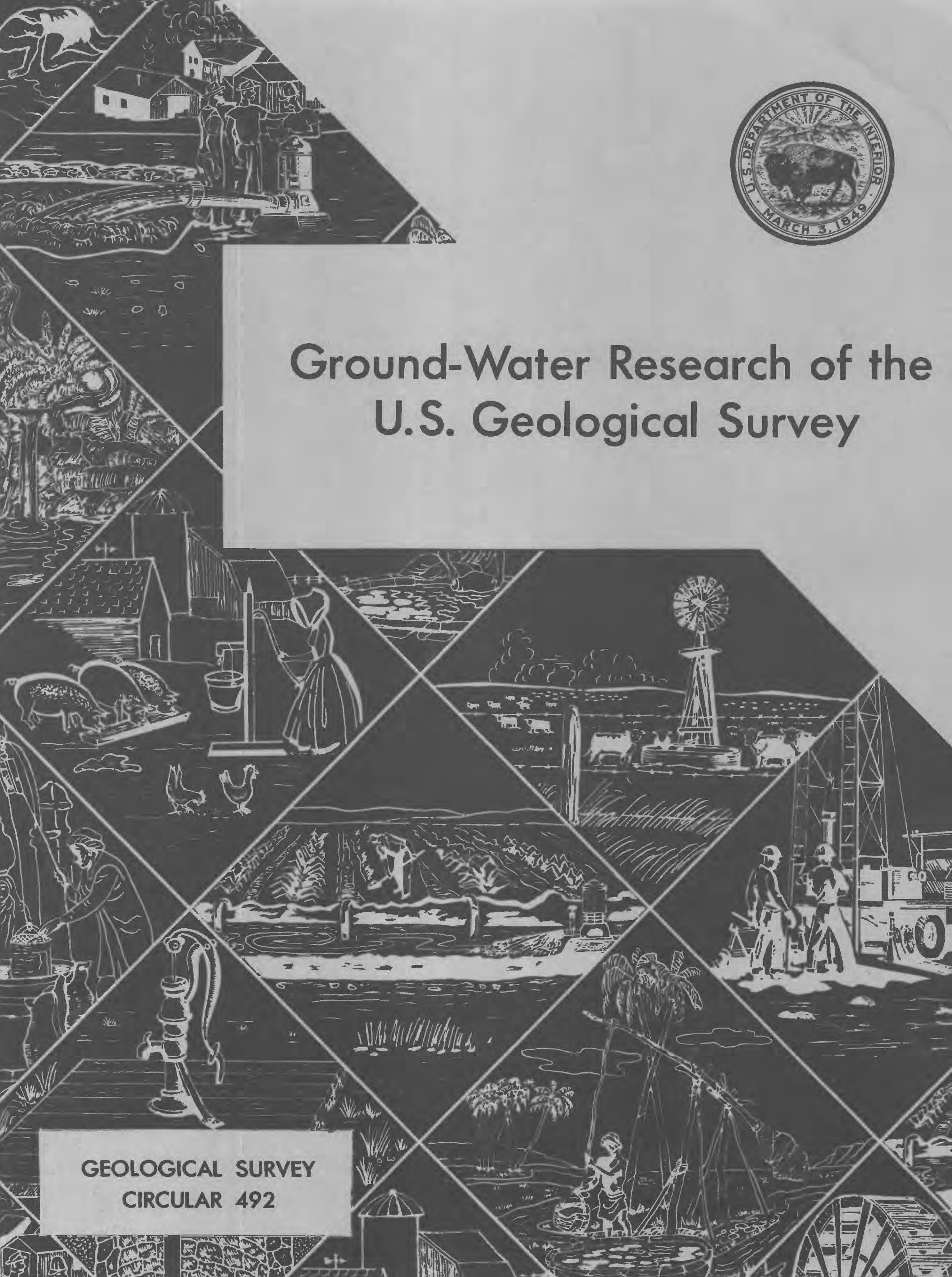

Ground-Water Research of the U.S. Geological Survey

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I have been asked to describe to this group the ground-water research program of the Geological Survey. The first question that might be asked is one of the toughest of all—what *is* ground-water research? There hasn't been a time, at least since O. E. Meinzer came along half a century ago, that ground-water workers have been permitted to forget that ground water and surface water are interrelated and interdependent, so that there is difficulty, at least in some subject areas, of deciding whether a given project is ground-water research or surface-water research. At the same time, we didn't appreciate these relationships quite as thoroughly as we do now, problems of ground-water—surface-water interference were relatively uncommon, and there was so much to learn that quite sizable segments of research in ground water could be considered not to impinge on the surface-water field, and vice versa.

But now, all of us in the water game are being forced to accommodate ourselves to the realization that water, the earth, the skies, the oceans, and the living things on and in them form one great big complex dynamic system and that any action affecting one part of the system has more or less widespread repercussions in other parts. This is our current philosophy in the Geological Survey—to look at hydrology as the complex field that it is and not as the simple subject we would like it to be and which we could break down into parcels for study in the most convenient way.

It isn't easy for us to decide just which parts of the field are appropriate for us to attack and, of those parts, which ones we ought to attack first in meeting our general obligation of explaining the fundamentals of water movement, chemistry, and interactions as a basis for development and management of water. However, I'll do my best to give you an idea of the direction of our current research activities involving ground water.

Recognition of water as the principal hydraulically and chemically active part of a complex system makes it necessary for us to adopt a "systems analysis" approach to our part of the solution of water-related problems. We have to set up a model—mental, mathematical, electrical, hydraulic, or mechanical—of the particular hydrologic system that concerns us, operate the model to see how its functions interrelate, and then change the operation in accordance with various proposed actions, such as development of water supplies, to see how the model reacts. If our model is a good one, we will have an idea of how the real system will react and thus be able to provide the planners a realistic set of alternatives from which to make a choice.

