, success was first obtained on a system which corresponds to the category of simple mechanisms on Figure 3 in section 2.3 above. If in hydrology we are unable to build up from the hydraulic scale to the various hydrologic scales we may be forced to skip some scales and seek entirely new laws of hydrologic behavior.

3.2. Parametrization of Microscale Effects

If a system is entirely linear, then the equations for conditions at a microscale can be spatially integrated over a specified area to give a relationship for the average values of the dependent variable at the macroscale model, and the parameters at the macroscale are the spatial averages of the corresponding parameters at the microscale. This facility is of no great practical advantage, since in such cases the linear equations can with equal ease be formulated initially at the macroscale. However, the problem of parametrization at the macroscale becomes extremely difficult if the process is nonlinear, as are most hydrologic processes, or if the boundaries of the fluid phase are ill-defined, as in flow through porous media.

It is necessary to realize that there is already a degree of parametrization in the equations used to describe hydrologic processes at a point in a catchment. The basic equations governing the motion of water or any other Newtonian fluid are the Navier-Stokes equations which are nonlinear. However, these equations cannot be applied directly either to free surface flow or to flow through porous media. In the case of free surface flow, hydraulics and hydrology both use the one-dimensional St. Venant equation, which involves the neglect of acceleration in two of the three directions and the incorporation of the effect of velocity distribution into a momentum coefficient. More serious than these assumptions is the effect of turbulence which produces a flow pattern so complex that solution of the Navier-Stokes equation is impossible. The alternatives are to develop a theory of turbulence which would involve large-scale computer simulation [Rodi, 1980] or to assume on the macroscale some empirical relationship giving the average boundary shear in terms of the channel geometry and the mean flow variables.

In most cases of flow through porous media, the flow is slow enough to be laminar and the Navier-Stokes equation remains useful. In practice, Darcy’s equation represents a dropping of the acceleration terms (thus removing the nonlinearity), followed by a double integration of these simplified Navier-Stokes equations [Bear, 1972]. The linking of the hydraulic conductivity which is a macroparameter to the microparameters of the porous media structure has been tackled using both deterministic and probabilistic models but remains a daunting problem.

Hydrology has attempted to model the runoff process at catchment scale by using simple conceptual elements for modules of the catchment. Thus prior to the advent of computers, the routing of flows through open channels was carried out by practical hydrologists by means of linear conceptual models such as the Muskingum method or the Kalinin-Milyukov method. For the case of uniform channels the bulk parameters of the macroscale conceptual models can be derived from the microscale hydraulic parameters for the linear case [Dooge and Harley, 1967; Dooge et al., 1982, also J. C. I. Dooge, unpublished manuscript, 1980]. The latter paper gives the solution for any shape of uniform channel and for any friction law.

The assumption of linearity in the common methods of hydrologic routing is a restrictive one but there are some indications that an aggregate of large number of nonlinear elements may exhibit linear behavior in the same way as an aggregation of a large number of nonisotropic water molecules may exhibit isotropic behavior at the scale of continuum mechanics. It has been possible to adapt equations from fluid mechanics to solve problems in hydraulics without being able to make a direct link between behavior on the microscale and behavior on the macroscale. In attempting to move from the hydraulic scale to hydrologic scale the same approach may be possible but has not yet been achieved.

3.3. Dimensional Analysis

In hydraulics the use of dimensional analysis greatly facilitates the planning of experiments, the compact organization of empirical data, and the comparison of hydraulic systems of widely different scale. Unfortunately, in hydrology we have not established any principle of similarity for catchment behavior and thus are in the situation that persisted in hydraulics 100 years ago before the introduction of the Reynolds number and the Froude number. The reporting of experimental results on pipe flow or channel flow at that time involved difficulties of presentation that are matched in catchment hydrology today.

Since flood runoff from the catchment is a phenomenon of flow with a free surface, if dimensional analysis is to be applied to catchment hydrology, the obvious candidate for consideration is the Froude number. If a distinction is made between vertical and horizontal lengths (corresponding to the distorted scale model in hydraulics), the effect of area and slope on the time to peak and the peak discharge according to the Froude number criterion would be

\[ t_p = \text{const} \; A^{1/4} S^{-1/2} \quad (1a) \]

\[ Q_{\text{max}} = \text{const} \; A^{3/2} S^{1/2} \quad (1b) \]

A comparison of (1a) with (1b) indicates that the constancy of the depth of rainfall on the two catchments is automatically maintained.

