THE PROGRESS OF HYDROLOGY

An Introductory Address Delivered to the International Symposium on the Use of Isotopes in Hydrology at the Headquarters of the International Atomic Energy Agency, Vienna, Austria, on November 14, 1966

by

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THE PROGRESS OF HYDROLOGY

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Abstract

THE PROGRESS OF HYDROLOGY. This paper discusses mainly the challenge of hydrology, recent activities, events, and major problems in hydrology, and advances in hydrological techniques. New scientific knowledge and techniques developed in many modern scientific disciplines, and the recognition of the importance of hydrology in water-resources development enable and encourage the hydrologist to advance scientific hydrology. Many programmes to promote hydrology and to expand its attendant activities have been developed in recent years. Therefore, the activities in the United States of America, such as the Universities Council on Water Resources and the President's Water for Peace Programme, and the programmes in the International Hydrological Decade are mentioned.

The most important advance in theoretical hydrology is the development of a new concept of dynamic sequential systems for the hydrological cycle, thus creating new fields of systems, parametric, and stochastic hydrology. Modern scientific instrumentation provide the hydrologist with better tools for solving his problems. The most important of these, such as electronic computers, remote sensing, and nuclear techniques are discussed.

Today various major problems, both theoretical and practical, face the hydrologist. Theoretical problems concern the basic understanding of hydrological systems and the mathematical simulation and physical interpretation of hydrological phenomena. Major practical problems are numerous and diversified, but they are mostly related to the multiple-purpose development of water resources. Four central problematical subjects are discussed; namely, the effects of man on his environment, the dynamics of aqueous flow systems, hydrological transport mechanism, and groundwater hydrology.

Also, the use of nuclear techniques in solving various hydrological problems is discussed. It is believed that the application of nuclear techniques would prove extremely valuable in helping solve problems, but their ultimate use in hydrology will depend upon close collaboration between the nuclear scientist and the hydrologist.

THE CHALLENGE OF HYDROLOGY

Hydrology deals with the circulation, occurrence and distribution of the waters mainly on the earth's land areas, their physical and chemical properties, and their interaction with the environment, including living things.

The central concept of hydrology is the hydrological cycle, which describes the various paths and patterns of water circulation largely within the earth's hydrosphere. This hydrosphere envelops the globe and extends from a height of about 10 miles in the atmosphere to an average depth of half a mile into the lithosphere. Within the hydrosphere water is stored in the atmosphere, in ice caps and glaciers, below ground, in lakes and rivers and, above all, in oceans. The water moves in various ways in the hydrosphere: by condensation of the atmospheric water; by precipitation of the condensed atmospheric water; by evaporation, transpiration and infiltration of the precipitated water; and by run-off of the surface and groundwaters to lakes, rivers, and oceans where the water returns to the atmosphere by evaporation.
waters, and also of the effects of man-made environmental changes on the water regimen. To meet the new challenge of hydrology, therefore, there is a definite need for close collaboration between the hydrologist and other scientists, to reach a complete understanding of the hydrological processes and the full development and utilization of the available water resources on earth.

RECENT ACTIVITIES AND EVENTS IN HYDROLOGY

The primary function of hydrology is to provide scientific facts about water so that the water planner, developer and manager can consider these facts alongside the economic and social factors when solving water problems. The challenge to the hydrologist and to other scientists concerned is to provide increasingly sophisticated scientific knowledge, instrumentation and methods for managing water resources under conditions of growing complexity and mounting difficulties so that the maximum benefit can be obtained from water with minimum harm to the environment.

In view of the new challenge of hydrology and the increasing recognition of its prime importance in resolving water problems, many programmes to promote hydrology and to expand hydrological activities have been developed in recent years. Four years ago, a group of twenty hydrologists from United States universities met at Lake Arrowhead, California, to discuss the need for expanded educational and research programmes in hydrology at universities to provide the manpower and knowledge required for present and future water-resources development [1]. This conference was organized in response to several documents reporting on the importance of hydrology. Two significant official documents, issued by the United States Senate Select Committee on National Water Resources in 1961 [2], and by the Committee on Natural Resources of the United States National Academy of Sciences-National Research Council in 1962 [3], both officially recognized the deficiencies in hydrology. Another document, entitled "Scientific Hydrology", and published in June 1962 by an ad hoc Panel on Hydrology of the U. S. President's Federal Council for Science and Technology [4], clearly pointed out the following:

"The water development and management problems of the last few years have created a need for scientific hydrology that exceeds the capacity of the relatively few individuals who have come into the field from bordering disciplines. The time has come to encourage colleges and universities to make a conscious effort to develop scientists to work on hydrologic problems from a broad base in the fundamental sciences."