There are all kinds of hydrologic systems, but the one with which we will be concerned most often is an actual block of the earth's crust—what we might call a "hydrologic terrane"—incorporating a drainage basin or an aquifer or a system of aquifers. According to the type and complexity of the system, the kind of model we choose might be any one of those I mentioned, but more often than not it will be the electrical analog model. This is the one that seems to offer the greatest promise for representation of real hydrologic systems, though we are still a long way from being able to incorporate in the electrical model all the flow and chemical factors that will have to be considered.

When we come down out of the clouds and take a hard look at the problem of modeling the ground-water phase of a system, we begin to see our needs for research. The first realization we come to is that we have to consider the entire subsurface part of the system instead of just the ground-water part; that is, we have to look at the zone of aeration as well as the zone of saturation, because the zone of aeration not only transmits most of the water that replenishes the zone of saturation, but in other places or at other times it receives water from the zone of saturation and transmits it to the atmosphere.

Our needs for knowledge relating to the subsurface part of the hydrologic cycle can be classified in various ways. One possible way involves four categories: (1) The zone of aeration and recharge, (2) water movement and storage in the zone of saturation, (3) discharge from the zone of saturation and ground-water—surface-water relations, and (4) physical and chemical phenomena.

1. ZONE OF AERATION AND RECHARGE

The zone of aeration, or the unsaturated zone, has been almost a no man's land in hydrology, in part because water movement in this zone is more complex than in the zone of saturation and thus more difficult to study and measure, and in part because we are only beginning to realize the importance of the zone of aeration as a medium for discharge from the zone of saturation as well as replenishment to it. Accordingly, difficult as the subject is, we are having to give it more attention. We need to know more about the mechanism of downward movement by gravity; the relation of capillary conductivity, or what you might call effective permeability, at various moisture contents; the effects on permeability of dissolved gases and entrained particles in the percolating water; the effects of ion exchange and colloidal swelling; the mechanism of hysteresis effects involved in alternation of downward and upward movement of capillary water; the relative importance of lateral movement in the zone of aeration above a sloping water table such as near a stream; the importance of water movement in the vapor phase; the mechanism of transpiration as a guide to estimating quantities discharged; and so on.