The Froude number criterion with geometrical similarity was applied to flood peaks and times to peak by McCarthy [Johnstone and Cross, 1949], O’Kelly [1955], and Erzen [Langhaar, 1960]. Extension to include slope and use (1) was
suggested by Dooge [1955]. The problem is complicated by such factors as the high dependence between slope and area in most regions, the variation in the form of this dependence for regions with different climate, and soil characteristics and the characteristic horizontal scale of the storm rainfall in the region. Thus the hypothesis underlying (1) (or any similar hypothesis) can only be falsified or confirmed by the compilation of carefully chosen catchment data and rigorous statistical interpretation of it.

The defect in the direct use of hydraulic dimensional analysis as above is that it ignores the fact that a catchment is a highly complex system whose form, drainage network, ground slope, channel slopes, and channel sections all represent the result of geomorphological adaptive processes. It may well be that further work in the vital task of studying scale effects in catchment behavior could benefit from a review of studies on scaling laws in adaptive systems studied in other disciplines.

Biological is a fruitful source for examples of the dimensional aspects of adaptive systems [Thompson, 1917; Schmidt-Nielsen, 1975; McMahon and Bonner, 1983; McMahon, 1984]. An approach similar to that outlined for catchments above would suggest that for animals oxygen uptake, heat production, and heat loss would be proportional to the square of some characteristic length and that the mass and the cross-sectional characteristic (D) bone or of muscle tends to be constant in all animals, the strength of elastic similarity, needed for safety against buckling when running, requires that the cross-sectional characteristic (D) is proportional to three half power of the characteristic longitudinal length (L). If the metabolic rate is taken as proportional to the cross-sectional area of muscle, then Kleiber’s three-quarter law as given in (2b) results. It is of interest to note that when the world records for weight lifting are plotted against the top body weight in each class, the points lie extremely close to a line with the slope of three quarters [McMahon and Bonner, 1983]. A final point of interest in relation to this example is that ecological studies indicate that within a given area the density of animals of any species is inversely proportional to the three-quarters power of their mass. A combination of this result due to Damuth [1981] with Kleiber’s Law indicates that the amount of heat production per unit area is a constant so that no species has an energetic advantage.

3.4. Search for Laws on the Macroscale

Instead of working from a microscale upward toward a macroscale of interest, one could attempt to find simple equilibrium laws at the macroscale in much the same way as in the statistical mechanics approach. If this could be done successfully, then the scale of interest would be bounded from above as well as from below and the hope of making substantial progress would be greatly improved.

The first notable step toward the development of hydrologic laws on a catchment scale was the now classical paper of Horton on quantitative geomorphology published in 1945 [Horton, 1945]. In this paper, Horton put forward, on a deterministic basis, laws of drainage composition stating that for a given channel network both the number of streams of successive orders and the mean length of successive orders of streams could be approximately represented by geometrical progressions.

In contrast to Horton [1945], who formulated his laws of stream composition on a deterministic basis, Shreve [1966] introduced the idea of a random population of channel networks. He defined as a topologically random population one in which all topologically distinct channel networks with a given number of sources are equally likely [Shreve, 1966]. It will be recognized that this approach closely mirrors the Gibbs postulate in statistical mechanics. Shreve [1966] developed formulae for the relative probability of different sets of stream numbers in such a population and showed that the most probable networks are in accordance with Horton’s [1945] law of stream numbers. Gupta and Waymire [1983] have shown analytically that as the size of the sample from an infinitely large topologically random network increases, the expected bifurcation ratio approaches the value 4. Empirical studies of actual catchments indicate bifurcation and ratios fluctuating about this value.

