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TECHNIQUES FOR ASSESSING HYDROLOGICAL POTENTIALS IN DEVELOPING COUNTRIES

(State of the Art and Research Priorities)

Office of Science and Technology
Agency for International Development
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January 1973

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PREFACE

This Report was prepared in connection with the activities of the Planning Group on Science, Technology, and Development established by the Organization for Economic Cooperation and Development. It is intended to serve as a basis for evaluating the current state of the art and research priorities with respect to techniques for assessing hydrological potentials in developing countries. This activity area was selected for analysis due to (1) its importance in the development context; (2) the relative neglect of research in the area by donor countries and international agencies; and (3) the likelihood that additional research will make major contributions to the solution of critical problems.

The Report is based in large part on a preliminary analysis prepared by the U.S. Geological Survey for the Agency for International Development 1/. This preliminary report was subsequently modified and supplemented as the result of comments solicited from numerous reviewers in U.S. Government agencies and universities, other donor countries, and international development institutions. A special panel of water experts from both developed and developing countries was then convened in conjunction with the First International Conference on the Transfer of Water Resources Knowledge, Colorado State University, September 14, 1972, to react to the revised document. The specific concerns and suggestions expressed by this panel served as the basis for preparing the final version of the Report.

Special appreciation is extended to the individuals in the following institutions which cooperated in the preparation and review of the Report:

--Organization for Economic Cooperation and Development (Development Centre)
--World Meteorological Organization (Hydrology and Water Resources Department)
--Food and Agricultural Organization (Land and Water Development Division)
--United Nations Resources and Transport Division
--United Nations Development Program
--International Bank for Reconstruction and Development
--O.R.S.T.O.M. (French Institute for Overseas Research), Paris

1/ Techniques for Assessing Water Resource Potentials in the Developing Countries (with emphasis on Streamflow, Erosion and Sediment Transport, Water Movement in Unsaturated Soils, Ground Water, and Remote Sensing in Hydrological Applications). George C. Taylor, U.S. Geological Survey Open File Report, December 1971.

--Brazil Ministry of Mines (Department of National Water and Electrical Engineering)
--Central American Hydrometeorological Project, San Jose, Costa Rica
--India Control Board for Major Products
--Mexico Federal Power Commission (Hydraulics Office)
--Pakistan Planning Commission (Water and Power Wing)
--South Africa Department of Water Affairs
--U.S. Geological Survey, Department of the Interior
--U.S. Office of Water Resources Research, Department of the Interior
--U.S. Bureau of Reclamation, Department of the Interior
--U.S. National Oceanic and Atmospheric Administration (National Weather Service)
--U.S. National Science Foundation (Office of Polar Programs)
--U.S. Environmental Protection Agency (Office of Water Programs)
--U.S. Department of Agriculture (Agriculture Research Service)
--U.S. Department of the Army (Engineer Agency for Resources Inventories)
--U.S. National Committee for the International Hydrological Decade, National Research Council/NAS-NAE
--Smithsonian Institution
--Colorado State University (Engineering Research Center)
--University of Arizona (Department of Hydrology and Water Resources)
--River Forecast Center (Sacramento, California)
--Geological Survey of Alabama

The Report describes current capabilities and future needs for assessing hydrological potentials under the following topical headings: Streamflow, Erosion and Sediment Transport, Water Movement in Unsaturated Soils, Ground Water, Precipitation, Evaporation, and Hydrologic Applications of Remote Sensing. Established techniques and methodologies are described under "State of the Art", while the most interesting emerging areas for attention by developing countries and foreign assistance agencies are presented under sub-topics entitled "Current Research" and "Research Opportunities for Application in Developing Countries." Where possible, generalized estimates of instrument and survey costs, based on 1971 U.S. prices, have been included. Given the close relationship between assessing the hydrological potential and developing and managing the water resource, a separate section has been added to the original scope of the report to describe some of the more promising research approaches toward improved utilization and protection of the resource. The Report does not cover measurement and monitoring of water quality although it is recognized that in many situations the chemical and physical properties of available water are major determinants of its utility and, hence, the overall "potential". Water quality has been omitted because of the current complexity and rapid evolution of the state-of-the-art of making such measurements, and the extensive literature that exists on the subject. Selected references are presented in the Bibliography.

CONTENTS

	Page
PREFACE	i
INTRODUCTION	1
STREAMFLOW	5
State of the art	5
Instrument and investigation costs	11
Recent and current research	13
Research opportunities for application in developing countries	15
EROSION AND SEDIMENT TRANSPORT	16
State of the art	17
Instrument and survey costs	18
Recent and current research	19
Research opportunities for application in developing countries	20
WATER MOVEMENT IN UNSATURATED SOILS	20
State of the art	21
Instrument and survey costs	22
Recent and current research	22
Research opportunities for application in developing countries	23
GROUND WATER	23
State of the art	24
Instrument and investigation costs	29
Recent and current research	30
Research opportunities for application in developing countries	32

Page

PRECIPITATION . . . 33

State of the art. 34

Recent and current research 36

Research opportunities for application in developing countries. 37

EVAPORATION 38

State of the art. 38

Recent and current research 41

Research opportunities for application in developing countries. 41

HYDROLOGIC APPLICATIONS OF REMOTE SENSING . . . 42

WATER DEVELOPMENT PRIORITIES. 51

CONCLUSIONS 56

SELECTED BIBLIOGRAPHY 59

INTRODUCTION

Although the earth is impregnated with or covered by vast amounts of water, relatively little is available for man's use. One significant constraint on more effective use of water is the present limited state of scientific knowledge and engineering technology related to water resources discovery, assessment, control and management. Yet ever-increasing demands are placed on available water resources by worldwide population growth and urbanization with attendant needs for greater food production through intensified irrigation and for disposal and dilution of man-generated wastes in the water environment. These demands, in turn, have stimulated rapid evolution of the science of hydrology during the past two decades toward a more sophisticated understanding of the natural role of water in the earth's physical, chemical, and biological processes. Advances in hydrologic science have also stimulated engineering technology to devise more effective ways and means for utilizing available water resources as well as water heretofore not available, notably "fossil" ground water,[1/] sea water and polar ice.

All water for man's needs must be obtained from the natural environment. To use and control water effectively requires knowledge acquired through collection, analysis and interpretation of hydrologic data. Such data includes observations of precipitation, snow cover, stream flow, ground water movement, sediment and solute transport, chemical quality, evaporation, soil moisture and many others. Also, the degree to which water resources can be effectively developed and utilized on a sustained basis is directly related to the level of understanding of the hydrologic environment. To draw the first bucket of water is easy enough, but to divert the flow of a large river from one drainage basin to another requires a high level of hydrologic knowledge and engineering technology.

At the present time it appears that conventional techniques for the measurement and evaluation of basic hydrologic parameters are well understood in most of the

1/ Water derived directly from the interior of the earth which has not previously existed as atmospheric or surface water, or been involved in the hydrologic cycle. It is sometimes referred to as "juvenile water."

the developing countries, albeit much more so in some than in others. On the other hand, application of these techniques is being impeded by institutional and economic constraints in many countries which inhibit the conduct of sustained programs of hydrologic data collection and, consequently, application of the data to priority national water resources development objectives. Moreover, experience in the less-advanced developing countries has proven that it may not always be feasible or even desirable to use more sophisticated methodology in hydrologic data collection and analysis, at least not until national hydrological institutions and local cadres of technicians and professional hydrologists have been developed. In addition -- and this is the major focus of this report -- hydrological assessments in developing countries are sometimes retarded by the unique climate, vegetative and geologic conditions encountered in unfamiliar tropical settings which limit or render inappropriate the use of instruments and methodologies utilized in advanced countries of the temperate regions. Consequently, the application of appropriate technologies to assess water potential must be geared to the circumstances and needs in individual developing countries.

The results of many types of hydrologic research in the more technologically advanced countries, although primarily directed toward domestic needs, are nevertheless potentially applicable to the rest of the world owing to universality of water problems. Such research can be grouped in three general categories as follows:

Process: Precipitation, evaporation, transpiration, infiltration and movement of soil moisture, surface and ground-water flow, channel flow, sedimentation, changes in chemical and physical quality.

Environmental: Study of water behavior in various climatic, geographic and geologic environments (e.g. tropical and arid zones, lakes and estuarine areas, and limestone and volcanic terranes); hydrological aspects of watershed management and water resources engineering, including irrigation and flood control; and water quality analysis, monitoring and protection.

Methodological: Mathematical analyses, use of digital and analog models of transient phenomena, nuclear and physiochemical techniques, automatic processing of data and use of computers, instrument development, water information systems, etc.

The developing countries, naturally, place highest priority on research oriented toward water resources development to meet pressing needs for economic growth. On the other hand, the developed countries are currently giving high priority to research designed to protect and conserve known and utilized water resources and to control deterioration of their quality.

There has been a number of outstanding international efforts over the past decade to advance and expand knowledge in scientific and applied hydrology which has been particularly relevant to the needs of developing countries. The International Hydrological Decade (IHD), initiated in early 1965 under the aegis of UNESCO with strong participation by UN specialized agencies and national committees of 107 governments, has played a key role in fostering scientific and technical exchange among participating agencies and governments; in furthering establishment of national networks for collection of basic hydrologic data; and in strengthening national programs of hydrologic research on a world-wide scale. The World Meteorological Organization has undertaken a broadly based program in the area of operational hydrology[1/] directed toward the establishment of relevant degrees of standardization in instruments, methods of observations and techniques of hydrological analysis for the developed countries, and providing technical guidance in operational hydrology to the developing countries. In addition, a large number of internationally-oriented water conferences, such as the Water for Peace Conference in 1967 and the aforementioned International Conference on Transfer of Water Resources Knowledge held in 1972, provided opportunities for in-depth evaluations and discussions of various aspects of hydrologic measurements of relevance to developing countries. The proceedings of these meetings afford detailed supplementary information on many of the topics covered in this report.

