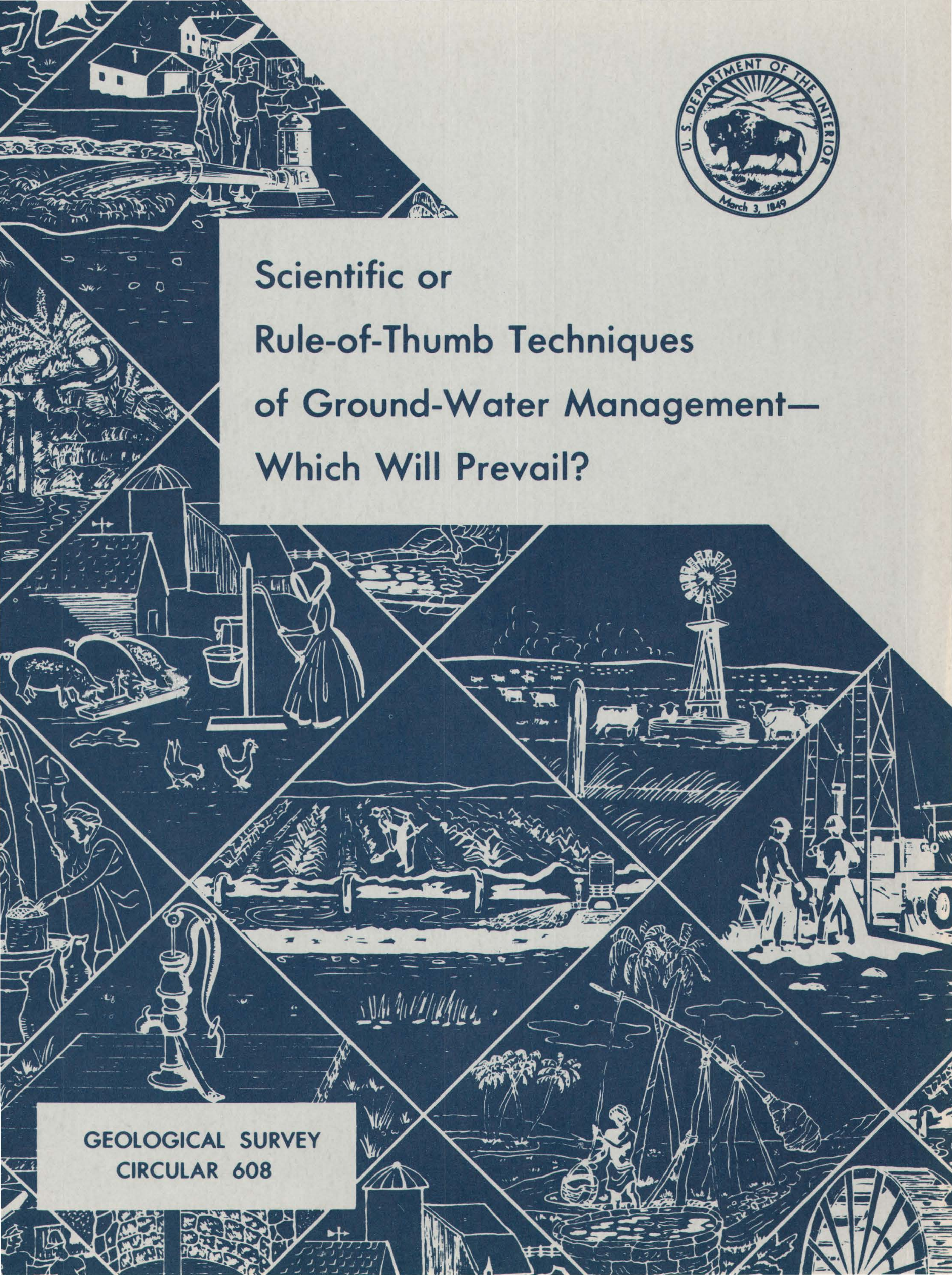

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Scientific or Rule-of-Thumb Techniques of Ground-Water Management— Which Will Prevail?