Research on water movement in the zone of aeration is concentrated chiefly at Washington, D. C., under W. O. Smith; at Denver, Colo., under R. W. Stallman and A. I. Johnson; and at Menlo Park, Calif., under Jacob Rubin. Smith, Johnson, and Rubin are making laboratory studies of unsaturated flow in columns of artificial and natural materials and trying to pin down the fundamental parameters controlling movement and retention of water. Stallman is studying multiphase flow—water and air or other gases, and waters of different densities. He is also experimenting with transient flow of gas as a means of measuring permeability in the field more rapidly than can be done with water.

Rainfall in the very dry southwestern basins is so erratic as possibly to rule out our normal water-budget approach to estimating perennial water supplies, and we need to know more about what actually does happen. A staff at Phoenix, Ariz., under H. E. Skibitzke is experimenting with radar techniques for locating areas of storm rainfall as a guide to estimating quantities of water available for surface runoff and ground-water recharge and for pinpointing areas of potential runoff so that stream gagers can get to the areas while the arroyos are flowing. Another project is to estimate amounts of infiltration, and for this purpose Skibitzke is experimenting with infrared-sensing equipment that can be flown over areas of recent rainfall to estimate amounts of infiltration from the cooling effect on the soil. Infrared is useful also in locating points of ground-water discharge into streams, lakes, or the ocean, and for tracing currents in surface-water bodies. It is an aid also in geologic mapping.

There is considerable research on or relating to evaporation and transpiration, including a series of projects in the Gila River valley in Arizona under R. C. Culler; a study of the hydrology of the "prairie potholes" of the Dakotas and western Minnesota under W. S. Eisenlohr; and several studies of water-plant relationships and the effects of vegetal modifications which of course touch on infiltration to and discharge from the zone of aeration, under C. R. Daum at Denver, R. M. Myrick on the Fort Apache Indian Reservation, Ariz., R. L. Phipps at Columbus, Ohio, and R. S. Sigafoos here in Washington. T. W. Robinson at Menlo Park is continuing his general studies of the evapotranspiration process. R. W. Stallman at Denver is working on ways to estimate evapotranspiration from data on humidity and wind movement at elevations between those reachable by instrumented towers and those which can safely be flown by manned aircraft. Radio-controlled model aircraft carrying humidity sensors are being used in this work.

2. WATER MOVEMENT AND STORAGE IN THE ZONE OF SATURATION

The zone of saturation is of special interest because it is a widespread economical water source whose importance is greater than might be assumed from the fact that it yields only about a fifth of the total water withdrawn for various uses, and also because it is a potentially important medium for storage of surplus floodwater as surface reservoir sites become scarce and existing reservoirs are filled with sediment. Even under natural conditions it is a far greater storage medium than all natural and artificial fresh surface-water bodies put together, and it is most important to be able to estimate quantities of water moving through and stored in the zone of saturation and the potential availability of water from and storability of water in the zone.

Therefore the zone of saturation is a quantitatively vital part of every analog model of a real hydrologic system. Our efforts are aimed chiefly at three major parts of the target of making adequate models of the zone of saturation: (1) Permeability distribution as it affects entrance of water into, movement of water through, and discharge of water from the zone of saturation; (2) movement of water through fine-grained materials, which make up the greater part of most aquifer systems and so surround and intertongue with the permeable materials as to be the real controls on water movement; and (3) the true nature and practical measurement of the coefficient of storage, which is equal in importance to the permeability distribution in relation to aquifers as sources of water and storage media.