Finally, the principal components of the hydrological cycle (e.g., precipitation, streamflow) are discussed separately in this report only because such disaggregation facilitates treatment of the subject matter. It is clearly recognized, and is implicit throughout the document, that we are dealing with a truly integrated, dynamically - interactive "cycle", and that the design and implementation of

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1/ Operational hydrology includes specification and installation of network stations and instruments; and measurement, collection, processing, transmission, storage, retrieval and publication of data for general hydrologic purposes and for forecasting.

water development projects, data collection networks, and systems models which involve measurement of hydrologic potential must be based on a full appreciation and understanding of the complex of interactions.

STREAMFLOW

Man's observation and measurement of the stage and discharge of rivers dates from antiquity when such knowledge was particularly important in the hydraulic cultures of the Nile Valley, Mesopotamia and the Indus Basin. Measurements of discharge were admittedly no more than crude estimates, but accurate observations of river stage were possible with simple staff gages. For example, the flood stage of the Nile at Roda near the head of the delta has been observed and recorded for more than 2,000 years.

State of the art

Observation and measurement of streamflow are fundamental to all broadly-based water resources investigations and particularly so to those dealing with surface-water resources. Also, as the water in streams is the most readily available and widely used component of the water mass in the hydrological cycle, methods and techniques of observation and measurement are highly developed. Consequently, it is possible to measure streamflow with a higher degree of accuracy than most other hydrologic parameters.

Perfected by repeated experiments during the past 80 years, the most basic and universally accepted instrument for measurement of streamflow is the current meter which enables one to measure velocity at selected depths in a vertical section of a stream. With this information and measurements of channel widths and depths, the point (in time) discharge of a stream can be determined. Observations of stream stage are conventionally made by reading a calibrated staff gage at a selected station--usually daily at a specific time. Continuous observations of stage at selected stations can be obtained by means of permanently installed clock-driven recorders with float and cable-driven drums. Graphs of changing stream stage are automatically registered by pen on calibrated charts mounted on the drums.

Records of actual flow volume are obtained from rating curves which are constructed by correlating stream stages with measured discharge. A common unit of flow is "daily discharge", which is the average volume for a calendar day. Daily discharge in the metric system is expressed in cubic meters or liters per second, and in the English system, in cubic feet per second. Annual runoff from watersheds or river basins is commonly expressed in millimeters of water or units comparable to those used for precipitation and evapotranspiration.

Discharge measurements in small shallow streams are made with the current meter attached to a calibrated staff as the observer wades the stream. For deep, wide and swift streams, the current meter is attached to a weighted cable which is lowered from a calibrated reel into the water by the observer from a boat, a bridge, or a suspended cableway. The number, location and distribution of stream-gaging stations on a river system would depend on such factors as run-off characteristics, diversions from streams for human use, silt and bed load character, and intended use of stream-flow information.

One of the most significant innovations in the collection of hydrologic data in the developed countries over the past two decades is the <u>digital recorder</u> used for the measurement of river stages. This instrument punches a digitized record of water level on a paper tape in a manner compatible with systems of computation by high-speed digital computers. The records may be used with any of several stage-sensing devices--floats, pressure transducers, or gas-purge (bubble gage) systems of head-pressure sensing.

The processing of the data begins with a stage record obtained from a digital recorder gage and ends with a computer printout listing mean daily discharge rates, computed monthly and annual averages, maximum and minimum rates of flow during monthly and annual periods, and flood-hydrograph data for floods meeting pre-selected criteria. The processing procedure is called a "gage to page" plan, for almost the entire process is accomplished by the use of machines with manual quality control utilized to correct errors caused by faulty operation of instruments and to interpolate when records are missing. The printout from the computer is ready for reproduction by photographic methods for formal publication.

Another significant development in the collection of river data is the invention of a stage-sensing device called a "bubble gage". This gage was developed to record reservoir and river stages at those sites where stilling wells and intake pipes are difficult to install and maintain.

The gage consists of a specially designed servomanometer, a transistorized control, a gas-purge system, and a recorder. The pressure corresponding to the head of water is brought to the manometer by the gas-purge system. Nitrogen gas is discharged slowly through plastic tubing from the gage house to an orifice located at a fixed elevation in the stream. The pressure at the orifice, and hence at any point in the delving tube, is related to the head or depth of water over the orifice. This pressure is in turn transferred to the manometer and then to the recording device. The manometers have a sensitivity of ± 0.005 foot, and the entire assemblage can be constructed to record ranges in stage in excess of 120 feet. A differential type of manometer may be adapted to the instrument to record directly the slope in a short reach of river channel.

Perhaps the most significant breakthrough in stream gaging in recent years is the "moving-boat" method which is admirably suited to the accurate and rapid measurement of large rivers in remote areas. The method requires no fixed facilities and lends itself to use of alternative sites if necessary. As with conventional current-meter measurements, the moving-boat technique requires information on the location of observation points, stream depth at each observation point, and stream velocity perpendicular to the cross section at each section of each observation point.

During the traverse of the boat across the river, a sonic sounder records the geometry of the cross section and a continuously operating current meter senses the combined stream and boat velocities. A vertical vane aligns itself in a direction parallel to the movement of water past it, and an angle indicator attached to the vane assembly indicates the angle between the vane and the true course of the boat.

The data from these instruments provide information necessary for computing the discharge for the cross section. Normally, data are collected at 30 to 40 observation points in the cross section for each run. As a point of interest--individual measurements of the Amazon River at Obidos, Brazil in 1963-64 required 1 1/2 to 2 days to complete by conventional methods. In late 1969, measurements at the same site and of comparable accuracy were found to require only about 20 minutes each by the moving-boat technique.

Dye-dilution methods of discharge measurement, known for more than 100 years, have also undergone considerable refinement in recent years. The development of commercially available fluorescent dyes and fluorometers, which can detect these dyes at concentrations as low as 0.5 part per billion, has greatly enhanced the use of dilution methods. In general, dye-dilution methods for measurement of discharge are not economically competitive with the current meter.

There are, however, several common flow conditions for which dye-dilution methods offer considerable promise. These are turbulent mountain streams, flow beneath ice cover and flow in closed conduits. Continuous or periodic measurement of flow in sand channels by means of automatic dye injection and sampling equipment is in the experimental stage. Dye-dilution techniques have also been used successfully for in-site calibration of orifices, weirs, flumes and laboratory models of spillways. Dilution measurements can be made by injecting a dye tracer at a constant rate for a given period of time, or by injecting a known volume of dye instantaneously. The accuracy of both methods is inherently related to dye loss in the measurement reach. Of course, the accuracy is also dependent on the mixing characteristics of the channel reach and the measurement of dye concentrations.

Much effort is being expended in the developed countries in the perfection of techniques of analysis for the generalization and synthesis of streamflow data. It is never possible to collect information at all potential sites of need. The problem usually faced requires generalization of existing data in such manner as to form a basis for the synthesis of flow data at ungaged sites to acceptable limits of accuracy. For example, methods for generalizing flood experience have been developed. One of these procedures uses statistical methods to choose geographic areas within which flood generation and probability are homogeneous. Flood experiences at all stations within these areas are composited to develop flood-frequency curves of much broader base than possible from records for a single station. The sizes of floods generated within these areas are expressed as ratios to the mear annual flood.

The single-size parameter, the mean annual flood, is related graphically to drainage area size and other topographic factors. To determine the size of a design flood in an ungaged area by this method, the following steps are taken: (a) determine the mean annual flood for the stream in question, using the graphical relationships and the applicable topographic factors, (b) derive the ratio of the design flood to the mean annual flood from the composite flood-frequency curve for the area in which the stream is located, and (c) multiply the mean annual flood determined in step (a) by the ratio determined in step (b).

Several other more or less sophisticated methods of generalizing flood experience are in common use. The choice between them usually depends on the amount of basic data at hand and on the personal preference of those engaged in the study. Techniques for the generalization of other streamflow data, such as mean annual runoff or low-flow quantities, are in common use in the developed countries. The description of even a sample of these techniques is not possible here.

Perhaps the most difficult problem facing water-data program planners is the design of appropriate networks for the collection of field measurements. The essence of network planning is to achieve some stated operational goal to meet a stated objective, not only for scientific reasons, but for administrative reasons as well. Therefore there is a need to evaluate as soon as possible a newly established data network and to re-evaluate constantly operating networks. A first step (where a network exists) is the classification of stations as to the purpose they serve--current purpose or resource evaluation--and their hydrologic coverage. A second step is the assessment of the information that will be needed considering present and prospective developments (this would become the first step in a no-network area). The third step would be the consideration of the various methods of meeting the informational needs subject to the applicable socio-economic constraints: usage of long and short-term stations, storage gauges, partial record stations and information transfer techniques.

Thus, intuitive and judgment factors are utilized in beginning such data collection networks. Appropriate weight is given to sampling areas having different topography, geology, and climate, and to existing needs for data at specific sites. As techniques are improved, and the needs for data increase, networks are expanded. As the network of streamflow gaging stations in a given country grows, it is necessary from time to time to evaluate the entire network. The principal classifications of stations that might be derived from such an evaluation would be as follows: (a) primary stations: those having essential hydrologic significance and operated for indefinitely long periods, (b) secondary stations: those at which continuous flow records are obtained for a period of only a few years (5 to 10), and (c) partial-record stations: those at which flows, or stages, are measured only during extremes of either high or low conditions. In testing the existing design of primary gaging stations, statistical methods are used to determine the degree of independence of stations in the network. With these criteria it is possible to eliminate some stations and to pinpoint new areas needing gaging. Thus the optimum extent of the required primary network is determined.