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By C. L. McGuinness

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ABSTRACT

Emphasis in ground-water development, once directed largely to quantitatively minor (but sociologically vital) service of human and stock needs, is shifting: aquifers are treated as possible regulating reservoirs managed conjunctively with surface water. Too, emphasis on reducing stream pollution is stimulating interest in aquifers as possible waste-storage media.

Such management of aquifers requires vast amounts of data plus a much better understanding of aquifer-system behavior than now exists. Implicit in this deficiency of knowledge is a need for much new research, lest aquifers be managed according to ineffective rule-of-thumb standards, or even abandoned as unmanageable.

The geohydrologist's task is to define both internal and boundary characteristics of aquifer systems. Stratigraphy is a primary determinant of these characteristics, but stratigraphically minor features may make aquifers transcend stratigraphic boundaries. For example, a structurally insignificant fracture may carry more water than a major fault; a minor stratigraphic discontinuity may be a major hydrologic boundary. Hence, there is a need for ways of defining aquifer boundaries and quantifying aquifer and confining-bed characteristics that are very different from ordinary stratigraphic techniques. Among critical needs are techniques for measuring crossbed permeability; for extrapolating and interpolating point data on direction and magnitude of permeability in defining aquifer geometry; and for accurately measuring geochemical properties of water and aquifer material, and interpreting those measurements in terms of source of water, rate of movement, and waste-sorbing capacities of aquifers and of confining beds—in general, techniques adequate for predicting aquifer response to imposed forces whether static, hydraulic, thermal, or chemical. Only when such predictions can be made routinely can aquifer characteristics be inserted into a master model that incorporates both the hydrologic and the socioeconomic facts necessary to intelligent social actions involving water.

INTRODUCTION

A quiet revolution—but a revolution nevertheless—is underway in the use of aquifers to meet human needs. Ground water has always been a high-quality resource—that is, it has commonly been used to meet high-value, high-priority needs such as for domestic and municipal water supply. Thus, even though in most highly developed countries ground water accounts for only a quantitatively minor share of the total withdrawal of water, its value has always been recognized as high—even incalculable—because in many places and situations there has been no feasible alternative source.

Now ground-water reservoirs are being asked to assume a larger and partly different role. As sources of naturally replenished water they are expected—and in many places are able—to yield larger amounts of fresh water to meet growing needs. But three additional and potentially important roles are now foreseen for them. One is the use of their vast storage capacity to accommodate large quantities of surface floodwater, incidentally to reduce flood damage but mainly to hold this water over from times of surplus to times of need. Another is the use of aquifers for the controlled storage of some waste products, as an alternative to other uses of these aquifers and to other methods of waste disposal. A third is withdrawal of saline water for desalination, in areas where fresh-water supplies are scarce.

[1] Prepared for presentation at the 23d International Geological Congress, Prague, August 1968.

At the outset, let me make clear that I believe firmly in the ability of ground-water reservoirs to meet the demands proposed to be put on them. The question is not whether they can do it, but whether they can do it at a cost which is less than that of alternatives and low enough that it will not create an undesirable drag on the economy.

Make no mistake about it. The economy of the United States, like that of other highly developed countries, is built in substantial part on inexpensive, readily available water. The people expect water to continue to be an abundant, low-cost commodity. Although they realize it will cost more than it used to, they are not willing for its price to rise high enough to cause a real reduction in their ability to buy other desired commodities.

Now I believe intuitively that ground-water reservoirs not only can meet the demands proposed to be put on them but can do so at reasonable cost and in many places at lower cost than that of alternative measures. But this is just an opinion. Between the assumption and the proof there is a substantial obstacle. It is that the need for information on the characteristics and capabilities of an aquifer goes up exponentially as the use of the aquifer increases from the moderate level associated with laissez-faire development of a part of its naturally replenishable supply to the higher (though, perhaps, not inordinately higher) level associated with near-maximum exploitation of its capacity.

To pull an example out of the air: It might be possible, in a year's time and at a total cost of $25,000, to study, and publish a description of, the basic ground-water capabilities of an area of a thousand square kilometers. The information might be adequate to form a sound basis for relatively casual, unplanned development of a total of 1,000 liters per second from 100 scattered wells, with only local difficulties due to inadequate spacing between wells.

