ELECTRICAL ANALOG MODEL FOR ANALYZING WATER-SUPPLY PROBLEMS

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The goal of all types of management is to improve or obtain maximum benefits from resources for the society in which we live. This role of management is much the same no matter what resource is concerned. Management of mental or physical capabilities of people, of factories producing goods, of farm land, of minerals dug from the earth, has the improvement of society as its ultimate goal.

A given resource will be used effectively only if the effort required to shape the resource into a useful product is less than society is willing to exert so as to gain the product. We might illustrate this by citing the simple act of driving a nail. A nail could be driven with a rock--a piece of iron ore, for example. But it is more convenient to process the iron ore and construct from it a hammer to simplify the chore of driving a nail. The conversion of iron ore to a particular shape and chemical characteristic is a fundamental management decision. The advantage to be gained in using the hammer outweighs the effort required to make the hammer, and therefore it is common practice to drive nails with hammers rather than with chunks of rock. Nearly every facet of our society has developed from such choice--or management.

The term water management is being seen in print and heard in conversation more frequently throughout the country as competition for water increases. Embodied in this term are all the frustrations and hopes of every water user. Some, frustrated by a water shortage, hope that water management will reduce or eliminate such shortages. Those struggling with deteriorating water quality hope that water management will somehow put some sparkle back in the streams. People using large quantities of water for economically marginal production hope water management will reduce their water costs, thus increasing the economic yield from their facilities. These are but a few examples of the many difficult tasks assigned to what is so often blithely called water management. I use the word "blithely" here, because it now seems to be more fashipnable than practical to approach the solution of many water-supply problems by improved water management.

To be effective, management decisions must be founded on fairly complete information of two different kinds: (1) the demands of our society, and, (2) the limits and characteristics of our resources under natural conditions and under conditions that might be created by human effort. Without adequate information of this type, people cannot judge whether a given resource can be applied effectively in a given way for improving society.

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In the field of water management, we have the same basic need for information on the demand and characteristics of supply. However, the issues are not easily defined. Many water-development plans are judged by the "cost-to-benefit ratio"--philosophically a very elementary means for judging if a proposed water-development plan will actually be of benefit to society. If all plans could be evaluated completely by such a means, there would be few unresolved questions in water management. Natural conditions are invariably changed by man's use of water and, just as invariably, it is impossible to place a realistic price tag on a tumbling fish-laden mountain stream, on the serene beauty of a lake, or on the waters in so-called "unused" streams coveted by people in another drainage basin.

Because many of the changes in water distribution arising from full development of our water resources cannot be defined in terms of dollars and cents, water-management decisions must be founded on examination of a curious combination of economics, artistic appreciation for the beauty of the natural landscape and, perhaps less ideally, human emotions. Most of the framework for decision-making in water management is founded upon the so-called common law, which has resolved many of the basic and diverse artistic and emotional attitudes of men. The more tangible economic inequities arising from water use are also arbitrated in the courts by procedures defined in the common law.

The common law, as applied, might be visualized as a rather formal expression of the way people feel their society should function. In the construction of regulatory water laws, the artistic and emotional attitudes of men are reinforced by excerpts from the technology of hydrology. Thus, we see water management through legal process as being at least partly dependent on our understanding of the characteristics of the resource.

Economic studies made to supply management with information are more directly based on an understanding of resource characteristics than are regulatory laws.

It is clear that without an adequate understanding of the hydrologic system, effective water management cannot become a reality. Hydrologic information includes data on the occurrence of water, and data on its economic and aesthetic significance to the water user. Data on the occurrence of water help define the resource; data on significance help define society's need for water. Keeping in mind that effective water management must be based on both these types of data, the remainder of this talk will be devoted to defining the water resource.

Field studies of the occurrence of water generally are divided into the following three categories: precipitation and other climatic factors, water on the land surface, and water below the land surface. Man has had but very little success in deliberately controlling the climatic factors. However, analysis of climatic data collected over a considerable period of time allows the hydrologist to make reasonably accurate estimates of the amount of water that may be supplied from precipitation in the future. Among many other uses, such information is also applied to help describe the occurrence of water naturally on the land surface and underground as afforded by precipitation, uncontrolled by man.

Detailed knowledge of the occurrence of surface and ground water as created by climatic factors alone is of relatively small importance to water management. Management is concerned with redistributing water from its natural habitat to points where it can be used most effectively by man. Therefore it is equally important for management to understand how the redistribution of water is restricted by environmental factors, or how it may be improved by taking advantage of natural circumstances existing on and beneath the land surface. If, for example, a stream basin has a topography unsuitable for reservoir construction, environmental factors preclude surface storage of runoff for use during dry periods. If the porous rocks beneath this basin are highly permeable, the excess runoff during storm periods might be stored temporarily underground. These and many other uses of the environment in water development are well known to all of us.