The basic rationale in the use of networks of secondary and partial-record stations is to obtain a maximum amount of data at minimum cost. Modern statistical methods in hydrology permit records from these shorter or less complete operations to be extrapolated to accurate estimates of flow parameters for longer periods. Networks of such stations become more dense as water development proceeds in an area and the need for more detailed hydrologic information increases.

A final consideration is the preservation of the data in a place and in a form useful and available to all. The emphasis in the developed countries is on data, accurate by high technical standards, centrally filed, permanently preserved, and readily available. High consideration is given to the introduction of new techniques where they have promise of adding accuracy or decreasing costs.

Virtually all the foregoing techniques and methodologies have been applied at one time or another in the developing countries with mixed measures of success. Streamflow measurement by conventional current meter methods, coupled with staff gage observations for river stage, is in almost worldwide use and is still the most trustworthy method in the majority of the developing countries. Graphic style recorders for more complete stage data are also widely and successfully used in the more advanced developing countries. However, even these relatively simple instruments require maintenance of a nature which inhibits their widespread and systematic use in the more remote regions of the world.

The digital recorder coupled with computers has been used experimentally in a few advanced developing countries; however, the high cost and sophisticated technology required mitigate against its wider application in these countries. The same can be said for the bubble gage recorder. Several of these, for example, were installed on the Mekong River in southeast Asia during the early 1960s and all are now inoperative owing to instrument and maintenance problems beyond the ken of the technical staff.

The dye-dilution method for discharge measurement has been used occasionally for special hydraulic model studies in the developing countries, notably in India, Pakistan, Egypt, and Turkey but is generally considered to be too costly for routine use in natural stream channels.

The moving-boat method developed during the past decade by the U.S. Geological Survey has been proven through repeated trials to be unquestionably the most efficient and economic means of gaging large rivers in remote areas. The method has now been applied successfully on the Amazon and Sao Francisco Rivers in Brazil, the Parana River in Argentina and the Mekong River in Thailand and Laos. It has the advantages of speed, high mobility and relatively low cost and thus has wide potential application throughout the developing world.

Office-based operations such as network design and evaluation, analysis and/or synthesis of stream-flow data, and processing and publication of hydrologic records present fewer logistic problems in the developing countries than do field observations and data collection. Nevertheless, the quality of office operations depends on intelligent direction, high standards, adequate financial support, and the personal motivation and competence of assigned office professionals and technicians.

Instrument and Investigation Costs[1/]

The costs for hydrologic instrumentation and for construction and operation of gaging stations for streamflow measurement range through a wide gamut and depend among other factors on gaging site location and accessibility, size and physical behavior of the stream at the gaging site, and the nature and duration of the hydrologic records required at the site. Gross estimates of some of the more significant of these costs are given below:

Simple staff gage station:

Construction and material costs----------	$ 250
Observer services and maintenance per year------------------------------	300

1/ Costs of equipment and, particularly, technical experts vary widely from country to country. In addition, they are likely to be affected by inflation rates of 5-10 percent and higher. Thus, the data presented in this report should be interpreted as providing relative and indicative cost information, and not current market-place prices.

Simple gaging station with automatic graphic recorder:

Construction and material costs	$ 2,500
Instrumentation	1,000
Hydrologist services and maintenance per year	1,500

Complex gaging station on major river with digital recorder, telemetry, cableway, and other instrumentation:

Construction and material costs	$25,000
Instrumentation	10,000
Hydrologist services and maintenance per year	15,000

Equipping one field hydrologist with current meter and ancillary equipment for simple streamgaging	$ 1,500
One continuous graphic water-stage recorder with ancillary equipment	700
One bubble-gage recorder with auxiliary equipment	1,500
One digital recorder with ancillary equipment	700

Moving-boat technique:

Instrumentation	3,500
Boat and motor	5,000 to 10,000

As an example of field operations for a typical (but hypothetical) surface-water investigations program in a small developing country with a network of 50 gaging stations, (costs estimated for the U.S.A., 1971) might approximate the following:

Installation of 50 staff gages	$12,500
Observer services and maintenance of the above, per year	15,000
Installation of 10 simple gaging stations with automatic graphic recorders	35,000
Hydrologist services and station maintenance, per year	15,000

Equipping 2 hydrologists for stream gaging	$ 3,000
Costs for 12 discharge measurements (one per month at $100 per measurement) at 50 stations per year	60,000
	$140,500

Office computations; compilation and processing of data; publication of records; and administrative and technical support of personnel might cost $50,000 to $60,000 a year bringing the initial cost of the program to about $200,000 a year. Continuing costs, however, would be in the order of $150,000 per year. For a large developing country, these costs might well be doubled or tripled.

Recent and Current Research

Recent and ongoing research in streamflow instrumentation and methodology may be grouped into two categories; (1) analysis, manipulation and interpretation of streamflow data; (2) improvement of proven, and development of new, instruments and methods.

With respect to the first category, much research is centered on the use of more sophisticated means of storing, retrieving and manipulating masses of streamflow data which have already been accumulated, as well as those yet to be collected, and also on the production of aids to interpretation of the data by computer methods. Automatic processing of hydrologic data is finding increasing favor in developing countries with large backlogs of unprocessed, unverified, and unpublished hydrologic data, particularly streamflow records. Such data are only of limited value until compiled in usable form so that they can be interpreted by professionals in terms of significant hydrologic parameters.

Several developing countries are resorting to automatic data processing to bring hydrologic records up-to-date and to keep them current, as for example Pakistan and India in south Asia; Brazil, Chile, Argentina and Mexico in Latin America; and Egypt, Tunisia, Nigeria and Zambia in Africa. National data banks with capability for storing, retrieving and manipulating masses of streamflow data could be much more widely used in the developing world in water resources investigations and management.

With respect to the second category, many governmental and private agencies in the developed countries are continuing the search for more accurate instrumentation and improved methodology to lower costs and to increase efficiency and flexibility. Mathematical modelling of hydrologic systems has undergone rapid evolution in the past decade, particularly with the wider application of digital and analog computers to complex water problems. Such models simulate natural and man-made stimuli for changes in hydrologic systems and may be either responsive or predictive.

Parametric modelling is the most widely used of modelling approaches. Since it requires input data with considerable detail in time it models transient responses well. Parametric modelling includes component modelling on the one hand and integrated system modelling on the other. In the former, individual components such as infiltration, evapotranspiration, aquifer response and streamflow routing might be considered. Integrated system modelling might consider, as examples, hydrological forecasting, rainfall-runoff and streamflow-aquifer relations, runoff prediction in various climatic and physiographic regimes, or ground-water basin modelling.

Conventional techniques for measuring discharge of streamflow by current water meters are standardized and well-known. Traditional means of measurement are not well suited, however, to conditions in large rivers influenced by tides, in extreme flood, in shallow turbulent mountain streams or in flow under ice cover. One evolving method for measuring discharge in tidal streams, where no stable stage-discharge relationship exists, is through use of the pendulum-type deflection vane. At gaging sites with stable channels, cross-sectional area is obtained from records of water stage. Mean velocity can be usually related to an index velocity at some point within the cross section. The index velocity can be obtained by the pendulum-type deflection vane. This type of vane can be installed totally submerged reducing the possibility for collecting floating debris near the river surface and for damage from ice jams.

A special depth-sounding and velocity-measuring device has also been recently developed for measuring extreme flood flows. This instrument combines a fathometer, a direction compass, and a Price current meter, and permits measurements of depth, direction of current and near-surface velocity with a single setting and without encountering the hazards of complete depth sounding by sounding weight. The technique of augmenting continuous flood records by operation of only crest-stage gages has been enhanced by the development a small cheap water stage recorder. This recorder may be operated intermittently in a 3-inch pipe well to obtain only flood hydrographs.

Nuclear techniques as applied to streamflow measurement are also evolving rapidly. Radioisotope tracers can be used in stream-gaging where current meter measurements may be impractical, such as in turbulent high-debris floods or mountain torrents. Radioisotopes are also used for time-of-travel flood-flow tracing and for tracing leakage from water conveyance structures or seepage from natural stream channels. Such techniques have already been applied experimentally by the International Atomic Energy Agency (IAEA) in a number of developing countries including Brazil, Turkey, Kenya, Chad, Greece, and Senegal. There is opportunity, however, for much wider application of these techniques in the developing world.

Research Opportunities for Application In Developing countries

Currently-available streamflow-measuring instruments run the gamut from inexpensive, simple measurement devices to highly sophisticated, expensive automated systems. Virtually all of them are directly applicable or easily adaptable to the streamflow parameters likely to be encountered in developing countries.

A principal need with respect to instrumentation is for low-cost automated instruments for unattended operation in remote locations. Such instruments should be designed for easy calibration and should be sturdy enough to withstand the rigors of harsh environments. Another need is for development of a device to convert existing strip chart records into digital records. As costs of digital records are reduced and used by more developing countries, there will be an increasing demand to change rainfall records from the old system to the new one.

Proven techniques designed in the developed countries for measuring and analyzing streamflow data also appear adequate for most applications in the developing countries. Ongoing research on modelling of hydrologic systems and on automatic data processing (as described in the previous section) should continue to be pursued vigorously. This research is not of an "adaptive" nature however, and can continue to be carried out by, and for, the more advanced nations. Obviously, benefits from breakthroughs will accrue to all countries which have the trained manpower and technological capacity (e.g., computers) to adopt them due to the apparent direct transferrability of the general concepts and methods. The biggest non-institutional gap with respect to application of new techniques is lack of basic data on streamflow characteristics needed to build acceptable analog or computer models.