One significant accomplishment of the Lake Arrowhead Conference was the establishment of the Universities Council on Hydrology in 1963. This Council was further expanded to form a Universities Council on Water Resources, abbreviated as UCOWR, in 1964. The major functions of both Councils are to encourage hydrological education and research, dissemi-
the International Hydrological Decade (IHD). In recognizing that a full understanding of the hydrological cycle requires an investigation on a global scale, and that water itself is a universal problem that is common to all nations, efforts to stimulate international co-operation in hydrology were initiated by the United States in 1961 [7] through discussions at several international forums. In the spring of 1964, UNESCO convened an inter-governmental meeting of experts in Paris to discuss the formation of such an international co-operative programme. This led to the formal adoption by UNESCO in 1964 of a resolution calling on interested nations to establish national programmes within the framework of an IHD to begin in 1965. It is just two years since its commencement. Some 80 countries have now formed national committees to co-ordinate their participation in the programme.

The general objective of the IHD is to benefit mankind by strengthening the science of hydrology through international co-operation. To implement this general objective, three basic goals have been agreed upon; namely, (1) to strengthen the scientific and technological base for water development, use and conservation; (2) to stimulate education and training in water science and technology; and (3) to improve the ability of developing countries to cope with their own problems.

For administering the Decade programme, a Co-ordinating Council composed of twenty-one rotating member states of UNESCO has been formed. During the first year of the Decade, the Council has received some seventy-five national programmes. The current activities in the programmes can be classified into five broad categories [8]:

(1) **Basic data:** This category includes Decade stations; hydrological benchmark basins and stations; vigil basins; network planning, design and establishment.

(2) **Inventories and water balances:** This category includes global water balance; hydrological maps; a hydrogeological map of the arid zones; a hydrogeological map of Europe; representative and experimental basins; world inventory of perennial and annual ice and snow masses; measurements of glacier variations on a world-wide basis; combined water-, ice-, and heat-balance measurements at selected representative glacier basins; gross sediment transport into the oceans; the discharge of tritium to the oceans by major rivers; hydrology of the fractured limestones of the Mediterranean basin.

(3) **Research:** This category includes two sub-categories:

(a) **On hydrological phenomena:**

1. Water balance of the earth and its variations in time
2. Chronological hydrology
3. Incidence and spread of continental drought
4. Hydrology of deltaic and coastal areas, estuaries and coastal marine waters
5. Relations between soil moisture and run-off
6. Relations between excess of soil moisture, drainage and the behaviour and yield of various plant species
7. Genesis and physical chemistry of natural waters
(4) Exchange of information and standardization problems: This category includes: dissemination and availability of results and data; improvement, comparison and standardization of instruments and techniques. (5) Education and training of hydrologists: In general, the IHD will promote world-wide assembly and analysis of scientific information about water, its quantity, its quality, its distribution and its behaviour. It will achieve world-wide realization that a science of hydrology exists; that teaching, training and research must be greatly expanded; and that many varied career opportunities are open for hydrologists and other scientists concerned with water.

Thus, it can be confirmed that numerous exciting activities and events in hydrology are developing rapidly and vigorously on both the national and the international levels.

ADVANCES IN HYDROLOGICAL TECHNIQUES

As the science of hydrology progresses, new knowledge is accumulating, and new techniques for hydrological studies are developing.

The most important recent advance in hydrological knowledge is a better understanding of the hydrological cycle on a more sophisticated level. The modern concept of the hydrological cycle is to treat it as a "dynamic sequential system" which consists of an input, an output, and some working fluid, which is water, known as "throughput" passing through the system. The study of a hydrological cycle or a part of it can be considered as a system or sub-system problem. For example, a watershed can be considered as a system. For this system, the input is the effective rainfall, the output is the direct run-off, and the throughput is the water moving through the watershed. The effective rainfall is that part of the rainfall that is deducted from evapotranspiration, infiltration, and other abstractions and thus contributes solely to that part of the run-off known as direct run-off.