It is evident that the environmental factors must be clearly defined before planning of large-scale water developments can be completely effective. General-purpose hydrologic studies already fill a part of this need for management data. Such studies have been made continually for many years in most areas of the United States to provide a general background of hydrologic data useful in planning almost any practical water development. Hence an immense store of information on water conditions is now available. More intensive studies made selectively during investigation of specific water-development projects have also contributed to the store of hydrologic data.

The great bulk of this information is in the form of individual measurements, such as of streamflow, discharge from aquifers, water stages, and the like. It is common practice to appraise the natural occurrence of water by analyzing there measurements. For example, we are aware that large groups of individual stream-flow measurements can be analyzed to find the probable frequency of floods, and the expected rates of discharge over selected time intervals. Analyses of this type are comparatively easy to accomplish--the hydrologist need only observe what has happened in the past, then apply his analysis with confidence to the future--provided man's use of water will not appreciably rearrange the water distribution naturally afforded by climate.

However, a fully developed water resource does not function according to the whims of nature. Indeed, the whole point of water control by man is to make water available for his use even when natural factors, uncontrolled by man, do not provide an adequate supply. Therefore, analysis of basic hydrologic information must be enlarged from emphasis on simply learning about the natural occurrence of water. As water development becomes more and more comprehensive, it becomes increasingly important to know accurately how the environmental factors can be changed and utilized by man so the natural distribution of water will be modified adequately to meet the demand.

Perhaps one of the most difficult problems faced by anyone undertaking such an approach is the problem of making predictions that indicate how the manipulation of environmental factors will affect or improve water availability. Because both the amount of water available to the system and the water demand are highly variable with time, predictions should foretell variations in the water supply with respect to time likely to occur as a result of a given development plan. Such predictions make management aware of the limitations on water supply inherent in proposed developments and, before construction begins, permit direct comparisons between the expected demand and the proposed managed supply.

If all pertinent factors in the hydrologic system remain constant as time passes, the system is said to be in the steady state. Such a system can be analyzed, but it is not ordinarily a simple matter to do so. Streamflow changes continually, and it is only rarely viewed as being in the steady state. On the other hand, for analytical purposes ground-water flow is frequently assumed to occur in the steady state. However, in a fully developed system ground-water flow is also changing continually and therefore it cannot be considered to be in the steady state any more logically than can surface water. It has been my belief that these seemingly opposite approaches to analyses of surface- and ground-water systems have their foundation in the relative difficulties of computation. Surface-water flow can be viewed as taking place along a single line in space, which represents the stream channel. Thus surface flow, varying with time, can be described by functions of only two dimensions--length and time. In most aquifers ground water flow is not confined to a long narrow channel but is free to move in any direction. To simplify our concept of ground water flow, we generally assume that it moves horizontally. To analyze even this simplified flow system requires two spatial coordinates for steady flow. Thus, mathematically it is just as difficult to study a highly idealized steady ground water flow as it is to investigate nonsteady surface flow fairly accurately.

Water distribution on and beneath the land surface is dependent on many factors. Thus, accurate predictions of the response of the hydrologic system to an impressed change in the pattern of water distribution are difficult to make. Most system analyses are performed on theoretical models which are very simple versions of the systems observed in the field. In all cases a simplification and consolidation of the myriad of detail observed is both necessary and feasible for making accurate predictions of response. However, accuracy is often sacrificed because the analytical difficulties posed by the problem are so great that the investigator simply "gives up." In such circumstances, the system generally is idealized to a form simple enough that the ordinary analytical techniques can produce a prediction of system response without undue expenditure of time. In the extreme, this does not produce a prediction of the response in the system we have tried to simulate--too often the idealized system we have concocted bears but slight resemblance to the field system, and the predictions made from the idealized system are not applicable in practical water management.

The technique most often applied by the hydrologist for making predictions involves selecting or deriving an equation which relates impressed change to the system characteristics and system response. The more complicated these factors are, the more complicated is the analytical equation and its derivation. As a general rule, analysis of combined surface- and ground-water flows by the analytical equation is not a practical approach. The mathematical model which adequately describes such flows is so complicated that the problem of deriving an analytical equation from it may seem to be more weighty than the problem of facing up to a water shortage periodically because of unenlightened management practice.

The science of hydrology has been eminently successful in providing management with relatively isolated and small bits of information indicating how various segments of the hydrologic system behave in response to change. However, each of these segments is dependent on all others, and unless all interactions are included in studies of system behavior, management operates with an incomplete concept of the system potential. Thus hydrologic data are often used very inefficiently even though every facet of the hydrologic system has been described in great detail as a separate item. One of the chief difficulties of the hydrologist striving to supply management with a truly comprehensive quantitative description of system behavior is that the simpler analytical techniques generally are ineffective, and the more complicated techniques overwhelm human capability. A change in the analytical approach is indicated as a possible means for making the hydrologist and his basic data more useful to management.