Investigations of minimum data requirements are also needed, adopted to different types and sizes of water bodies and watersheds. Given the costs of data collecting, and the relative unavailability of instruments in many developing countries, improved guidance is needed on what to measure, where, and how often in order to maximize collection of essential data and to minimize extraneous data and, most important, the overall cost of data collection, analysis, and file maintenance.

EROSION AND SEDIMENT TRANSPORT

Erosion and sediment transport phenomena are operative in greater or lesser degree on most of the exposed surfaces of the earth. Erosion often begins with the impact of raindrops on the land surface and continues with the cutting force of running water in stream channels. Sediment transport begins in rill wash on exposed soils, continues as suspended and bedload materials in natural stream channels, and ends with deposition in flood plains, lakes, reservoirs and the oceans.

Although commonly included in the science of geomorphology, erosion and sediment transport processes are nevertheless of great importance in hydrology and to practical problems of water use and management everywhere. Questions that the hydrologist might expect to be asked could include, for example

What is the useful life of the reservoir?
What will happen to the stream (channel) above and below the dam when it is completed?
What will be the effect of artificial levees on the stream channels?
What will happen if the reach of the river is straightened?
What type of bank protection is needed to prevent the river bank from eroding?
What depth of scour can be expected at the bridge pier?

To answer questions such as these, a variety of instrumentation and methodology has been developed, some of which are briefly outlined in following sections.

State of the art

For many years streamflow data collection programs in the developed countries have also included provision for determination of the wash load (about 80-90 percent of the total) of transported sediment in stream channels. The suspended load is conventionally measured with a depth-integrating sampler, which typically consists of a stream-lined case carrying a conventional milk bottle as the collecting container. An exhaust vent allows escape of air when water enters the bottle and keeps the inlet velocity approximately equal to that of the stream current. Interchangeable inlet nozzles of various sizes are available to adjust the rate of filling of the bottle. The sampler is suspended in the stream from a wading rod or cable. Tail vanes are provided for large samplers to keep them stable when suspended from a cable. At a uniform speed, the sampler is lowered from the surface to the bottom of the stream then raised to the surface. The sample thus collected is an integrated quantity, with the relative portion collected at any depth proportional to the velocity (or discharge) at that depth.

During recent years several models and sizes of depth-integrating samplers have been developed for use in different types of streams under varying conditions. Continuous sediment samplers are also commonly included as components of stream-gaging stations with automatic recorders.

Bed material sampling under flowing water is difficult because the finer particles are frequently lost in the sampling process and because the instrument itself disturbs the flow path and hence the material being moved. Clamshells (as for example the Foerst bed-material sampler) and similar grabbing devices are commonly used but must be carefully checked for leaks. Bucket-type devices, which sample as they are dragged over the bottom, present similar problems.

Reservoir sedimentation surveys are generally made by measuring the accumulation of sediment in a reservoir of known age against original bottom configuration (commonly from original topographic maps) and adjusting for sediment losses over the spillway. Sediment accumulation can be measured periodically by boat, sextant and fathometer traverses along established range lines with boat position fixed by on-shore transit. Accumulation of sediment can also be determined by periodic sampling of streams flowing into a reservoir.

Radioisotope tracers are also being used increasingly for sediment studies such as determining the direction and velocity of sediment transport in streams; the stream-bed length affected by transport; the effects of transport on stream-bed configuration; and longitudinal and transverse dispersion coefficients. Erosion processes are also being studied by labelling soil particles with suitable radioisotopes and monitoring the decrease of activity with time in experimental plots. Valuable information can be obtained by this method on the roles played by splash or raindrops and overland rill wash in erosion of soil and the relation between erosion and the duration and intensity of precipitation.

Sediment sampling programs have been undertaken on a small scale in many developing countries in conjunction with basic stream-gaging networks. There are, however, at present few viable or systematic programs of sediment data collection extant among the developing countries. The chief problem is usually cost. In many instances developing countries choose to dedicate limited financial resources to streamflow data collection and neglect in the process to give adequate attention to sediment data. A reordering of priorities is the indicated corrective measure.

Instrument and Survey Costs

Sediment sampling and survey programs are commonly integrated with stream-gaging networks. Costs for sediment sampling instrumentation, however, must be identified over and above those for streamflow instrumentation described in the previous section. Some of the more significant costs for conventional instrumentation and surveys (estimated for the U.S.A., 1971, except as noted) are given below:

Instrumentation for automatic sediment measurement at one stream-gaging station--	$ 2,500
Equipping one field hydrologist with sampler(s) and ancillary equipment for simple sediment sampling-------------	1,500
One hand-operated sediment sampler---------	700

One complete sediment determination laboratory facility with full instrumentation (based on experience in Brazil)	$ 25,000
One complete reservoir sedimentation survey including equipment and personnel costs (based on experience in Afghanistan)	25,000
One large combined outdoor and indoor hydraulic modelling facility (based on experience in Turkey)	150,000
One small outdoor hydraulic modelling facility (based on experience in Brazil)	50,000

Recent and Current Research

Most current research in erosion-sedimentation problems is directed toward better understanding of the mechanics of initial sediment movement in stream channels, bed-load movement, suspended-load movement, channel-bed form, sediment yield, scour at engineering structures, riprap, and river-control works and canal design. Applied research on problems of this nature is being actively pursued through studies of operating scale hydraulic models in virtually all of the more advanced developing countries as for example Brazil, Chile, Venezuela, India, Pakistan, Iran, Turkey and Thailand, to name several. Applications of mathematical modelling to erosion-sedimentation problems in the developing countries is of more recent vintage. Mathematical models should, however, gain increasing favor in the near future because they are versatile and involve much lower initial investment and continuing cost than operating hydraulic models.

Nucleonic instruments have been developed during the past decade and are now being perfected for estimation of the suspended sediment concentration of streams. They offer some attractive advantages over conventional methods. The nucleonic instruments provide continuous measurement and immediate readings in the field and eliminate the need for collection of samples to be taken to a sediment laboratory for analysis. Two general types of gages have been developed, one for semi-permanent installation and the other a portable unit. Both work on the principle of attenuation of a beam of low-energy electromagnetic radiation by the suspended sediment. These gages operate in the concentration range

0.1 to 50 grams per liter with an accuracy of $\pm$ 20% for low concentrations improving to $\pm$ 5% for higher concentrations. The t. types of gages are complementary. The portable instrument can be used for spot measurements and also for the siting of the semi-permanent gage, which can provide continuous monitoring of suspended sediment concentration.

Nucleonic instruments for sediment studies have been used experimentally in the developing countries and offer considerable promise for wider applic ion if initial costs can be reduced.

Research Opportunities For Application In Developing Countries

As in the case of streamflow measurement and interpretation, the broad range of instruments and techniques currently available for investigating erosion and sediment transport phenomena appears to be directly applicable, or easily adaptable, to developing country needs. However, virtually all have shortcomings -- either in terms of accuracy and reproducibility, or in the high costs of procurement and operation -- which suggests that additional research in this general area might have significant payoffs. A special need is development of better methods of measuring stream bed-loads for introduction into developing countries.

Short-term objectives should include simplifying and reducing the costs of the more sophisticated instrumentation, particularly that based on nuclear techniques. A second important need is to develop a better understanding of sediment source areas (i.e., provenance studies) and the rate of erosion associated with difference rock types, vegetative covers and cultural patterns unique to developing countries. Such research could provide the basis for improving the sedimentation data input into existing and emerging predictive models of specific hydrologic systems.

WATER MOVEMENT IN UNSATURATED SOILS

Soil scientists, hydrologists and engineers are, and have long been, concerned with that part of the hydrological cycle which deals with the transport of water from the land surface through the soil profile down to the water table. A variety of hydrologic processes occur in this zone, including infiltration, redistribution, percolation, drainage, and evaporation. The water content of the zone is in constant flux, being either in the process of abstraction from the soil profile by evapotranspiration, or of replenishment by rainfall or irrigation. Knowledge of water availability requires detailed mapping of water content and pressure-head distributions in space and time. What is needed are techniques for estimating the flux of water past a given point and the pressure head or water content at the same point.

State of the art

Instrumentation and techniques evolved in recent decades in the developed countries include: the tensiometer for field measurement of point pressure head; buried porous blocks of gypsum or fiberglass; and laboratory "hanging water column" and pressure cell methods for determination of pressure-head and water content of soil samples.

The tensiometer in its simplest form consists of a stoppered water-filled column attached to a porous cup or cell, which is placed in a chosen position in the soil profile. The column is connected to a vacuum gage or manometer. When the cell is positioned in the soil, water moves from the porous cup into the surrounding soil, causing thereby a reduction of pressure within the instrument and the consequent depression of the mercury in the right arm of the manometer. The drier the soil, the greater will be the amount of water leaving the cup and the greater therefore, the depression of the mercury. The level of mercury will remain steady once the suctions in the cup and the surrounding soil are in equilibrium. Tensiometers give fairly accurate results within their operational range.

Buried porous Bouyoucos blocks provide an alternative means of measuring soil moisture suction (negative pressure head) beyond the range of the normal tensiometer. Blocks of gypsum or fiber-glass are buried in relatively undisturbed field situations to measure in situ moisture changes. The method is based on the fact that as the moisture content of the block changes so does its capacitance or its electrical or thermal conductivity which can be readily measured.

The "hanging water column" or Haines apparatus uses a saturated sample of representative soil which is placed on a porous plate attached to a vessel with a water-filled open-armed U-tube. The water level in the open-arm is lowered to a chosen position. The soil solution flows out of the sample and a hydraulic equilibrium is established between the soil water and the water in the "hanging" column. The pressure head at equilibrium is measured by the vertical distance from the soil sample to the free water level in the open arm. The water content of the soil sample is obtained either by direct gravimetry or by indirect means such as measuring the volume of outflow.