The linking of catchment characteristics to hydrograph parameters is a constant endeavor of the practicing hydrologist. The development of laws of drainage composition, first, on an empirical and deterministic basis, and later on a theoretical and statistical basis, lead naturally to the question as to what would be the characteristic shape of the hydrograph for a catchment obeying Horton’s or Shreve’s laws of drainage composition. Rodriguez-Iturbe and Valdez [1979] used a state transition approach and numerical experimentation to solve this problem. Typical of the results obtained by them was a relationship between the product of the unit hydrograph peak and time to peak and the bifurcation ratio (R_b) divided by the area ratio (R_A):

\[ Q_{\text{max}} = 0.58 \times R_b \times R_A \times 0.55 \]

Further work is continuing in this field which represents one
possible route to the development of hydrologic laws on a catchment scale.

Another notable attempt at describing behavior at the catchment scale is that due to Eagleson [1978], who tackled the problem of the long-term water balance using a stochastic-dynamic approach. By using representative probability density functions for the climatic variables such as the interstorm interval, the storm duration, the rainfall intensity, and the potential evapotranspiration, Eagleson derived from simplified assumptions in regard to the hydrological processes the probability density functions of the actual infiltration during storms and the actual evaporation between storms. On the basis of this approach Eagleson was able to relate the key ratio of actual over potential evaporation to five parameters, three of them related to the soil and two to the vegetation.

In a further development Eagleson [1982b] suggested that information concerning the space average and the time average of the actual evapotranspiration could be deduced from the state of the vegetation canopy. Noting that soil moisture reached a maximum at an intermediate canopy density [Lvovich, 1979; Eagleson, 1978], he introduced the hypothesis that a water-limited system of vegetation would produce a canopy density that led to minimum water stress for the given climate and soil conditions. For the case where the vegetative biology is limited by available energy rather than available water, Eagleson [1982b] introduced the hypothesis that the vegetation system would tend to maximize the productivity of biomass for the given amount of energy and thus producing a maximum vegetative density.

By applying these hypotheses to his 1978 model, Eagleson [1982b] derived the equilibrium conditions shown in Figure 5 for the relation between the species dependent plant coefficient and the vegetation canopy density. Preliminary results tend to confirm these curves both for humid and semiarid conditions [Eagleson and Tellers, 1982].

The discussion in sections 2.1-2.4 above on general approaches to the analysis of mechanisms and aggregates and of intermediate systems and the review in sections 3.1-3.3 above of the dependence on scale of the available models of the properties and movement of water provide a context for an evaluation of the historical development of hydrology and a background for the development of a research strategy in hydrology. The remainder of the paper will be devoted to a review of the historical development of techniques in flood hydrology against this background and some brief comments on lessons that might be learned and how research programs might be planned.

4. Seeking Regularities in Flood Hydrology

4.1. Use of Empirical Formulae

The search for regularities in the frequency of occurrence of extreme flood events had tended to follow one of three paths: a purely empirical approach based on measured flows and catchment characteristics, the fitting of frequency distributions to selected flood measurements and their extrapolation, or the derivation of a design storm of high-return period and the estimation of the corresponding flood magnitude. None of the three approaches has proved markedly superior to the others and none of them has proved as reliable as the designer of a water resources project would wish.

The use of empirical formulae relating the maximum flood of any defined return period to catchment characteristic has a long history, and many formulae have been proposed. One of the earliest of these was due to O'Connell [1868] and it is interesting that he starts from the concept of similar basins of varying size:

If a series of natural basins could be found increasing regularly in area, having natural features as the slope soil, etc. all tending in the same degree to discharge the rain falling on them and if the distribution of the rain was the same in all these basins, then doubtless the rate of discharge in floods might be represented graphically by some regular curve, the abscissa of which would represent the area drained and the ordinate the flood discharge per second.

O'Connell confesses himself unable to proceed in this way due to lack of suitable data:

Such however are the diversities of physical features in river basins and in the distribution of rainfall in the world that the search after the desired series of natural basins possessing exactly similar characteristics would probably be a vain one. This is to be regretted for rivers small and great might alike be referred to some such curve and classified as flood discharge, according as they took up position near to or distant from the curve.

O'Connell decided that in the absence of this information he would assume that the curve had the simple form of a parabola, and he accordingly wrote his empirical formula for the maximum discharge in terms of the catchment area as

\[ Q_{\text{max}} = \alpha A^{1/2} \]  

and calculated the value of the constant of proportionality for a considerable number of maximum observed flood flows which had been published for the major rivers of the world.