Much of the hydrologist's analysis is made from a mathematical model, as indicated earlier. The mathematical model is simply a creation of symbols and equations which in concert are supposed to behave mathematically in the same fashion as the hydrologic system behaves physically. The difficulty in using this type of model is that it must be manipulated according to prescribed rules of mathematics before an analytical equation can be obtained. The complexity of this manipulation is the immediate source of the hydrologist's trouble. Some flow problems are inherently so complicated that passage from the mathematical model to the analytical equation is not only impractical--it is impossible. Fortunately, it is unnecessary to plod along this fruitless avenue, because other types of models are far more efficient to use.

Viewing in mathematical form the laws of flow of heat, electricity, sound, and other forms of energy or matter transport, it is clearly evident that many are remarkably similar. That is, the response curves showing changes in flow have identical shapes if in each flow system the changes of flow at the boundaries and the shapes of the systems are identical. It can also be noted that the only difference among many such flow equations is the physical meaning ascribed to the symbols used and the values of constants contained in them. These identify the properties of the medium through which flow takes place and the properties of the substance or energy in transit. Thus the relative magnitudes of the constants are simply scale factors which indicate how much the response observed in one system should be shifted, amplified, or attenuated to obtain an estimate of response in another system. Recognizing, evaluating, and applying these scale factors form the complete basis for designing all types of models.

Because the laws of water flow are identical with the law defining many other types of flow, a great variety of modeling media are available to us for studying water-supply problems. Which should the hydrologist choose? The need is for a type of model which is (1) capable of automatically performing all the intricate manipulations required by the development of analytical equations, (2) relatively simple to design, construct, and operate, (3) versatile enough to produce flow predictions for a staggering variety of problems, and (4) moderately priced. Review of the possibilities for modeling the flow of water indicates that electrical models probably will be the most satisfactory. Widely published experiences with a variety of electrical model studies of open channel and pipe flow, and to a lesser extent of ground water flow, have shown their feasibility.

The analogy between flow of electricity and water is basically as shown in the following list. Each item of the electrical analog listed in the left column is proportional to the item opposite it in the right column.

Electrical-analog property	Water-system property
voltage	head
density of current flow	velocity
capacity	storage
resistance	viscous drag
inductance	momentum

One of the chief attributes of the electrical analog is the availability of ready-made components from which models may be constructed. Resistance, capacity, and inductance can be built into a model using standard parts that are mass-produced by the electronics industry and are available at low cost. Voltage and current measurements can be made in the analog using readily available laboratory and production-control instruments. Likewise, voltage and current can be controlled on the perimeter or at selected internal points of the model using commercially available regulating equipment. Thus the complete hydrologic system may be analogically duplicated by electronic components. The wide variety and excellent quality of components available bring all hydrologic problems within reach of practically useful analysis at moderate cost. Today, electrical analog devices can be constructed and observed with greater accuracy and detail than can be attained in field observation of hydrologic data.

Ground-water flow in confined aquifers is simply proportional to the ability of the aquifer to transmit water and the hydraulic gradient. Changes in head at any point in the aquifer cause a change in storage. Thus, referring to the list above, such flow through a given part of the aquifer can be simulated by resistors of fixed value which represent the viscous drag between the rock particles and water; and, the change in storage can be simulated by connecting a capacitor between the resistor net and an electrical ground. Surface water is somewhat more complicated to model because flow is not directly proportional to head gradients. For this purpose electrical components that change resistance nonlinearly with gradient or voltage may be applied. One such is the "varistor" which has much the same physical appearance as an ordinary resistor, but its resistance decreases approximately logarithmically as current flow through it increases. Another is the transistor, which can be combined with resistors to simulate the slope-stage-discharge characteristics of streams. Variable storage dependent on water stage can also be simulated by using a bank of biased diodes and capacitors, or special vacuum-tube circuits. There exists virtually an infinity of devices and combinations of devices by which the hydraulic properties of the hydrologic system can be modeled. We may say, without qualification, that any system or part of a system that is defined can be modeled electronically.

The people concerned with water in our nation have done a wonderful job of initiating and continuing a program of hydrologic-data collection. However, the analytical methods commonly used for translating basic data into predictions of response to full water development are inadequate. They do not provide water management with an adequate understanding of the consequences of man-made changes in water distribution. This is because the commonly used methods are at best capable only of describing the interrelationships between relatively few factors in the hydrologic system, and then only if these factors are of simple form and, of course, are known. It is suggested that the electric analog be used for predicting the response of the hydrologic system to proposed man-made changes. With such an analytical tool, the hydrologist can include all the pertinent hydrologic factors in his analysis. He may model the hydrologic system much more accurately than by mathematical methods, because few accurate and complete mathematical models can be analyzed successfully. The improved accuracy and comprehension of data analysis through electrical models should lead to better water management, which could lead to a more effective use of water for us all.