The pressure cell method uses gas pressure applied to the top surface of a soil sample resting on a porous plate or membrane whose pores contain water at atmospheric pressure. When the applied pressure just fails to drive water from the soil pores, the applied pressure is considered to equal the soil moisture suction force against which it is working. The expelled water is collected in a container and weighed periodically.

Studies of soil moisture have been undertaken in most of the advanced developing countries during the past 25 years, but mostly in connection with soil surveys and land-use problems. Relatively little attention has been given, however, to movement of water in unsaturated soils as related to hydrologic processes and much remains to be done in this field.

Instrument and Survey Costs

Some of the basic costs for instrumentation in soil moisture determinations are given below (for the U.S.A. in 1971). This list, however, is by no means comprehensive.

One simple field tensiometer----------------	$ 200
One set of Bouyoucos blocks with electrical conductivity meter----------------------	500
One "hanging water column" apparatus for laboratory use with auxiliary equipment---	1,000

Recent and Current Research

Perhaps the most notable advance in recent years in the measurement of moisture in unsaturated soils is the neutron moisture gage, which is still undergoing development. The gage consists of a probe, which can be set at various depths, containing a source of fast neutrons and a detector for slow neutrons, which is connected with an electronic instrument. This instrument displays the slow neutron count rate. The principle of operation is that the fast neutrons are slowed down by elastic collision with hydrogen atoms, which occur primarily in the water molecules. Thus the count rate is a function of the moisture content of the soil. Proper interpretation in use of this technique requires knowledge of the soil bulk density, so it is common now to have a combined soil moisture-density gage. The neutron moisture gage offers a number of advantages over conventional methods previously described, such as being non-destructive, easily repetitive, rapid and convenient.

The development of methods for satisfactory hydraulic conductivity and diffusivity measurement in the unsaturated zone continues to be an important research need.

Research Opportunities for Application In Developing Countries

The assessment of water movement in unsaturated soils of developing countries is not being seriously impeded either by the absence of knowledge of how to measure, or by the lack of adequate instrumentation. A variety of proven conventional techniques and equipment exist which are relatively simple to utilize and available at a fairly modest cost. In addition, a growing array of nuclear-based instruments are being developed which have already greatly advanced the state-of-the-art in this field by virtue of their simplicity and speed of operation, as well as by their improved accuracy.

Based on this perspective, priority research areas would appear to include: (1) lowering the cost of nuclear instrumentation; (2) development of new methods for measuring hydraulic conductivity and diffusivity; and (3) intensive investigation of the behavior of water infiltrating into, or contained within, a variety of pervasive but poorly understood soils of developing regions (e.g., unique chemical, physical, and biological properties of lateritic soils).

GROUND WATER

Ground water, or water in the saturated portion of the earth's crust that sustains springs and is tapped by wells, is perhaps the most widespread source of available water for the use of man. Because it must be measured and observed indirectly, however, its physical behavior is not as well understood as that of surface water. Nevertheless, ground water is extensively developed for rural water supplies, particularly in areas remote from perennial streams. Also in arid and semiarid regions, ground-water reservoirs assume special importance, as perennial streams may be widely separated or non-existent, and wells may provide the only dependable source of water for domestic, livestock, irrigation, municipal and industrial use. Even in more humid regions, ground water may be developed in preference to surface water because of easy accessibility, superior sanitary quality, freedom from suspended material and relatively uniform temperature. Although ground water is mobile, it generally moves at slower rates and through relatively shorter distances underground than does water in open stream channels. Consequently, it must be used essentially where it is found and hence from a practical standpoint usually is not exportable.

State of the art

During the past two decades, important emphasis has been given to the search for and the exploitation of ground water in the developing countries, particularly those in the arid and semi-arid tropics. Optimum utilization of the resource demands adequate appraisal through collection of relevant data by appropriate surveys and the analysis and synthesis of such data both before and subsequent to development. Ground water, of course, is a phase of the hydrologic cycle, but the investigation of this water involves techniques and methods that may be distinctly different from those appropriate to other phases of the cycle.

The study of ground water entails evaluation of the interrelations of the biological, physical, and chemical characteristics of the water in terms of its geological environment as well as evaluations of other phases of the hydrologic cycle, both in time and in space. Such study includes as important elements the areal occurrence, rate and direction of movement, the natural recharge-discharge balance, the geochemical balance of dissolved solids in the water resulting from natural and artificial causes, and the hydraulic response of aquifers to man-made changes in the natural regimen.

The techniques employed in ground-water investigations depend in large measure on the relative sophistication, complexity, and scope of the actual or proposed development of a ground-water system. A total evaluation might include surface and subsurface geological, surface and subsurface geophysical, geochemical, hydraulic, and hydrological studies.

A simpler ground-water investigation, however, might include only a few selected segments from among these.

Good aerial photography and topographic maps are fundamental to all surveys related to ground water. Also, as the rocks are the natural reservoirs in which ground water is stored, and the natural conduits through which it circulates, knowledge of the geologic framework of a ground-water system is essential to its understanding. Surface and subsurface geologic surveys provide important information on structural features, such as faults, folds, and unconformities, and on the areal distribution of water-bearing formations (aquifers) and associated impermeable formations (aquicludes). All these geologic features affect the head, direction, and rate of movement of ground water; the chemical quality of the water; and the design of development programs.

During the past two decades, geophysical studies have been used extensively in the developing countries in quantitative and semi-quantitative evaluations of ground-water systems. Among surface geophysical methods, electrical-resistivity, seismic, aeromagnetic, gravimetric, and sonar surveys have been employed with varying degrees of success, depending upon accessibility and the geologic character of the area surveyed. It must be understood, however, that most geophysical data analysis is subject to the inherent problem that an equal response can be brought about by widely differing lithologic and stratigraphic conditions and that a proper interpretation of a given data in terms of actual field conditions requires a thorough knowledge of the geology of the area. Surface electrical-resistivity surveys[1/] are used successfully in one-, two-, and even three-layer systems, where marked discontinuities occur in the electrical-resistivity profile and where the thickness of each layer is appreciable in relation to the depth of the discontinuity. Such surveys are particularly useful in establishing fresh water-salt water interfaces in coastal aquifers.

Seismic surveys are used mainly to map discontinuities between impermeable bedrock and overlying water-bearing unconsolidated or semi-consolidated sediments. The method is adequate only where there is a marked contrast in the

1/ Electric-resistivity surveys induce electricity into the ground and measure the resistance of earth materials to its flow.

elastic properties of the two types of rock.

Aeromagnetic and gravimetric methods are also used to locate buried bedrock surfaces where appreciable discontinuities in rock magnetism and density exist in two-layer systems. Aeromagnetic methods are particularly useful where rapid reconnaissance interpretation of the occurrence of aquifers is required over broad regions. Mapping of bedrock surfaces and thickness of unconsolidated overlying deposits by techniques and equipment using low-frequency sound waves also is finding increasing application, particularly in underwater problems in coastal areas. The principles employed are the same as those used in sonic depth finders.

Subsurface or borehole geophysical methods are now widely employed in practically all moderately intensive or detailed ground-water investigations in the developing countries. Electrical logging is perhaps the most useful probing tool in distinguishing aquifer contacts, formation porosity, water quality, and fresh-salt water interfaces in uncased boreholes. Also, this method can be used quantitatively, if other supplementary field data are available. Gamma-ray, gamma-gamma, neutron-gamma, and neutron-neutron logging is also increasingly used for stratigraphic correlation; and for determining porosity, water saturation, bulk density, and water quality in subsurface formations. Proper interpretation, however, of such radiation logs requires a considerable fund of knowledge of the local lithology. Limestones and dolomites, for example, have radioactive intensities similar to sandstone.

The importance of depth-temperature relations in ground-water systems is increasingly recognized, particularly with respect to water viscosity and the effective permeability of aquifers. An important tool in the analysis of these relations is the temperature log, which utilizes conventional electrical logging circuits to measure resistance change of a temperature-sensitive metallic conductor. By this method, which can be used in both cased and uncased wells, a temperature log and a corresponding reciprocal-gradient log are derived. From these logs it is possible to identify the aquifer or aquifers tapped by wells.

Borehole diameter or caliper logging is an important tool in long-range stratigraphic or aquifer correlation. The caliper log is also used to determine the condition of an under-reamed section of a borehole prior to placement of a gravel pack and well casing, and to estimate the volume of cement necessary to fill the annular space between the well casing and the borehole wall. This technique is based on variation of borehole diameter which reflects differences in the lithologic character of the rocks penetrated by the drill.

Another borehole technique of wide application is flow-meter logging which provides a record of the velocity and direction of movement of water in a well. The log may be made while the well is discharging water at the land surface, while water is being introduced, or while the well is idle. The flowmeter log serves to identify and evaluate the aquifers tapped by cased wells having multiple screens, leaks in cased wells, and permeable zones penetrated by cased wells.

Still another borehole probing technique is fluid conductivity logging which provides a record of the electrical conductivity of the borehole fluid at all depths. Such a log provides useful information on the position of salt-water leaks in cased artesian wells, and the depth and relative artesian head of salt-water aquifers penetrated by cased wells. More recently, compact television cameras with wide-angle lenses of short focal length have been designed for on-site inspection of well casings and examination of the lithologic character of borehole surfaces.

Drilling time logging, which represents perhaps the latest development in well logging, may, in its simplest form, be usefully based on the actual drilling time records of the driller.