1. A substantial group of projects are underway in relation to permeability distribution in rocks. R. R. Bennett and J. D. Bredehoeft here in Washington are working on textural characteristics of sands and sandstone as a guide to depositional patterns and, thus, distribution of permeable channel deposits. P. M. Brown at Raleigh, N. C., is heading a project aimed at an understanding of depositional patterns and resulting distribution of permeable sediments in the entire Atlantic Coastal Plain. Norman Payne at Baton Rouge, La., is making a similar study of the Sparta Sand, one of the principal aquifer systems of the Gulf Coastal Plain. J. G. Ferris at Tucson, Ariz., is making a general study of the geometry of porous media.

Akio Ogata in Honolulu is studying the fundamental physics and mathematics of saturated flow to develop new equations that can be used in interpreting permeability data. H. E., Skibitzke at Phoenix and A. I. Johnson at Denver are making studies of flow in artificial and natural sands in columns and tanks. Skibitzke is continuing to contribute to the design of analog models of ground-water flow systems by the unit that has been set up at Phoenix. W. S. Keys at Denver is studying all aspects of borehole geophysics in an effort to devise well-surveying techniques that will get more permeability and other information per dollar spent on test drilling and surveys of production wells. Three "terrane studies" are underway to develop more knowledge of the movement of water in certain important nongranular rocks—R. C. Newcomb at Portland, Oreg., on basalt; F. A. Swenson at Denver on limestone and other "carbonate" rocks; and F. W. Trainer here in Washington on fractured crystalline rocks.

2. H. W. Olsen, B. B. Hanshaw, and W. O. Smith, all here in the Washington area, are concentrating on water movement in fine-grained materials, especially to ascertain whether Darcy's law of flow in proportion to hydraulic gradient holds for material of increasingly low permeability, in which electrical and membrane properties become increasingly important.

3. The principal current effort related to the coefficient of storage is that at Menlo Park and Sacramento under the direction of J. F. Poland and is aimed at separation of elastic and plastic deformation in aquifers and associated strata that are subjected to new stresses, such as those resulting from lowering of head. The project was started mainly to learn the parameters controlling land subsidence in the San Joaquin Valley, but it has important implications in better understanding of the coefficient of storage under both artesian and water-table conditions.

Research is undertaken as a part of numerous cooperative ground-water investigations, as well as in the federally supported research program. During the last year advances have been made in such things as evaluating the relation of horizontal and vertical permeability by finite-difference equations, analyzing the recession curve of the water table in shallow sediments in dry weather in terms of permeability and storage coefficients, analysis of temporary artesian conditions created by freezing of soil moisture, and analysis of earthquake-induced fluctuations in water level in terms of local hydraulic properties of the aquifers.

3. DISCHARGE FROM THE ZONE OF SATURATION AND GROUND-WATER—SURFACE-WATER RELATIONS

We are not yet doing much on upward movement from the zone of saturation into the zone of aeration, beyond what is involved in the studies of the zone of aeration. The other principal type of discharge—that into surface-water bodies—is receiving considerable attention, in what might be called studies of ground-water—surface-water relations.

Such discharge is of enormous economic importance because, in drainage basins lacking large artificial reservoirs or natural lakes and swamps, ground water is the source of the low, or base, flow of streams. It is important to study the geologic and climatic controls of water movement from aquifers into streams and the effect of rises in stream stage in stopping or even reversing this flow and thus contributing to ground-water storage.

H. H. Cooper, formerly at Tallahassee, Fla., and now here in Washington, and his associates have made important contributions to the discharge of coastal ground water as affected by tides. He is now working on the mathematics of "bank storage" along streams. M. I. Rorabaugh at Tacoma, Wash., who made important contributions to the theory of induced infiltration from streams in his work at Louisville, Ky., is working on the estimation and prediction of base flow as a guide to stream management, in cooperation with the Bonneville Power Administration. R. F. Hadley at Denver is studying infiltration losses from ephemeral streams—the principal source of ground-water replenishment in Western alluvial basins. D. R. Dawdy at Menlo Park is attempting to develop an overall analytical model of the hydrologic cycle, of which one important element would be base flow of streams. E. C. Pogge, G. R. Kunkle, and their associates at Iowa City are studying streamflow in relation to aquifer characteristics, including especially bank storage during floods and origin of base flow.