The first systematic attempt relating floods of any particular return period to catchment area on the basis of a reasonable amount of data seems to be that due to Fuller [1914]. He related the average of the annual maximum floods \((\bar{Q})\) to the four fifths power of the catchment area \((A)\):

\[ \bar{Q} = CA^{0.80} \]  

and related \(Q_T\) the annual maximum of return period \(T\) to this mean annual maximum \(\bar{Q}\) by

\[ Q_T = \bar{Q}(T/\text{mean annual flood})^{1/2} \]
It is interesting to note that in the case of the Flood Studies Report [National Environmental Research Council (NERC), 1975] in the United Kingdom carried out half a century later the best relationship found for relating the average flow value ($Q_{\text{max}}$) to catchment area was quite similar

$$Q = 0.677 A^{0.77}$$

The question of such regional relationships is discussed at some length in chapter 5 of the United Kingdom's Flood Studies Report [NERC, 1975]. We have already seen in section 2.2 above that the assumption of geometrical similarity would suggest a value of 0.75 for the exponent of the catchment area ($A$) which is quite close to the values obtained by Fuller [1914] and in the Flood Studies Report [NERC, 1975].

If two catchment characteristics are used, then some measure of catchment slope is nearly always taken along with area. As early as 1853, Hawksley [1853] suggested the formulae

$$Q_{\text{max}} = CA^{0.75} S^{0.23}$$

More recently, the Flood Studies Report (NERC, 1975) found

$$Q_{\text{max}} = CA^{1.19} S^{0.84}$$

Benson [1962], using linear regression on 164 catchments in New England, found for the annual maximum flow

$$Q_{\text{max}} = CA^{1.05} S^{0.84}$$

Benson [1962] was able to improve the fit of his linear regression by introducing the additional catchment characteristics of lake storage, an orographical factor, and a temperature factor. In the Flood Studies Report [NERC, 1975] the most significant additional parameters were found to be a stream frequency factor and an urbanization factor followed by three other catchment parameters.

While empirical relationships of the type described above give an estimate of a flood of a given return period in a given region which is better than pure ignorance, undue reliance should not be placed on such estimates. The predictive power of such empirical formulae is often quite low. Until we know more about the regularities underlying catchment morphology, we cannot be certain that the characteristics which we are using to grind out the regression relationships are the most suitable ones. The search for regularities might more profitably take the form of a search for significant laws of catchment morphology rather than the search for recurring values of coefficients produced by forcing the data into the straitjacket of linear regression.

Procrustes, a giant who lived near Eleusis in Greece, stretched his visitors if they were too short for the bed and lopped off their extremities if they were too long. Eddington [1939] in a warning against simplistic theories and nondiscriminatory measurement suggests that on the following morning Procrutes may have measured up these adjusted victims and written a learned paper "On the uniformity of stature of travellers" for the Anthropological Society of Attica. Many reported regressions in hydrology seem to follow the same tradition.

It should be well worth while to seek ways of incorporating considerations of dimensional analysis into the formulation of the variables which are subjected to the automatic process of linear regression. The use of factor analysis or principal component analysis is not of any great assistance in this connection, since it depends completely on the data and has like linear regression itself a tendency to follow the noise of the data as well as the underlying signal. In dealing with the problems of catchment hydrology we are at a distinct disadvantage in that we do not know the underlying laws of catchment morphology and thus are in the same position of confusion as hydraulic experts were in regard to the flow in pipes or channels before they knew of the Reynold's number of the Froude number. We still have to discover our topographically significant dimensionless variables. There is a distinct possibility that we will find, as in the case of the size of mammals referred to in section 2.2, that the actual dimensional relationships are close to but not identical with the relationships based on geometrical similarity.

4.2. Use of Frequency Distributions

Hazen [1914] introduced the idea of plotting the series of annual average flows on probability paper. At first he used arithmetic probability paper on which the normal distribution would plot as a straight line. He later changed to logarithmic probability paper, on which the lognormal distribution would plot as a straight line, since his observed annual maximum series showed much less curvature when plotted in this way. Foster [1924] was the first to tackle directly the question of skewness in flood distributions and to recognize that the estimate of the coefficient of skew was dependent on the length of the series. Foster suggested the use of the Pearson type III distribution as suitable for representing the typical skewness of flood distributions.