But now, say that it becomes desirable to develop all the ground water that the area can comfortably yield on a long-term basis to a particular pattern of wells without artificial replenishment. This quantity might prove to be, say, 4,000 liters per second. Can this maximum-scale development be planned and managed effectively on the basis of additional studies bringing the total cost of ground-water investigations to $100,000? No indeed. Very likely a total of one to several million dollars would have to be spent over a period of several years to provide a sound factual basis for the water-management operations required.

The obstacle is not only financial. It involves time than can ill be spared. It involves the availability of trained ground-water hydrologists, of whom there is a shortage. And it involves hydrologic unknowns which may or may not prove to be amenable to clarification at a feasible cost in money, manpower, and time.

Small wonder, then, that there is widespread ignorance or uncertainty as to the role of ground-water reservoirs in tomorrow's water picture. Not enough hydrologic facts are available, and grave deficiencies still exist in the ability of hydrogeologists and water planners to communicate meaningfully with each other.

THE HYDROGEOLOGIST'S JOB

What does the hydrogeologist see as the deficiencies in knowledge it is his responsibility to remedy? At one time he had a rather simple job. He mapped the geology of his area, or refined mapping done earlier by others. He gathered as much information as he could on the depth and productivity of wells, the kinds of rocks they penetrated, and the kinds of water they yielded. He interpreted these data in terms of the subsurface stratigraphy and structure and of the water-bearing properties of the different geologic units. Ultimately, he prepared a report, maps, and charts showing where and at what depths water could be obtained, and, in a general way, how much and of what quality. For rocks not penetrated by enough wells in his area to yield reliable information, he extrapolated information from other areas where similar rocks were better known, according to his experience and his familiarity with the literature.

This procedure was fine for a start. As ground-water development progressed and demands became larger, he found it necessary to think in quantitative terms about the permeability and storage coefficients of the aquifers and the effects on ground-water levels of pumping increasing amounts of water from more closely spaced wells.

He tried to keep track of the effects of the withdrawals, not only on water levels but in diminishing natural discharge, perhaps increasing natural recharge, inducing the inflow of salt water or other water of undesirable quality, and so on. He discovered that it was not only water levels that were affected. In certain areas he found the withdrawal actually causing the land surface to subside.

Gradually, he began to realize that he was dealing with a *system*—a geologic-hydrologic-chemical-biologic system—in which substances and events of nature and the actions of man interreacted so complexly that only by understanding how the system operated could he predict its response to future events of nature and actions of man and, thus, provide a basis for controlling the response in desired ways.

This is where we are today. We are trying to define subsurface hydrologic systems in terms of their internal characteristics and their external boundaries, and to devise models of them that will simulate their response to various planned or otherwise anticipated events. Repeated tests of the models will reveal the fidelity of their simulation of the prototype, and will reveal also their sensitivity to data inputs of various types and thus serve as a guide to data-collection programs. In addition, the models will form the physical basis of the planner's overall model of the hydrologic-socioeconomic system.

THE GROUND-WATER SYSTEM

What is this ground-water system whose operation the hydrogeologist must understand? It is first of all a geologic system. It consists of rocks, consolidated and unconsolidated, formed and placed where they are by geologic processes. It is a hydrologic system because the rocks contain openings that can store and transmit water. It is a chemical system because the rock skeleton, far from being inert, reacts chemically with the water and its dissolved and entrained constituents, and in this reaction changes are produced in both the rocks and the water. It is a biologic system because living organisms play an important part in the chemical reactions that take place in it, or at least in determining the chemistry of the water that enters it.

The principal aquifers are sedimentary, and therefore the controls on their size, shape, and position and on their hydraulic properties are primarily sedimentologic and stratigraphic—primarily, but not exclusively. It is most important to recognize that it is the water and not the stratigraphy that makes the rules so far as definition of aquifer-system boundaries is concerned. Porosity and permeability may extend right across major stratigraphic boundaries. Thus, an aquifer conceivably could include, for example, Quaternary, Paleozoic, and Precambrian rocks and still be a hydrologic unit in spite of its stratigraphic heterogeneity.