4. PHYSICAL AND CHEMICAL PHENOMENA

The description of the program so far has stressed the movement and storage of subsurface water and left for the last the studies involving the chemical properties of water and such physical characteristics as temperature. Actually, these factors cannot be separated from the flow problems because they are closely interrelated. For example, as I mentioned, electrochemical and membrane effects are importantly involved in the movement of water through fine-grained materials. Temperature also is important because of its effect on viscosity, the effect being rather direct in subsurface flow whereas it is a relatively minor factor in turbulent flow in streams, and it will become still more important as surplus surface water is deliberately injected into aquifers and then recovered.

Obviously, studies of fundamental chemistry relate to the whole hydrologic cycle, not just ground water or surface water.

The project classification used in our description of the hydrologic research program for fiscal 1963 follows the hydrologic cycle. Studies relating to the chemical or physical properties of water are found in each of the sections, and there are some dozens of individual projects, including those described briefly below.

G. L. Stewart and his colleagues here in Washington are studying the use of various radioactive and stable isotopes for tracing water flow both on the surface and underground and for identifying sources and dating periods of replenishment. The project is concentrating on tritium at present. W. D. Haney is carrying on a related program to develop methods for age dating of water.

D. E. White of the Geologic Division and Robert Schoen of the Water Resources Division at Menlo Park are studying the chemistry of deep thermal waters and their relation to the enclosing rocks. These waters play a relatively minor part in the hydrologic cycle, but the information gained on water-mineral relationships can be applied to the fresh-water part of the cycle.

A. W. Gambell, Jr., here in Washington, D.C., is heading a project to study the chemistry of precipitation as it reaches the ground, as a determinant of the quality of surface and groundwater. The project is trying to identify the source of certain constituents and the general pattern of transport by air. It appears that the quality of water in some areas, such as parts of the Atlantic Coastal Plain, is determined more by constituents contributed in precipitation than by those from terrestrial sources. In a related project, Gambell and W.H. Durum are studying sediment particles carried in suspension and the state of chemical equilibrium between them and water when they are washed out of the air.

The hydraulic-model studies of H. E. Skibitzke and others at Phoenix include one of coastal discharge of fresh ground water and of dispersion and diffusion of salt from the adjacent sea water into the coastward-flowing fresh water. Studies by H. H. Cooper and others have shown how tidal fluctuations and the accompanying advance and retreat of the salt-water front provide energy for the movement of salt from the sea to the zone of diffusion and back to the sea. These relationships are fundamental to an attack on problems of saline encroachment in both coastal and inland areas.

Temperature is a basic control of evaporation and transpiration and is involved in all the studies mentioned previously on this subject.

R. S. Aro at Denver is heading a project to determine the ecologic criteria that will be involved in proposed conversion of semiarid pinyon-juniper areas to grass to increase water yield. The criteria studied include soil pH and chemistry as related to vegetal type under both natural and changed conditions.

F. A. Branson at Denver and his staff are studying the distribution of plant species along the 103d meridian from southeastern New Mexico to Nebraska in relation to air temperature, and also the response of soil moisture and some other soil characteristics to the same thermal gradient. In related projects R. F. Miller and his staff are studying the chemistry of soils in relation to amount and seasonal movement of soil moisture in areas of both dry-land and phreatophytic vegetation.

M. F. Meier and associates at Tacoma, Wash., are studying the hydrology of glaciers, especially their response to climatic fluctuations, as a guide to long-term prediction of water availability from mountainous areas.