Transformations of the distributions mentioned above have also been used in flood analysis. The most important of these are the power transformation of the gamma distribution [Kritski and Menkel, 1950] and the logarithmic transformation of the Pearson type III [U.S. Water Resources Council (USWRC), 1967]. The Wakeby distribution introduced by Houghton [1978] seems capable of reflecting some of the properties of historical samples of flood data better than the distributions previously used, which is not surprising, since it is a five-parameter distribution. A few authors [e.g., Hall and O'Connell, 1972] have suggested the alternative strategy of fitting a stochastic model to the full sequence of observed flows and then using simulation to study the behavior of the extremes of large numbers of realizations of the assumed process.

The concept that the distribution of extremes of samples would approach asymptotically a form which is independent of the underlying distribution was introduced to hydrology by Gumbel [1941, 1958]. Though Gumbel mentioned all three forms of the asymptotic extreme value distribution, hydrologists concentrated on the application to flood estimation of the type I distribution. Jenkinson [1955, 1969] proposed a generalized extreme value distribution with three parameters which reduces to the type I extreme value distribution (commonly known as the Gumbel distribution) when the additional parameter is zero. More recent publications on extreme value theory [de Haan, 1976; Karr, 1976; Galambos, 1978; Leadbetter et al., 1982] are a source for suggestions of one way in which statistical theory could be combined with new knowledge on catchment morphology to make progress in this area.

The two basic problems in flood frequency analysis are the
choice of distribution and the estimation of the parameters for the chosen distribution. The latter problem is largely one of statistical techniques and involves a study of the efficiency and possible bias in parameter estimators for small samples and a study of the robustness of both sample estimators and candidate distributions. A recent review [Cunnane, 1985] suggests that the general extreme value distribution and the Wakeby distribution are distinctly more robust than other distributions. However, no amount of statistical refinement can overcome the disadvantage of not knowing the frequency distribution involved. As Moran [1959] puts it, 'Gumbel's distribution depends solely on the form of the tail of \( f(x) \) which, as we have just seen is usually outside the range of observations and can only be guessed at. No amount of mathematical presdigitation can remove this uncertainty.' Moran goes on to stress the importance of keeping sharply in mind what kind of probability statement we are making.

From time to time a number of heuristic arguments have been put forward in favor of one or other forms of frequency distribution. Many of these depend on the assumption that the asymptotic properties of a particular procedure will hold for a sample size well short of that at which theory would indicate that the asymptotic properties might be expected to hold. Thus the classical central limit theorem could be invoked to justify the use of the normal distribution for representing floods as the superposition of a large number of small random events. This hypothesis of normality is negated by the evidence that the distribution of floods is usually heavily skewed. Chow [1954] adapted the central limit theorem by suggesting that floods are the result of the product rather than the addition of a large number of small factors of unknown statistical distribution thus providing some justification for the use of lognormal distribution. Kalinin [1971] argued from the considerations (1) that alternative wet and dry spells of fixed but unequal probability would generate a binomial distribution; (2) that as shown by Velikanov [1962], continuous interpolation of this binomial distribution of rainfall would give a gamma distribution; and (3) that nonlinear catchment response would convert this gamma distribution to a transformed gamma distribution as represented by the Kritski-Menkel distribution.

It is possible to dismiss these arguments as post-hoc rationalizations designed to support a choice of distribution already subjectively made. However, models designed to link various forms of frequency distribution with assumptions of a more hydrological nature are certainly worth exploring [Eagleson, 1972; Klemes, 1978; Zhu Yuansheng, 1985]. An example is the extension of the ideas underlying a geomorphic unit hydrograph to the problem of the probabilities of extreme flows. [Hebson and Wood, 1982; Daczyn-Dobrawa et al., 1984]. Though the approach is worth pursuing, a great deal of development and assessment is still required [Bras, 1985].