On the other hand, a stratigraphically or structurally insignificant feature might constitute an important hydraulic boundary or conduit. A bed of clay so thin that it could hardly be seen in outcrop and would never be recognized in drill cuttings might divide a mass of permeable sand and gravel into two aquifers. A joint, only one of many, might carry more water than a major fault, clogged by its own clayey gouge.

The hydrogeologist therefore must "see it the way it is," as the currently popular saying goes. He must learn to identify the rock features that actually control the location and movement of subsurface waters in a given body of rock, and to define his hydrologic system on their basis rather than in the usual stratigraphic terms.

THE MODEL

To understand his system the hydrogeologist must make a model of it. If the "system" is an extremely simple situation, then the model too is simple, just a mental picture. The decision maker considers two or three alternative actions, visualizing their effects on the system, and makes his choice of actions according to the desired result and the costs and benefits—all mentally. Such a situation might involve the choice among a well, a cistern, and a solar still to obtain a domestic water supply. The information at hand might be adequate to enable an easy choice of one as much less costly than the others, or feasible where the others are not.

If the system or situation is a little more complicated, involving calculations that cannot be made mentally, it is possible that a simple mathematical model will do. For example, the problem might be to predict the drawdown to be anticipated if a well is located so as to draw, eventually, its water from a stream cutting an alluvial aquifer, yet be located at a certain minimum distance from the stream to achieve adequate filtration of the water to remove bacteria. The work of C. V. Theis (1941, p. 734), perhaps supplemented by that of J. G. Ferris (Ferris and others, 1962, p. 146–151) if the aquifer is narrow, forms an adequate basis if the transmissivity and storage coefficient of the aquifer can be determined or estimated.

Few situations are so simple. Generally, aquifer systems are complex, replenishment and natural discharge rates are variable and difficult to determine, there are existing ground-water developments that must be considered, there are possible quality complications resulting from waste-disposal practices or the presence of natural bodies of inferior water, there are economic or legal ramifications, and there is not enough information. Always, there is not enough information.

The problem now is to develop, at feasible cost and in feasible time, a model of the system—generally, a passive electrical analog or a digital computer, or a combination of these—that will operate like its prototype, and that can be tested for its response to the effects of various planned actions and for its sensitivity to the various kinds of data that must be gathered to refine it once its basic character is established. Such a model of the hydrologic system, supplemented by economic and social facts or assumptions, becomes the water planner's tool for scientifically correct—or at least scientifically generated—decisions as to how to attack problems (Skibitzke, 1967).

THE MOMENT OF TRUTH

For ground water the moment of truth arrives early. In many cases the question is not whether ground water can be used, but whether it use can even be considered, in view of the expense and time required to obtain enough information for a reasonably accurate assessment of costs, including the cost of side effects such as interference with other supplies or encroachment of inferior water; and of benefits, including benefits resulting from decisions such as that to leave a stream in its natural state instead of damming it up.

For the plain fact is that for too many areas we are not able to give the decision maker the facts he needs, in the form in which he must have them, for rational decisions and choices affecting ground water. In the press to make decisions now, he may choose ground water for its anticipated—or hoped-for—benefits, later to learn that his choice was a costly one. After one or two such experiences, he may be inclined in a new situation to avoid ground water—later, perhaps, to reach the same conclusion, that his choice was a costly one because ground water turns out to have been the preferable source after all.

Another plain fact is that ground-water studies cost money, and the more detailed the information needed, the higher the cost. Working with a "marginal" commodity such as water, one whose cost is low and is expected to continue to be low, it is not at all impossible that in a particular situation the cost of a study required to prove that ground water is the most economical source of water for a given use might raise the total cost of the development—cost of study plus cost of wells and pumps—to or above the total cost of developing the next most economical source.