R. C. Newcomb's basalt-hydrology project centered at Portland, Oreg., is now getting into the geochemical phase in an attempt to derive useful generalizations about the chemistry of the water in relation to rock type and to movement of the water. Similarly, F. A. Swenson's limestone-hydrology project is studying the sources of carbonic and other acids which cause solution to take place hundreds or even thousands of feet below the water table. V. T. Stringfield is making a similar study of the artesian limestone of the Southeastern States.

J. H. Feth at Menlo Park is assembling maps showing the location, depth, and salt content of saline water in the conterminous United States, as a contribution to the saline-water conversion program of the Department of the Interior.

P. R. Stevens at Austin, Tex., is heading a project to study the occurrence of brine in selected areas of the Permian basin. The objective is to determine the mode of occurrence of the brine and its dynamics, so that projects for controlling its discharge may be designed realistically. Some brine-control projects have been based on the assumption that brines are generated by solution of salt from the strata by locally infiltrating precipitation and that damming spring outlets and creating back pressure will reduce the discharge of brine. At least one or two such attempts have failed. The brine may be a regional body which discharges at the most convenient points but which, if those points are dammed up, will simply discharge elsewhere. The research project is designed to get the answer to this fundamental question, which is an important one because of the quantity of otherwise usable water that is spoiled by the brine.

D. W. Hubbell and his associates at Ft. Collins, Colo., are studying sorption of radioactive wastes on particles of stream sediments and the dispersion, transport, and deposition of the contaminated sediments.

R. G. Godfrey and associates here in Washington are studying flow and salinity relations in estuaries as affected by tides. The project is related more to flow than chemistry but obviously has important implications in relation to the quality of water available from estuaries and adjacent aquifers and the conditions affecting deposition of sediments and contaminants.

W. O. Smith here in Washington is studying the freezing point of moisture in clays in relation to mineral type and exchange-ion content. The objective is to provide information applicable to the study of ground-water availability in permafrost areas.

Smith is also studying the dielectric properties of moist soils and rocks to determine their relation to moisture content. The goal is to develop another technique of soil-moisture measurement that doesn't involve disturbance of the moisture itself.

The studies under H. W. Olsen and B. B. Hanshaw mentioned previously are aimed largely at liquid movement in clays, including the role of hydraulic, thermal, chemical, and electrical gradients. Hanshaw's work is aimed especially at the "membrane" properties of shale, which have what could be called a physicochemical basis and which may be important to understanding certain anomalous potential distributions observed in deep basins.

R. C. Scott and K. W. Edwards at Denver are heading studies of the distribution of radioelements in natural water. The general objective is to provide basic information to assist studies of the relation of these elements to health, to mineral exploration, and to the movement and chemistry of water throughout the hydrologic cycle.

B. F. Jones and his staff at Washington are studying the composition, especially as to minor elements in water, in closed lake basins of the West, where, in spite of some losses to and gains from outside the basins, the geochemical processes and budgets are largely contained within the basins and are especially amenable to quantitative study.

Ivan Barnes at Menlo Park is heading a project aimed at elucidating some of the fundamental reactions in ground water. One of the most important applications is in problems of acid mine wastes. One product to date is a geochemical model, supported by field tests, which demonstrates that water and sulfides do react in the absence of oxygen. Thus air is not the only source of mine acid, and sealing mines is not necessarily a satisfactory way to ameliorate these problems. It is proposed to study gases generated in deep waters to provide further information on the exact reactions involved under anaerobic conditions.

W. L. Polzer at Menlo Park is studying the solubility of kaolinite as a step in understanding the solution of silica and aluminum and equilibrium with the solid phase.

E. A. Jenne and his staff at Denver are making a broad study of ion-exchange phenomena and the chemical reactions of radioactive substances, largely with the objective of evaluating the decontaminating effect of earth materials on waste waters disposed of underground.

In collaboration with the Atomic Energy Commission, W. A. Beetem and his staff at Denver are studying the movement of radionuclides through earth materials and also the solubility of materials formed by underground nuclear explosions in relation to contamination of adjacent ground water. In one part of the program a study is being made of the solubility of radioactive materials from particles of various sizes washed down by rain.