4.3. Use of a Design Storm

The existence of longer records of rainfall and of climatic homogeneity over extended areas has encouraged the development of expressions for rainfall of a given return period which could be used as a basis for predicting the corresponding flood event. The rational method for estimating maximum flood peaks first put forward by Mulvaney [1851] is the earliest model in this category. Mulvaney defined the concept of the time of concentration and put forward the proposition that the maximum flood could be taken as that corresponding to the maximum rainfall of a duration equal to the time of concentration. In this early form of the rational method, the design storm was taken as the maximum recorded rainfall of the required duration in the region. An elementary form of storm transposition was thus involved, since the rainfall intensity was often taken from a rain gauge well outside the catchment of interest. The conversion from rainfall to runoff was through the crude model of the runoff coefficient \( C \) which in those early days was often taken as one third for flatter catchments and two thirds for steepish catchments.

Later empirical formulae for the maximum rainfall of a given duration in a given region were derived in many parts of the world and used in connection with the rational formula. The direct linking of rainfall and runoff for events smaller than the maximum was a natural development from the crude approach of the elementary rational method. In a number of regions, rainfall records were used to produce empirical relationships expressing rainfall depth or intensity as a function of duration and return period. In many of these cases the rainfall records were fitted by a frequency distribution such as the extreme value type I or the gamma distribution and extrapolated to higher return frequency. Typical of such a study is that carried for the United States by Hershfield [1961].

One difficulty in regard to the use of estimates of storm rainfall of given return period is the fact that the return period of a large flood is not necessarily the same as the return period of the excessive rainfall causing the flood event. To overcome this difficulty it is necessary either to study the relationships between the frequency distribution of major floods for a simple catchment model [Nash, 1956; Eagleson, 1972] or to redefine the original rational method so that the runoff coefficient \( C_T \) is not the runoff coefficient for any individual storm but the ratio of runoff for the given return period \( T \) to rainfall of the same return period.

An alternative approach which has attracted the interest of a number of hydrologists involves an estimate of 'probable maximum precipitation' which has been defined as [World Meteorological Organization (WMO), 1973; Hansen et al., 1982] 'The theoretically greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location at a particular time of year.' This approach assumes a model for the design storm based on convergence, lifting, and condensation and seeks to maximize all three factors [Bernard, 1944; Wiesner, 1970; WMO, 1973, Hansen, 1985].

Since moisture maximization is based on increasing the dew point (which is a measure of the precipitable water) from the observed value in the major storm of record to the maximum recorded dew point in the region, the frequency distribution of high dew points is implicitly involved. The moisture maximization is sometimes supplemented by convergence maximization based on an increase from observed wind speeds to the maximum wind speed of record. Finally, there is the critical step of transporting the worst storm in the region from the site in which it actually occurred and placing it over the catchment of interest.

Anyone using such methods would be well advised to study the paper by Willeke on the "Myths and uses of hydrometeorology in forecasting." Willeke [1980] suggests that there are four major myths that occur in the estimation
of extraordinary flood events by hydrometeorological methods. The first myth which he describes as the "Myth of the Tails" is 'statistical distributions applied to hydrometeorological events that fit through the range of observed data are applicable in the tails.' This difficulty also arises in the direct application of statistical distributions to flood events and reminds us of the need to remember the tails of distributions as highly uncertain [Kaczmarek, 1957; Nash and Amoroch, 1966].

Willeke's [1980] second myth is the "Myth of Infinitesimal Probability," which reads, 'The probability of occurrence of probable maximum events is infinitesimal.' In commenting on this myth, Willeke draws attention to the difficulties in using Chow's frequency factor \( k \) [Chow, 1951] in cases where the variance by which it is multiplied is not known with high accuracy.

Willeke's [1980] third myth is the "Myth of Impossibility": 'Hydrometeorological estimates of stream events are so large they cannot or will not occur.' Here he points out that a number of storms have been recorded in the United States which exceeded the estimates of probable maximum precipitation. He also comments that this method is a direct contradiction of Murphy's Law which is quoted in section 2.3 above, which seems to be empirically well established.

The final myth in Willeke's [1980] listing is the "Myth of Stationarity": 'The distribution of events is not changing in a trend, cyclic, persistent or catastrophic fashion.' The fact that the climate has changed and will change forces us to consider carefully the meaning of our probabilistic statements. Willeke stresses the importance of considering our hydrologic model in the context of decision making and of the role of sensitivity analysis in this context.