But let us not downgrade ground water just because it is a difficult subject. There are situations where its potentialities are very clear and very great. Take Long Island, N.Y., for example. New York City is an area where desalination has been considered as one possible means of supplementing the fresh-water supply in the future. The lowest estimated production cost of desalted water I can recall is about 22 cents per thousand gallons (5.8 cents per m^3) for the 570,000 m^3/day plant to be built in southern California, and this expected cost is far less than any that have actually been achieved to date. Long Island has ground water by the millions of cubic meters per day. The recharge and natural discharge amount to perhaps more than 1 million gallons per day per square mile (1,460 $m^3/day/km^2$), or well over 1 billion gallons (3.8 million m^3) per day for the 3,600-km^2 island (Jacob, 1945, p. 938). A large proportion of the natural discharge must be allowed to continue, to hold back salt water. Also, more than a million cubic meters per day is already being pumped. On the other hand, some of the water is or can be used more than once—that is, used, returned to the ground, and pumped and used again.

Without presuming to suggest that large amounts of Long Island water are available for the public supply of New York City (for the island's water by and large will be developed to meet island needs), it can be pointed out that under carefully controlled conditions another million cubic meters per day or more of additional water could be developed, much of it at a well-head cost of a cent or two per cubic meter. Here, then, is a place where existing knowledge is sufficient to point to ground water as currently a cheaper source than at least one proposed alternative. The additional knowledge required to make these additional volumes of water become real will cost several million dollars to obtain—but the difference between 22 and, say, 5 cents per thousand gallons (6 and 1.3 cents per m^3) amounts to more than a million dollars per year for each hundred thousand cubic meters per day.

The title of this paper asks a question, but one that seems rhetorical. Of course, scientific decisions are to be preferred to rule-of-thumb decisions. But the Long Island example just described is a rule-of-thumb judgment that large quantities of ground water are available at a cost low enough to justify easily the expenditure for studies needed to provide a scientific basis for the management actions involved in obtaining the additional water. Other similar situations could be cited, many of them in the water-rich Coastal Plain of which Long Island is one of the northern outliers. Example: Florida, our most permeable State, where a high proportion of 1,350 mm of rainfall goes underground each year. Example: Mississippi, where 99½ percent of the public water-supply systems use wells but where the remaining ground-water potentialities greatly outweigh the existing developments. Example: Southeastern Louisiana north of Lake Pontchartrain, where millions of cubic meters per day of soft, good-quality ground water awaits development. There is even water to be had in our driest State, Nevada, where ground water in only four of more than 100 major alluvial valleys can be considered fully developed or overdeveloped (McGuinness, 1963, New York, Florida, Mississippi, Louisiana, Nevada sections). By choosing the best areas, we could undoubtedly develop several times the current total of about 60 billion gallons per day (about 225 million m^3/day) now withdrawn in the United States, and do it with only moderate effect on existing wells and on streams.

WHAT ELSE DO WE NEED TO KNOW?

It appears that rule-of-thumb evaluations such as the above have their place. At least, they tell us that large quantities of ground water are available, and where. But they are only the beginning. It is not enough to know that water is available. To produce it for use costs money—tax money, or business or personal income—and those spending the money have both the desire and the obligation to see that it is spent wisely. So, even in areas of known abundant supplies and little pumping, scientific information is needed as a basis for decisions.

And the needs are here and now. The persistent increase in water demands and the desirability of using ground-water reservoirs to supplement variable and increasingly expensive surface-water supplies and for storage of wastes mean that the detailed questions are being asked now, before we are ready to answer them. Thus, many rule-of-thumb decisions are having to be made and will have to be made in the future, though there will be situations when any decision about ground water will be considered too risky until additional information becomes available. To avert the tragedy of misuse or nonuse of the ground-water reservoirs for lack of enough information to make rational decisions, every effort must be made to close the information gap as rapidly as possible.

A two-pronged attack is called for. One is to accelerate as rapidly as possible the coverage of areas of interest by reconnaissance or slightly more detailed ground-water studies. Such studies provide enough information for planning and undertaking many uses of ground water, and they are relatively straightforward. About half the area of the conterminous United States plus all of Hawaii (but only a minor fraction of Alaska) has been covered by such studies.