One of the more sophisticated techniques now in use in the analysis of simulated ground-water systems and the effects of man-made changes on these systems is the passive element analog model which is based on the direct analogy between electric and fluid force fields. For any ground-water system, an analog model employing resistor-capacitator networks with analysers can be constructed with a degree of complexity dependent upon the nature of the ground-water system and the available basic data. The electric analog model affords a useful means for computing the distribution of potential (or head) at any point in the system under complex boundary conditions, as well as variable recharge and withdrawal by pumping. Increasingly, also, the digital computer is being utilized to analyze hydrologic interrelationships including streamflow-aquifer behavior.

Knowledge of the chemical characteristics of ground water is very important in planning its optimum development and utilization, and also for understanding and analyzing the functioning of ground-water systems. Geochemical techniques based on the presence of identifiable chemical constituents in minute concentration are particularly useful in tracing the direction and velocity of water movement through the rock skeleton, but must be used in conjunction with adequate geologic and hydrologic knowledge of the ground-water system. Introduced tracers such as salt solutions, fluorescein, and radioisotopes commonly are used for this purpose. For example, radioisotope tracers are being used extensively for geohydrologic studies in many areas of the developing world including the Chad Basin and Nile-Lake Victoria Basin of Africa, the Parana Basin in Brazil, and Cheju Island in Korea. Also radioisotopes such as carbon-14 and, under certain conditions, tritium are proving useful in determining the relative age of water in different parts of a ground-water system and the span of the "life cycle" of such a system.

Chemical quality and temperature relationships also enter into the quantitative evaluation of other ground-water problems, including salt-fresh water relationships in coastal aquifers, base exchange, influx of mineralized waters or brines, aquifers as heat exchangers, induced infiltration, artificial recharge, and disposal of radioactive wastes.

Hydraulically, an aquifer serves a dual role as both a transmission conduit and a storage reservoir. In the former role, it transports water from areas of intake to centers of interception by wells or to areas of natural discharge such as the sea, a stream, a lake, a marsh, or a drain or locale of evapotranspirative consumption.1/ Secondly, as a storage reservoir, the aquifer provides a reserve of water that may sustain base flow in streams or well discharge during extended periods when net intake from precipitation is exceeded by the aggregate discharge of wells, leakage to the sea, to springs, drains, or streams, and consumptive use in vegetated areas.

Because of the importance of the transmission and storage characteristics in the hydraulic behavior of aquifers and ground-water systems, a considerable number of methods have been evolved for the mathematical analysis of problems

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1/ "Evapotranspiration" embraces that portion of the precipitation returned to the air through direct evaporation or by transpiration of vegetation. No attempt being made to distinguish between the two.

of fluid mechanics as they apply to ground-water flow systems. To enumerate, borehole and well methods for analyzing aquifer hydraulics include those involving constant discharge or recharge without vertical leakage, instantaneous discharge or recharge, constant head without vertical leakage, constant discharge with vertical leakage, and variable discharge without vertical leakage. Channel or drain methods include those applicable to constant discharge, constant head, and sinusoidal head fluctuations. Numerical analysis and flow-net analysis provide the chief areal methods of aquifer evaluation. Also, the analysis of hydrologic boundary problems has been built on a number of methods involving the theory of images.

Quantitative evaluation of ground-water systems by hydrologic methods has had a considerably longer history of evolution in the developed countries than the genesis and use of hydraulic methods. Appraisal of the ground-water resources requires an accounting of the perennial intake, discharge, and changes in storage with relation to man's existing and future needs for ground-water supplies. In addition, water quality must be adequately defined with regard to temporal and spatial changes in ground-water systems and the effects of such changes on man's use of the water.

Among the methods for evaluating the recharge-discharge balance in ground-water systems are seepage surveys keyed to streamflow records from gaging stations and analysis of stream hydrograph analysis, and water-budget studies. Methods for estimating recharge or discharge from changes in ground-water storage include lysimeter or tank studies, observation-well hydrographs, isopachous[1/] maps of net change in water level, saturation or drainage techniques, and indirect methods. In all storage methods, specific yield must be known to convert changes in storage volume to water volume.

Instrument and Investigation Costs

The instrumentation and costs for ground-water surveys and investigations run the gamut and depend on such factors as extent of the area to be studied; intensity of areal coverage; and duration of the study. Many ground-water

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1/ Analogous to contour lines, but representing thickness.

development programs begin with a broad reconnaissance and then are followed by more detailed investigations as development proceeds. It is not uncommon for an investigation of a given ground-water basin to continue over a term of several years. Indeed where intensive ground-water development occurs, as for an example in the Punjab region of West Pakistan, the Ganges Plain of India, and the alluvial plain of Taiwan, almost continuous ground-water observations and study are required to monitor changing conditions during and following development. Representative samples of some of the more common instrument and survey costs (in the U.S.A. in 1971) are given in the estimates below.1/

One weekly graphic water-stage recorder with auxiliary equipment for use in observation well	$ 250
One continuous graphic water-state recorder with auxiliary equipment for use in observation well	700
One borehole geophysical logger, fully instrumented	6,000
Test drilling:	
One combination percussion-rotary drilling rig	120,000
Drilling costs, 8-inch hole, per foot	
Dolomite and limestone	5- 50
Unconsolidated sediments	2- 20
Sandstone	4- 40
Quartzite	25-250
Basalt and granite	15-150
Analog model of small ground-water basin	15,000
Digital model of a stream-aquifer system	25,000

Recent and Current Research

There have probably been few major break-throughs in ground-water science since the work of C.V. Theis, who

1/ The cost figures are intended to be indicative and to represent relative costs and values. They are subject to wide variability based on the specific nature of the project and quality of equipment used. Drilling costs are particularly susceptible to wide variations.

founded modern well hydraulics in 1935, and Muskat's and Hubbert's formulation of the theory of ground-water flow in the late 1930s and early 1940s. Nevertheless, ground water hydrology has evolved substantially toward more sophisticated applications of basic principles during the past two decades.

Most solutions to ground-water problems are concerned with one aquifer. When more than one aquifer is to be considered, a system of simultaneous differential equations with appropriate boundary conditions has to be solved and the results become very complicated and difficult to evaluate. For this reason, practical multi-aquifer problems can only be solved by analog models and digital computers, both of which have been much refined in recent years and are now widely used.

Analog models have been and still are widely used to study ground-water problems. They have the advantage of being pictorial or graphic in the analytical presentation, but they are bulky and difficult to store or transport. Moreover, they lack the mathematical flexibility of digital computers. Thus, digital modelling is currently growing in favor in the analysis of more complex multi-aquifer ground-water problems, as well as surface-water to ground-water and other hydrologic relationships.

Knowledge of hydrodynamic dispersion has advanced in recent years through study of the movements of contaminants in ground-water flow and the intrusion of sea water in coastal aquifers. Solutions for flow equations pertaining to such problems, however, are available only for relatively simple and idealized cases. Practically, it must be assumed that the zone of diffusion between fresh and salty water is very thin and that conditions of immiscible flow prevail. Radioisotopes also have been used to determine specific yield and hydraulic conductivity of aquifers and to identify the origin of saline water that contaminates some coastal aquifers.

In recent years, mathematical solutions have been developed for evaluation of problems in aquifers of non-uniform thickness, with sloping impermeable bedrock floors, with varied lateral replenishment and under various conditions of upward or downward leakage. Non-linearities in ground-water flow have been analyzed by analog models. Also,by means of computers it has been possible to arrive at simplified solutions to problems relating to two-phase fluid systems in heterogeneous porous media.

Studies of groundwater in recent years have been predominately deterministic in their approach. Stochastic methods have been employed in ground-water problems to considerably less degree than they have in surface-water hydrology. There is, however, growing emphasis on the use of statistical methods in the evaluation of ground-water interrelationships.

There are few if any significant research deficiencies in instrumentation and methodology insofar as needs for ground-water exploration in the developing countries are concerned. In the area of ground-water development, a number of such countries -- India, Pakistan, Iran, Turkey, Egypt, Libya, Tunisia and Chile to name a few -- have already embarked on moderate to large-scale ground-water development projects which equal or exceed in scope comparable projects in developed countries.

More critical are institutional and socio-economic factors such as the training and motivation of ground-water scientists; level of technical and administrative support of existing ground-water agencies; and requirements for establishing new institutions at both the national and regional levels.

Research Opportunities for Application in Developing Countries

It was noted earlier in this chapter that there are few significant research deficiencies in instrumentation and methodologies with respect to ground-water exploration in developing countries. This does not mean, however, that we know all there is to know about locating and appraising groundwater, and that it is simply a matter of obtaining the necessary tools and applying them. What is meant is that the non-institutional factors encountered in developing countries (e.g., climate, geology, vegetation) are not constraining or limiting with respect to applying the present state-of-the-art. Aerial and ground-based geophysical techniques wich have been developed to meet domestic needs of the advanced countries can be applied in developing countries at a reasonable cost, either under contract or by local experts.

The major research requirements and opportunities related to developing country needs are associated with lowering the cost of existing equipment; improving modelling techniques; describing and interpreting water movement throughout river basin systems of major importance in developing countries;

and in developing new remote sensing techniques for ground-water location and appraisal.

Modelling of ground-water systems, including surface water interactions, is an extremely complex undertaking which requires an expansion of ongoing work. Special attention should be given to the application of both analog and digital models to ground-water systems in desert areas with sandy, porous soils (e.g., Kalahari Desert of Botswana and Southern Africa) and in the vast areas of the developing world underlain by thick sequences of crystalline and volcanic rocks (e.g., Deccan Plateau of India, Ethiopian Plateau; and Southern Brazil).

In view of the rapidly growing demand for water in urbanizing areas of the developing world, model studies should be carried out to determine the water supply/demand relationships for major aquifers, and requirements and options with respect to ground-water recharge.