By the system concept hydrological phenomena are treated, with a much broader outlook, as a system or various sub-systems of the hydrological cycle rather than taken independently as individual hydrological processes. Thus, more generalized approaches to a hydrological problem can be achieved that would also be applicable to other problems of a similar nature. The hydrological system can be readily interpreted physically by modern system analysis techniques that have been developed in some other scientific disciplines, and then it can be simulated by mathematical formulation. The mathematical models so formulated may contain a number of parameters than can be determined either statistically or non-statistically from given sets of hydrological data. Numerous mathematical and statistical tools are now becoming available for use in hydrological analysis. For example, the Duhamel integral, the Laplace transform, and Laguerre functions are being introduced into the analysis of inflow-outflow-storage systems. In statistics and probability, such techniques as periodogram, autocorrelation, correlogram, power spectrum, and multivariate analysis are being used to analyse the hydrological data.
or force. For example, it is possible to spot diseased crops or polluted water with infra-red cameras, survey ice thickness and distribution with microwave detectors, and measure soil moisture by radar. These and many other potential applications have aroused great interest among a diversity of scientists ranging from agronomist to zoologist. Many remote sensing techniques are considered extremely promising for hydrological investigation. The most important ones involve the use of radar, special photography, and artificial satellites.

Radar was first introduced into hydrology to ascertain the area extent of rainfall and to attempt approximate delineation of intensities by use of various gain settings. A very short-pulse VHF radar, mounted in a ground vehicle, has been used for analysing soil moisture. High definition radar, operating at a height of about 41,000 ft, has been investigated as a new means of studying large hydrological regions and identifying drainage patterns. Its main advantages are the very wide area coverage and the almost all-weather capability.

Special aerial photography can provide various kinds of unusual hydrological measurement. Time-lapse stereo aerial photography has been used to determine river-flow velocity from one-quarter to 14 miles/h from measuring a floating object in the river. Coloured aerial photography enables a superior interpretation for water-depth mapping as compared with black-and-white pictures. Infra-red photography is vastly superior to standard photography in delineating a shoreline or water course. It is also useful for the hydrothermal mapping of large water-bodies and for locating hydrothermal features such as geysers and hot springs. Since there is some relation between thermal radiation and ice thickness, the infra-red sensing has been used to study lake ice. Concerning groundwater, it has been found possible to locate fresh-water seeps by the interpretation of 8 - 14 µm infra-red imagery. These images, depicting temperature variation, will show areas of fresh-water leakage into the sea, thus assuring no danger of salt-water intrusion owing to increased pumpage. The sensitive infra-red imagery can also detect areas cooled by evaporation and can thus be used to study water and energy balance in a region.

A unique airborne multispectral camera has been developed, operating in the 0.35 to 5.0-µm band of the visible and infra-red spectrum. The multispectral photography then allows an interpretative study of vegetation, moisture content, and geological conditions of a water-shed. Air photographs provide an inexpensive method for checking the availability of groundwater through identification and location of water-dependent vegetation and water-bearing deposits of sands and gravels.

The United States National Aeronautics and Space Administration is currently planning scientific payloads for future earth satellites [11]. Remote sensing devices being considered for the payloads include detectors of infra-red, microwave, X-ray, and gamma-ray emittance; active radar systems; multispectral photography; and gravity and magnetic sensors. An "Interrogation, Recording and Location (IRL) System" has been designed at the Goddard Space Flight Center for an experiment on the Nimbus B spacecraft scheduled for launch early in 1967. Data will be relayed via the Nimbus satellite to Command and Data Acquisition (CDA).
from radioactive isotopes can penetrate material in a fashion that can be correlated in some way with certain external and internal properties of the material, such as thickness, density and composition, thereby determining these properties. Several applications of radioactive isotopes in hydrology, because of their radiation penetrability, can be quoted as follows:

(1) Measuring the thickness of snow cover by a radioisotope gauge that produces gamma radiation that penetrates the snow for recording on film or for transmitting by radio to a remote recording station

(2) Measuring the variation of a river bed during floods by a back-scattering gamma-ray densimeter

(3) Measuring the concentration of suspended sediment or bed load in rivers and reservoirs by radioisotope probes that have been calibrated in a hydraulic laboratory

(4) Determining the soil moisture by gamma back-scatter probes or gamma transmission gauges

(5) Determining the infiltration rate above a root zone by gamma transmission

(6) Estimating the diffusion coefficient in natural waters by gamma detectors.