On the other hand, there are not enough trained hydrogeologists to complete the studies in time to avoid the risk of many incorrect decisions and choices. This means that increasing emphasis must be put also on the second prong—research. Research is the means by which techniques are developed for (1) improving, accelerating, and reducing the cost of the areal studies; and (2) learning how to extrapolate information from one area or situation to another on the basis of fundamental principles, instead of on the basis of empirical measurements that may prove to have little transfer value.

Financing and staffing a ground-water research effort is no less a problem now than it was in O. E. Meinzer's day, when he complained (Meinzer, 1934, p. 30–31) that the urgent demands for information on ground water in specific areas made it difficult to devote even a small part of the total effort to the research that might, in the end, prove to be worth ten or a hundred times as much as an equivalent expenditure on routine areal studies. Then, there were only a few dozen hydrogeologists in the United States. Now, there are more than a thousand, but the information needs have grown even faster than the number of ground-water specialists.

Hence, it becomes necessary to pick and choose carefully among the many topics on which research might be done, in order to concentrate on those aspects that would meet the most urgent needs and promise the greatest payoff. A recent paper points out some of these (McGuinness, 1967; see also McGuinness, 1964; Hackett, 1966).

ARTIFICIAL RECHARGE

Natural replenishment of ground water in the conterminous United States amounts to an average of a few inches per year over the area of 3 million square miles—say, 3 inches, or 75 millimeters, over 8 million square kilometers. This is enough that ground-water discharge accounts for perhaps one-third to two-fifths (W. B. Langbein, oral commun., 1950) of the total streamflow, which averages 8½ inches (215 mm) per year (Langbein and others, 1949, p. 5; see also Busby, 1963).

This natural ground-water recharge represents an enormous amount of water, on the order of 400 billion gallons per day (1½ billion m^3/day). But in many areas it would be desirable to increase greatly the natural rate, either to prevent the depletion of a valuable aquifer or to store surplus floodwater for later use.

Artificial recharge is practiced on a rather large scale in California and to a much smaller extent elsewhere in the United States. The total rate is not known, but at present it is on the order of several hundred million cubic meters per year, or perhaps even a thousand million cubic meters per year or more—a cubic kilometer! This is a respectable amount of water, but if ground-water reservoirs are to do what is expected of them, the total will have to be increased to several tens of cubic kilometers per year.

It will not be easy to reach these totals. Under favorable conditions, recharge by spreading surplus water over permeable alluvial fans can be done for a dollar or a few dollars per thousand cubic meters. (See papers annotated by Todd, 1959, such as that by Clyde, 1951.) But such favorable conditions are absent in many places where artificial recharge would be desirable. In such places, artificial recharge at a substantial rate will be either impossible, if suitable aquifers are missing, or at least relatively expensive, if the water must be injected through basins occupying valuable land, or through wells. Recharge through wells could easily cost a cent to a few cents per cubic meter, which might make the practice unfeasible for storing large quantities of floodwater during the brief time that it is available.

The need for, and the promise of, artificial recharge are so great as to justify substantial expenditures for both research on techniques to reduce the cost and on areal studies to locate and evaluate aquifers suitable for recharging. This is one of the highest priority needs in the field of ground-water hydrology.

PERMEABILITY DISTRIBUTION

Prediction and, then, management of the operation of hydrologic systems require that suitable models be devised. That such models can be devised is due to the fact that the two hydraulic parameters controlling ground-water flow—permeability and storage coefficient—can be measured quantitatively by means of pumping tests and other techniques. However, we can never afford as many test holes and pumping tests as would be desirable to determine permeability distribution with the desired accuracy. Research is critically needed, therefore, on the principles of sedimentation, and of other determinants of permeability, that will enable extrapolation and interpolation of scattered point data in such a way as to form a model more realistic than one based on simple proportioning of values between points. Some research is underway, including that by R. R. Bennett, P. M. Brown, and their colleagues in the Geological Survey, but much more is needed.

VERTICAL PERMEABILITY

Crossbed permeability ("vertical" permeability because most aquifers are sedimentary and most are nearly horizontal) is important to long-term predictions of aquifer response because of leakage of water to, from, or between aquifers through beds of low permeability. Yet, no economical technique of measuring vertical permeability has been devised. R. W. Stallman and his colleagues in the Geological Survey have been trying a number of new techniques to get around the time, expense, and uncertainties involved in measurements of actual vertical flow under field conditions. Some of these techniques involve measurements of pressure and temperature with sensitive instruments. The pressure measurements reflect the vertical permeability of fine-grained materials to air, which can be interpreted in terms of water permeability. The temperature measurements show the movement of water at rates so low that direct measurement would be difficult.