V. C. Kennedy and staff at Denver are studying the mineralogy of stream sediments in relation to particle size and ion-exchange capacity, in an attempt to understand the chemical balance between water and sediment in the streams.

J. D. Hem and his staff at Menlo Park are continuing their studies of the fundamental chemistry of certain hydrosolic metals. Work on iron has been largely completed and published. Work on manganese is well underway; that on alluminum is in an early stage.

M. W. Skougstad and his staff at Denver are working on improvements of analytical methods, especially of minor elements for which available methods are not satisfactory.

K. V. Slack here in Washington is heading studies of the relation of stream biology to water chemistry. Phases include the chemical controls on generation of stream biota and, in turn, the effect of the biota on water quality; the chemistry of a calcite-precipitating stream in California in which the controls are still all natural; and the effect of leaf mulch on water composition.

William Back here in Washington is studying the equilibrium of carbonate compounds as a guide to source and movement of ground water, especially in the Atlantic Coastal Plain. He has recently visited Israel to help with the geochemical aspects of that country's ambitious water-development plan.

Studies under A. O. Waananen at Menlo Park on the hydrologic effects of urbanization will, of course, devote attention to the water-quality effects. Work is now underway in the San Francisquito Creek watershed.

The chemistry of organic compounds in water is of increasing importance in relation to water contamination. W. L. Lamar at Menlo Park, Eugene Brown at Sacramento, C. H. Wayman at Denver, and their staffs are studying the identification, separation, and estimation of various organic substances. Wayman's work on detergents is well known. The Survey now has a very modest program of research on pesticides and herbicides, which of course are among the principal actual and potential contaminants of water. About 14 areas have been selected for study. One of these is the Loxahatchee Refuge in Florida, where 2, 4-D has been used to control water hyacinth. Wayman is also supervising a study of the sulfur-water system under both aerobic and anaerobic conditions, which has potentially important applications in the study of both organic and inorganic contaminants.

Frank Clarke is studying problems of the corrosion of well casings and other underground metallic structures. The vast New Valley program in the Western Desert of Egypt, one of the principal hopes for economic growth there, is imperiled by severe corrosion of wells. Similar problems exist in Pakistan, where Clarke is at the moment.

The Survey, along with other agencies, is participating in the international program of research on stream waters under the Organization for Economic Cooperation and Development. The problems cover the same range as similar problems in this country. H. A. Swenson and M. W. Skougstad are the Survey's representatives in the United States delegation.

One important support activity related to water quality is the project under G. A. Billingsley at Raleigh, N. C., to develop automation and processing techniques for water-quality data.

CONCLUSION

Obviously, what I have described is an extremely wide-ranging and diversified program. Even so, it covers only a small part of what still remains to be done both inside and outside the Survey before the Nation will have a sound basis for water management and quality control. We in the Survey feel that we have a good general understanding of the hydrologic cycle, and we are making progress in orienting our research toward aspects of the cycle where our ignorance is greatest and where at the same time the need for information to handle current national water problems is most intense. However, we can't do and have no intention of trying to do the whole job ourselves. We acknowledge with pleasure that scientists and engineers in other agencies, in universities, and among consultants are doing excellent work in all parts of the hydrologic cycle, including parts such as ground water where we are more or less widely recognized as leaders. Our pleasure is especially great where these men are Survey graduates, as some of them are.

One of our most difficult and yet most necessary jobs is to keep in touch with related research all over the country and the world, so as to take advantage of new developments and avoid duplication and lost motion. Your group has a related problem—to help the Federal Government decide what ought to be undertaken in the way of hydrologic research and water-management projects. The job is a tough one because of the innumerable cross-connections throughout both the hydrologic cycle and the spheres of interest of Federal and other agencies and institutions interested in water. I wish you good luck in your delibearations.

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