Since basic data on parameters such as rainfall frequency and amount, rate of infiltration, evapotranspiration, and runoff is essential to building predictive capabilities, an intensification of research designed to expand and upgrade the data base should be carried out for major water systems in developing countries.

Finally, our present technology is incapable of rapidly locating and appraising ground-water reservoirs, regardless of their geographic location. Research has lagged in this field because the advanced countries have not, generally speaking, suffered from insufficient water. Many developing countries of the arid zone do not enjoy this same luxury, and their entire mode of living and economic development is tied to water availability. Thus, new techniques for ground-water identification in the arid zone are urgently needed. New remote sensing techniques (e.g. multi-spectral scanning) offer a potential for rapid reconnaissance over vast areas, and these techniques should be carefully and systematically explored on a priority basis by the developed countries to assess their applicability to specific field problems.

PRECIPITATION

Precipitation is intrinsically part of the hydrological cycle, and knowledge of its quantitative distribution in time and space is paramount to any water resources evaluation. Historically recorded earlier than other elements of the hydrological cycle, data on precipitation are in certain regions the only factual information available for water resources assessment. Where these data are available conjunctively with streamflow, they collectively provide the basis for employing rainfall-runoff models for hydrological forecasting and/or for data transfer.

State of the Art

Precipitation in its various forms - rain, snow, sleet, etc. -- is usually expressed as the depth of liquid that would accumulate on the earth's surface if there were no loss. The choice of site, the form and exposure of the measuring gauge, and the prevention of loss by evaporation, wind and splashing effects are therefore important points to be observed.

Rainfall amounts are usually measured by raingauges. These instruments record the height of the column of water collected in a container exposed to the local weather environment. Readings are usually collected and recorded on a daily basis but storage gauges are used to measure total seasonal precipitation in remote, sparsely-inhabited areas. Rates of precipitation are measured by recording gauges of which there are three principal varieties: the weighing type, the float type and one which employs a tipping bucket principle. Each has its merits, but the tipping bucket instrument is usually considered to give the poorest results. Most recorders suffer from too condensed a time scale on their charts whereas the newer paper tape or magnetic tape recorders allow a more flexible approach because their resolution can be carried over a range of time intervals. The recent introduction of these tape registers has offered a partial solution to the problem of manual processing of numerous chart records.

Precipitation gauge costs run from $60 for standard 8-inch rain gauges to $1200 for the more advanced recorders. Installation averages about $225, and inspection and maintenance costs run around $150 per year.

The difficulties of determining rainfall amounts and the bias in the measurement introduced by the instrument appear negligible in comparison to errors involved in assessing snowfall. Consequently snowfall totals and rates are not readily available even in countries where snow is an important part of the hydrological cycle. Snowfall is directly measured on the open ground with a graduated ruler or scale. The water equivalent of the snowfall is determined by one of the following methods:

(1) extracting cylindrical samples of the fresh snow with a suitable snow sampler and weighing or melting them;

(2) utilizing either ordinary raingauges (for immediate readings) or recording (weighing) instruments;

(3) employing the approximate 10 to 1 relationship which exists between the depth of fresh snow and the water equivalent;

(4) utilizing pressure snow pillows that can be monitored remotely and automatically; and

(5) applying nuclear techniques based on the alternation by the snow mass of either the earth's natural radioactivity or that omitted by artificial radioisotopes.

Point data are usually used to compute areal values of precipitation by means of various averaging methods. These may range from a straightforward arithmetical averaging of the various point data in the area under study, to the averaging by mathematical models that relate the point data to topographical and meterological parameters.

Radar offers promise as an effective technique for the direct measurement of precipitation over large areas (i.e., watersheds). Its full potential, however, has yet to be realized because of inadequate techniques for processing the radar-produced data and lack of satisfactory correlations with raingauge calibrations. In addition, the most powerful radar that exists today measures only areal distribution of precipitation; measurements of intensity and rates are not possible. And radar costs can be prohibitive, reaching upwards of $300,000 for the most useful of existing systems. Observations by satellite are also possible and, though the observations cannot be used for quantitative precipitation measurements, large and important storm systems can be observed. From these observations, useful information as to the probable areal extent and time distribution of precipitation can be inferred.

Undoubtedly the system with the greatest potential for gathering information would be one consisting of a group of telemetering gauges and rader, controlled by a computer - the type of system that has been installed in a number of basins for river regulation. Since this is also the most costly network to install and maintain, the value of the data produced would have to be high in order to justify such an expenditure.

Recent and Current Research

Research activities in the field of precipitation involve both instrumentation design and testing and data analysis and interpretation. The mentioned usage of radar to assess areal values of rainfall offers perhaps the greatest promise to achieve rapid and vast aquisition of important data. Operational usage of experimental radar systems for these purposes, however, is years away. Research in raingauge instrumentation to overcome the inherent problem of the instrument itself affecting the measurements is also being conducted. In addition, international intercomparisons are made between the national raingauges and the pit gauge (a collector-receiver gauge placed in the ground).

Research is also underway on the application of satellite imagery to the assessment of snow cover. At present, the resolution of the imagery is still quite coarse (order of 1 mile at best) but future satellites and newly-developed sensors should greatly improve the resolution (order of 100 metres) in the next few years. Research in the application of multi-spectral imagery appear to offer good promise for the detection of snow condition (including water content) and depth of snow. In addition, two relatively new methods are currently under investigation for the continuous measurements of snow density at remote sites; one employs radio-active isotopes, the other snow pillows. Both are readily adaptable to telemetering by either radio or land line. The radioactivity method relies on the attenuation by the snow cover of gamma radiation from natural sources or radioisotopes such as Cobalt-60. Measurements can be made on the ground or from aircraft. The water equivalent can be measured with radiation techniques with a standard error or four to six percent when compared with snow tube and snow pillow measurements. The snow or pressure pillow is essentially an air mattress filled with antifreeze solution and fitted with a manometer. It may be air-dropped and left in the field to record and telemeter the weight of accumulating snow cover. Some snow pillows have been modified to include a catchment for a separate measurement of the liquid runoff from the snow cover, thus measuring daily liquid runoff as well as the water equivalent.

Research on improved methods and technologies for analysis and interpretation of all types of precipitation data is underway in a number of important areas including:

--data network design;

--conjunctive use of precipitation forecasting and river forecasting;

--application of precipitation data to derive rainfall-runoff models for forecasting or design data development; and

--rainfall intensity mapping.

Research Opportunities for Application In Developing Countries

Virtually all existing operational instrumentation is directly applicable to developing countries and, where available to them, is generally in use. While there is every reason to expect that any new breakthroughs in precipitation assessment will be employed by the developing countries, their special conditions pose a series of priority research needs and opportunities.

A principal need is for inexpensive data collection instruments and techniques. The former would be enhanced if they were of the expendable type, geared to automatic recording and transmission from harsh, remote environments.

Also reflecting the scarcity of investment capital in developing countries is the need for improved techniques for obtaining precipitation data over large areas based on measurements at a minimum number of point sources. This could involve additional studies in the areas of network design and synthetic hydrology aimed at maximizing information content while minimizing data collection requirements. The application of rainfall-runoff models could greatly upgrade developing country capabilities but it is presently constrained by lack of basic data on rainfall distribution and frequency. Development of better rainfall models and additional research on design of networks could have significant payoffs.

In addition, intensified research on radar, infra-red, and multi-spectral sensor systems could lead to new techniques for the rapid acquisition of data on precipitation distribution and rates over large areas. If developing countries only have to pay for the imagery and not the hardware as is the case with the ongoing U.S. Earth Resources Satellite Program, then utilization of these techniques could also be relatively inexpensive.

EVAPORATION

The hydrological "potential" of an area is reduced by, among others, the loss of otherwise available water directly from water bodies, soil, and vegetation through the process of evaporation, and from vegetation through a combination of evaporation and transpiration (evapotranspiration).

In semi-arid and arid lands where agricultural and domestic water are generally scarce and therefore expensive, it is often necessary to rely on water stored in ponds and reservoirs during times of surplus streamflow for use in times of drought. The rate of evaporation from the water surfaces varies monthly and is influenced by the geographical location of the pond or reservoir, its elevation above sea level, and the size of the surface area. Knowing the amount of evaporation is important for evaluating overall hydrological potential in support of water management programs and for planning future water resource development. For example, it has been estimated (Leopold and Langbein, 1960, A Primer on Water), that 70 percent of the precipitation falling on the United States is returned to the atmosphere through evapotranspiration.

State of the art

There are no universal standard instruments for measuring combined evapotranspiration losses from a complex area such as a watershed. By means of several direct and indirect techniques which utilize a variety of common and specialized instruments, it is possible to measure the losses from various components of the watershed. Evaporation pans and lysimeters are often used to provide index data on potential evaporation or evapotranspiration which in turn are used to estimate actual losses from lakes, reservoirs, streams, soils, or fields.

Evaporation pans are relatively inexpensive items which can be purchased or constructed. The standard U.S. National Weather Service pan is a round metal drum, approximately 4 feet in diameter and 10 inches in depth. The costs of establishing a Class A Evaporation Pan station is approximately $1600, which covers the pan, a stilling well, and installation. Twice a year inspection and general maintenance averages another $300. It is also possible to construct evaporation pans from 50-gallon oil drums or 5-quart oil cans although it is essential that experts be consulted on the installation and use of makeshift equipment. Pan evaporation is calculated on the basis of the volume of water that evaporates during a given period of time from a water filled container which is exposed to the evaporative forces of a given environment. Hook gauges and/or floats are used to record the amount of evaporation. Daily evaporation is computed as the difference in water level in the pan on successive days, corrected for precipitation during the period.