STORAGE COEFFICIENT

Besides permeability (or, rather, transmissibility, or transmissivity—the overall permeability of a whole aquifer), the parameter essential to flow prediction is the storage coefficient—the quantity of water that comes out of, or goes into, storage when the ground-water head is lowered or raised. The Theis equation for nonsteady-state flow (Theis, 1935) is based on heat-flow theory, in which it is assumed that heat comes out of, or goes into, storage instantaneously with a change in temperature. For simplicity the Theis equation assumes that water behaves in the same way, but in reality it does not; a perceptible time is required for water to flow out of, or into, pores, some of which are very small. So far, there is no practical way of predicting and allowing for this delay, which is important when the equation must be solved for very short periods of withdrawal or recharge to avoid interference from boundary effects—for example, the presence of a recharging stream or impermeable bedrock wall not far from the test well. At present, the principal research underway to try to "get a handle" on this problem is that by J. F. Poland and others, in a project entitled "Mechanics of Aquifers," which is aimed at the causes of land subsidence due to withdrawal and application of irrigation water in the San Joaquin Valley, Calif. Work being done by Rubin (1968) also is of interest.

UNSATURATED ZONE

The unsaturated zone, or zone of aeration, has a host of unsolved problems. Water movement in it is more complex than in the saturated zone, principally because the flux occurs in both liquid and vapor phases and because the permeability changes with moisture content. There is not space here to do more than point out that there is need for a theory of flow based on fundamental characteristics of earth materials that can be measured at reasonable cost in time and money. Flow measurements at present are mainly empirical and of limited transfer value because it is not even known which soil characteristics are the important controls of flow. An unusually impressive justification for research on the unsaturated zone is that it is largely in that zone that possibilities exist for reduction of the huge loss of water by evapotranspiration. A small percentage reduction in that loss would add many millions of cubic meters of water per day to the world's available supply. Also, this zone is of crucial importance in both natural and artificial recharge.

GEOCHEMICAL PROBLEMS

There are many important research targets which basically are chemical—effects of injection of water (or wastes) into an aquifer whose water chemistry is substantially different from that of the injected fluid, acid mine drainage, and evaluation of saline water as both a potential resource for desalting and a threat to fresh-water supplies in coastal areas. Desalination of salty water is already practical in some areas of high water cost, and it is bound to become more important. Studies of saline ground waters are even more expensive than those of fresh water, but they must be made nevertheless.

GEOPHYSICS

Both surface and borehole geophysical techniques include important research targets. Both serve to extend at relatively low cost the results of test drilling, a critical need in view of the low unit value of water and the desirability of obtaining hydrologic data at minimum cost. The borehole work is especially promising in this regard. Among recent developments are some in which hydrologic knowledge contributes significantly to the understanding of seismic phenomena (Cooper and others, 1965) —an interesting departure from the common situation where geophysical knowledge developed in another field, such as petroleum geology, is adapted for hydrologic use.

CONCLUSION

The list of research needs in ground-water hydrology and subsurface hydrology in general could be extended and detailed indefinitely. The field by no means is being neglected. In the United States some 600 research projects are underway in "subsurface hydrology"—ground water, water in soils, water and plants, and ground-water management—and several hundred more are closely related to the subsurface in some way. But the needs for both research and areal hydrologic descriptions are still great. It has yet to be confirmed that ground-water reservoirs are worth all this effort, but at least the hundreds of scientists engaged in these projects in the United States, and the hundreds more in other countries, are convinced that they are. By the time of the next Geological Congress the outcome should be less in doubt. I, for one, am among those who think that the outcome will be favorable. I believe that, little by little, the balance will be swung in favor of scientific rather than rule-of-thumb techniques of answering questions about ground water—questions that are among the most important now being put to man in his struggle to control his environment.

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