By radioactive decay, radioactive isotopes will produce alphas, betas and gammas at a rate according to an exponential function of time. This property provides a unique means for dating the age of water. Several interesting applications of this property may be mentioned as follows:

(1) Determination of the isotopic exchange, storage times, stratification, recent recharge, and old waters in aquifer by $^{14}$C and environmental tritium dating

(2) Determination of the transient state of groundwater by the pulse method using bomb-tritium dating

(3) Study of the pattern of water balance between the precipitation and the run-off from a river by determining ages of the fall-out $^{89}$Sr and $^{90}$Sr produced by nuclear-bomb testing.

The ability to detect in minute quantities makes the radioisotope tracer excellent for application. An ideal isotope to be used as a tracer in water should travel at the same velocity as the water without any loss and its decay and radiation properties should not affect later similar experiments nor be hazardous to the user or the environment. The adequate use of certain radioactive isotopes as tracers depends more or less on the nature of the problems being investigated. Several interesting applications on the basis of detectability may be listed as follows:

(1) Flow measurement in canals, streams and rivers by dilution, continuous sampling, or total-count method, using injected tritiated water or other suitable isotopes such as $^{24}$Na, $^{82}$Br and $^{131}$I

(2) Study of the movement, i.e., velocity and direction, of groundwater or hot springs by using $^{131}$I, $^{32}$P, $^{85}$Rb, $^{60}$Co or tritiated water

(3) Determination of sediment transport and littoral drift by using radioactive glass particles

(4) Study of flow processes in karst or fractured terrains by using tritiated water
the water engineer and planner can use alongside economic and social factors in resolving water-resources problems.

A complete enumeration of all hydrological problems is impracticable, if not impossible. However, there are noted problem areas in hydrology where urgent action is needed. These can be seen from the classification of current hydrological activities as recommended by UNESCO for the IHD [8]; namely, basic data, inventories and water balances, research and special data, education and training, and exchange of information and supporting services. The need for the last two categories is self-evident. The work on basic data, for the time being, consists almost entirely of data collection. If basic data will be used promptly for such purposes as estimating global water balances, they are classified as part of the "inventories and water balances" activity. Non-repetitive basic data obtained for special and immediate research projects are classed as "research and special data". Regardless of the classification, the solution of all hydrological problems depends virtually on basic and applied research. From the scientific standpoint, the American Geophysical Union Committee on Status and Needs in Hydrology [15] has recently identified 63 areas in hydrology requiring research. This Committee pointed out that to establish criteria and priority for selecting these areas was extremely difficult and it was not precisely implied in the identification. For practical purposes, the United States Committee on Interior and Insular Affairs recommended 18 categories of important-water research programmes [16], which included the application of nuclear products in research.

For the purpose of the present paper, it is desirable to mention a few hydrological research problems, including those that have been or are being studied by means of nuclear techniques and those that appear to have a great potential for solution by the use of isotopes.

The major research problems facing the hydrologist today are of great variety and of both a theoretical and a practical nature. Major problems of a theoretical nature deal essentially with the basic understanding of hydrological systems and with the mathematical simulation and physical interpretation of hydrological phenomena. Concerning systems hydrology, physical-mathematical models of the atmospheric-terrestrial hydrological cycle are necessary to describe, understand and predict large-scale phenomena in the cycle. Given initial and boundary conditions of hydrological, hydrogeological, and hydrometeorological parameters, the objective would be to forecast subsequent states of the hydrological system in both time and space. The knowledge of parametric hydrology and stochastic hydrology is therefore needed to set up meaningful but tractable governing equations. Such equations are then to be tested with real data. For these types of theoretical studies of the global hydrological cycle, the hydrological time series, inventories and water balances must be assessed. For such purposes, nuclear techniques can be very useful. For instance, the insertion of tritium products as a result of nuclear-bomb testing is well known. Tritium is being sampled in rain throughout the world. The measurement of the discharge of tritium to oceans by major rivers is an active programme of the IHD. Thus, the terrestrial sources and some measurements of fallout are known. The link between the source and

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changes in land use may be detected by statistically correlating the historical data with virgin data employing methods of chronological hydrology and paleohydrology. Radioisotope dating may be useful to determine these data. On small watersheds, run-off data are usually insufficient and flow behaviour is very sensitive to land use. Isotope tracing may be used to establish a better relationship between the rainfall and the run-off. This relationship can then be used to augment the run-off data from the rainfall data, which usually have a longer record. Isotope tracing should be also useful to measure the often arbitrarily estimated "time of concentration". As the city population is growing rapidly in many countries, the problems in urban hydrology require urgent solution. For promoting research in this area, the American Society of Civil Engineers has recently created a Research Council on Urban Hydrology and a Task Force on Effect of Urban Development on Flood Discharges. The IHD Coordinating Council has also established a Working Group on the Influence of Man on the Hydrological Cycle. There are many other such problems that need research. Wastes and by-products of human activity may hasten the aging processing of eutrophic lakes. Industrial and atomic wastes pollute the groundwater and streams. Conversion of free-flowing streams to impoundments results in water-quality changes. There will be many opportunities to apply nuclear-tracing and dating techniques to all these problems.