4.4. Conclusions

The above discussion is intended as a background to a consideration of the extent to which present practice in flood hydrology is scientifically based and of the direction in which an effort to improve the situation might best be made. The present section summarizes the personal conclusions of the author on these two questions.

Flood hydrology at the present time draws both on a microscale approach based on continuum mechanics and on a macroscale approach based on the statistical study of large aggregates. Neither approach is entirely appropriate to catchment hydrology, which involves systems intermediate in size between the local scale of hydrologic physics and the global scale of a major geographical region. Nevertheless, the microscale and macroscale approaches are relevant to the formulation and verification of hydrologic laws at the intermediate mesoscale of the catchment. This is obviously true if the laws of catchment hydrology are to be based on a parametrization of the microscale nonlinear equations of physical hydrology or on a disaggregation of long-term macroscale equilibrium relationships or on a combination of both these approaches. It is equally true if the attempt is made to derive special hydrologic laws on the catchment scale, since results from microscale hydrology and macroscale hydrology can be a source for the generation of analogous hypotheses at the mesoscale of catchment hydrology.

If results are to be obtained at the catchment scale that contribute toward developing hydrologic laws rather than the fitting of empirical expressions to data with an unknown signal to noise ratio, then the scientific method must be followed either explicitly or implicitly. The first step in such a venture must be the generation of plausible hypotheses that can be tested. One group of such hypotheses can be developed by attempting to combine the nonlinear equations describing hydrologic processes at a continuum point with simple assumptions concerning the variation of the microscale parameters. In such an approach, it may be possible to simplify considerably the models of the various microscale processes and the variation of the microscale parameters without reducing significantly the predictive power of the resulting mesoscale model. Another group of hypotheses for catchment scale hydrology can be generated by working downward from the macroscale by disaggregation, of global scale relationships relating to such factors as soils, vegetation, drainage networks, rainfall patterns, energy budget at the land surface, etc. In this case also, a start should be made with simple hypotheses which should only be abandoned when proved inadequate by careful testing. A third source of hypotheses on catchment flood behavior for testing is disciplines other than hydrology in which similar problems involving scale have been encountered. The need for a deep study of geomorphic processes in this connection is obvious. The results of adaptation revealed by ecological systems may appear less relevant but could prove equally fruitful.

The generation of hypotheses is the necessary prelude to prediction and the rejection of a hypothesis or its incorporation in an accepted paradigm. At first sight, the testing of any hypothesis concerning flood frequency seems an impossible task because of the limited length of record available. The situation in this regard is now changing. The range of proxy data used in paleohydrologic analysis has been extended from pollen analysis and tree rings that gave information on general climate and its annual fluctuations to include analysis of surviving flood sediment deposits which can provide evidence of both the magnitude and the dating of prehistoric floods. Such information is an extremely valuable adjunct to instrumental data used for the calibration of existing methods in flood hydrology. In addition, satellite data is now available which increases greatly our bank of knowledge both in respect of prehistoric landforms and of current geomorphic and hydrologic processes. To extract the maximum amount of information from the available data it is necessary to formulate clear hypotheses and to deduce from them unequivocal predictions that can be tested against the data by rigorous statistical techniques.

Those elements of present flood hydrology that are soundly based on deductions from hypotheses confirmed by data either hydrologic or nonhydrologic would contribute in varying degrees to a scientific theory of flood hydrology at the catchment scale. It is obvious that a good deal of work needs to be done to develop such a theory through synthesis and new inspiration. It is appreciated that in the interim practical hydrologists must continue to use existing techniques to solve problems of economic and social importance. However, the endeavor to produce such a theory would be well worthwhile. It would improve our understanding of hydrologic phenomena, improve our decision making in relation to water resources, and improve our standing among geophysicists. To accomplish it, we require a broad background knowledge of our own subject and of cognate subjects and a real capacity both to think imaginatively and to
work hard. Even these capabilities might not be sufficient without a grand strategy of research within which the individual hydrologist could work. There is a real challenge therefore not only for the individual hydrologist but also for such bodies as the American Geophysical Union and the International Association for Hydrological Sciences. Hydrology can establish itself as a science but not without a degree of organization in planning and in thinking that has not been evident before now.

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