2. Dynamics of aqueous flow systems

Aqueous systems, both above and below the ground surface, offer many fundamental and challenging problems. Such problems of prime importance include water transfer by evapotranspiration; mechanics of flood flows and estuarine flows; stratified flow in lakes, reservoirs, and large rivers; seepage and dispersion in groundwater; and movement of glaciers. Some of these problems may be further discussed.

Water supply by impoundment and consumption in irrigation depend much on evapotranspiration. Several methods have been devised to conserve water by suppressing evapotranspiration, such as the use of monomolecular films to reduce evaporation; but our knowledge of the mechanism of evapotranspiration is still imperfect. Recent laboratory results indicated that adding fatty alcohols to soil reduced by 40% the use of water by potted corn plants [18]. The use of $^{14}$C hexadecanol made it possible to trace the movement of fatty alcohol molecules from the roots to the leaves. During 1965, a co-ordinated research programme on the application of radiation techniques to water-use efficiency studies was initiated by the IAEA and FAO to examine such problems. From experiments at Lake Hefner, Oklahoma, new methods for evaporation and transpiration measurements have been developed on the basis of the energy-budget principle and the mass-transfer theory. However, the available instrumentation for measuring energies in the energy-budget method is inadequate to determine evaporation for short periods, say less than 10 d. Simple and more accurate instrumentation must be found. The mass-transfer techniques are applicable to the determination of evaporation and evapotranspiration.
cannot be economically and practically constructed. In such cases, an analytical model perhaps is more suitable, but it requires better methods of data sampling and measurement than at present available. Coastal aquifer involving salt-water intrusion; groundwater movement in fractured terrains and arid regions; and lithographic, climatic, microbiological, agricultural, and geochemical influences on groundwater quality, are problems that have not been fully investigated. Radiochemical techniques have already contributed much to our understanding of chemical geo-hydrology [19], but they should be extended fully to all these problems.

Lastly, a few words should be said about the application of nuclear techniques in hydrology. Nuclear techniques, if adequately used, are powerful tools, but they have their limitations. A clear understanding of these limitations and of the nature of the problem being investigated is very important to both nuclear scientists and to hydrologists. As nuclear techniques are developed largely by nuclear scientists, many hydrologists are unfamiliar with their characteristics and capabilities and some are even unaware of their usefulness and value. Therefore, much education is necessary concerning nuclear techniques in the training of hydrologists. On the other hand, nuclear scientists would appreciate learning of the nature and type of problems that are currently met by hydrologists. An international symposium like this one and the current IHD programmes can serve such purposes very effectively.

Before tackling a hydrological problem, an adequate communication between the nuclear scientist and the hydrologist is a necessity. The hydrologist may specify the problem to be solved. His specification should include, for example, the limits required on accuracy. If this is not done, much effort may be wasted in developing undesirable systems and techniques; or else a system may be developed that cannot be used because it does not answer the question to the required degree of accuracy. The use of nuclear techniques is also limited by many other factors. For example, nuclear measurement is usually done by sampling, and the results of sampling require correct interpretation and involve statistical errors, as well as errors due to time and space variables introduced in the course of measurement. Nuclear material may develop physical and chemical reactions with the environmental substances such as soil and aquifer material. Health problems inherent in the use of radioisotopes require qualified personnel, supervision and control. Some nuclear material may be useful but too expensive for extensive field applications. Furthermore, there are possible instrumental malfunctions under adverse conditions, and also problems of maintenance and availability in remote areas. The use of nuclear techniques may need unproved but necessary assumptions. For instance, the method may relate to the properties of the atom in the material tested, and these must be, in turn, related to the properties of the material actually desired. The relation may imply assumptions that are only approximate. In applying nuclear techniques, observations may be made on site with personnel, on site by remote control, or on samples in the laboratory. In all these cases, the change of property with time and space as compared with what is being sought must be acceptable.