Lysimeters are tanks made of metal and, more recently, plastic, and are used principally for studying plant-soil-atmosphere relationships under natural conditions, and can measure evapotranspiration either directly or indirectly, depending on the type of lysimeter employed. They are emplaced into the ground to contain a prescribed area of soil and associated vegetation. In most past studies, steel tanks of about 2-6 feet in diameter and 4-6 feet deep were used. Currently plastic tanks having 1,000 square feet of surface area or larger are being utilized for agricultural studies. These instruments usually provide very accurate measurements but some designs are expensive and all are difficult to maintain. Soil lysimeters are subdivided according to their method of operation into the following types: (1) weighed (using mechanical scales and weighing machines), (2) hydraulic (based on the hydrostatical principle of weighing), and (3) volumetric (evaporation is measured by the amount of water poured in or out of them).

While evapotranspiration losses are of great significance in assessing overall hydrological potential, hydrologists are concerned principally with the evaporation component associated with open bodies of water (e.g., lakes and reservoirs). Four general methods have been developed to compute the rate of evaporation from open water surfaces: (1) Water - Budget; (2) Mass-Transfer;(3) Energy-budget; and (4) a coefficient applied to pan evaporation.

The Water-Budget method is a simple and, under certain conditions, an accurate and direct method if all inflows, outflows and changes in storage can be measured precisely. The application of this method is often limited to those sites where the ground water flow component is negligible and where inflow and outflow are small compared with evaporation. In some cases, observation wells along the shoreline can be used to refine the measurements and are particularly useful where significant ground water flow and bank storage occurs.

The Mass-Transfer method usually uses a simplified empirical equation. Evaporation is treated as the turbulent transport of water vapor from a water surface through the overlying boundary layer to the atmosphere. The minimum amount of measurements required are those of wind velocity, relative humidity, and water surface temperature.

The Energy-Budget method is based on the principle of conservation of energy which requires more parametric measurements than the Mass-Transfer method.

Evaporation from open bodies of water can also be estimated with evaporation pans by multiplying the loss reading by a known coefficient.

For the Mass-Transfer, Energy-Budget, and evaporation pan methods, the equipment required to measure the factors is installed on a stationary raft located at a position which represents the average reservoir condition. During the planning stage of a water resource development project, the evaporation pan may be located on land near the proposed reservoir site. Raft installations to collect data for the Mass-Transfer method typically include a tape recorder which records wind velocity from two elevations, relative humidity, and water surface and air temperatures. The tape can be transcribed for computer computation of evaporation.

Gross estimates of the costs of this installation are:

Raft	$2,000
Recorder	3,000
Total	$5,000

Telemetering equipment may be installed for transmitting data from inaccessible locations or for quick computations, although this will more than double the cost of instrumentation.

Recent and Current Research

Most recent and ongoing research in this area involves improvement of techniques for measuring evapotranspiration from agricultural plots. Only limited studies have addressed the need for improved techniques and instruments for measuring evaporation from lakes and reservoirs.

Research Opportunities for Application in Developing Countries

What was said for precipitation can be transferred in toto to this heading. In addition,however, the long-standing research requirement concerning the development of low-cost accurate equipment is particularly relevant to applications in developing countries. And even more than with precipitation, the need for standardization is particularly felt in the field of evaporation as the data collected from widely different evaporation instruments are far less compatible than those collected from rain-gauges. The high cost of instrumentation needed to provide evapotranspiration data of required accuracy is a limiting factor with respect to future expansion of research in this particular area and, hence, suggests the need for additional investigation.

Another fruitful field of research is in the development of atmospheric numerical modelling which can provide reliable areal evaporation data. Also of high priority is the formulation of equations for specific areas or reservoir sites which would give better approximations of evaporation when the various computational methods are employed. Finally, observations from towers, aircraft, or satellite using visible and infra-red photographic techniques offer a range of new possibilities with respect to repetitive measurements of evaporation and evapotranspiration losses over large areas.

HYDROLOGIC APPLICATIONS OF REMOTE SENSING

Remote sensing is the technique of detecting the nature of an object from a great distance without actually touching it. In a restrictive sense, remote sensing activities include only those involving the detection of electro-magnetic radiant energy. Aerial photography, the most widely used form of remote sensing, records an image or picture on film sensitive to the electromagnetic energy constantly emitted in some degree by all objects or matter. Such energy travels as waves, with a spectrum or range of various wave lengths. The longer wave length forms of electro-magnetic energy are known as infrared radiation, microwaves, and radio waves. The shorter wave length forms include ultraviolet radiations, X-rays, and gamma rays.

Instruments are in use that can produce images, both photographic and nonphotographic, of energy distribution in each part of the electromagnetic spectrum. These instruments include photographic cameras, scanning radiometers, and radars. The observations made with such equipment are limited to the surface or to very shallow penetration. They provide, however, a basis for discriminating among natural materials because of the contrasts, in black and white or in color, produced by the detection of differences in heat radiation and light reflectance from the surface below.

In most instances, as a practical matter, remote sensing data are interpreted and used in conjunction with information from surface observations acquired independently of the remote sensing system. Such "ground-truth" information obtained at precisely known, key locations enables the interpreter to correlate patterns, colors, or shadings on his images or photos with known ground-based phenomena, and to extrapolate to other areas which have not been examined on the ground.

Remote sensing has perhaps the greatest potential of all advanced techniques thus far evolved for identifying appraising, and monitoring -- on a regional or even continental scale -- the earth's mineral, land, and water resources and its environmental processes, including the hydrologic cycle. Whereas water development and control has traditionally been carried out on an ad-hoc, local basis, remote sensing now offers a capability for approaching water-resources development and management on a more rational and integrated basis, and also on a regional scale. A number of excellent possibilities in this regard are described below. It should be borne in mind, however, that remote sensing technology is still in its infancy, although evolving rapidly. If its use becomes widely operational (a very good possibility), it will offer great opportunities for the assessment of areal hydrólogic conditions. Usage of geo-static satellites with improved resolution sensors may offer, in time, essentially continuous monitoring on a global scale.

Surveys of Water Resources - As noted earlier, good aerial photography and topographic maps are fundamental to surveys of both ground water and surface water. Remote sensing provides a means for rapid reconnaissance of geologic units, rock structures, surface water, and soil moisture over large areas. This in turn can provide the basis for selecting the most promising areas for more detailed ground-water surveys. Multispectral imagery, from the aircraft or satellites, can greatly assist in mapping surface waters and drainage areas, and in planning and managing irrigation and hydroelectric projects. The selection of appropriate remote sensing techniques for these purposes will depend in each case on the types of terrain and vegetation cover, the general nature of the geologic materials to be surveyed and other factors.

The feasibility of using thermal infrared techniques to locate outflows of fresh water along coastal areas has been demonstrated in the Philippines and in the Hawaiian Islands. In these instances, remote sensing revealed discharges of fresh water into the sea in the form of submarine springs or as surface runoff.

Watershed Management - Remote sensing offers a variety of new tools for comparing the moisture input of watersheds with total water availability and potential output for such purposes as hydroelectric power, municipal water systems, irrigation and the other needs of society. In many regions, the accumulation of snow at high elevations provides a major source of water supply. By means of space photography, coupled with a limited ground-truth sampling program, the season's snowpack can be surveyed as to area, depth, and moisture content to provide estimates of expected seasonal runoff. The prediction of flood conditions and the monitoring of flooded areas are important applications of this technique.

In a very large and relatively inaccessable watershed, such as that drained by the Indus River in southern Asia, synoptic satellite observations have been used successfully to monitor total snow-cover, snow line delineation, and other hydrological features. Infrared radiometer images were obtained for this same watershed and used to establish a close relationship between the percentage of snow cover and the mean monthly runoff.

Another application of remote sensing to watershed management involves the analysis of the disposition of precipitation through surface runoff, infiltration, and evapotranspiration. Through remote imagery, a given watershed can be classified by areas of homogeneity with respect to types of vegetation, water absorption characteristics, and runoff coefficients of the ground surface. Equipped with such a classification of the watershed and a table of coefficients, it is then possible to predict the quantities of precipitation which will be absorbed by the watershed and lost through evapotranspiration under varying conditions.

Monitoring Surface Water Resources - Through synoptic coverage of surficial water resources via aircraft or satellite, it is possible to monitor variations in the areal extent of surface water bodies, bank and beach erosion, seasonal variations in sedimentation patterns, and the degree of siltation in reservoirs and waterways. Changes in the distribution and density of water plants or aquatic weeds, and fluctuations in surface water temperature also can be determined.

Remote imagery will reveal the intrusion of salt water into freshwater streams, showing the shape, size, and position of saltwater wedges. The sources and extent of thermal pollution and industrial effluents also can be detected and monitored. In regions where the formation and melting of ice covers is of practical importance, space imagery is a promising technique for the regional monitoring of ice thickness and ice jams, and for tracking ice masses.

Current and potential hydrologic applications of remote sensing are covered fully by C. J. Robinove in his report entitled "Space Technology in Hydrologic Applications" (see Selected Bibliography) and are herein summarized in the tabulation that follows. The tabulation includes both conventional aerial photography as well as more recently evolved remote sensing techniques which are still in the experimental stage.

A. General Sensor Characteristics and Applications for Hydrologic Studies

Remote-Sensor System	General Comments on Potential Value and Use of Remote-Sensor System for Hydrologic Studies
Panchromatic Photography	Panchromatic photography is the most widely used remote-sensing technique because of its availability and relatively low cost. Interpretative techniques are well developed and formal training in its use is available. Much aircraft data has been taken for many purposes. Some special data and some space data available.
Multispectral Photography	Multispectral photography interpretation requires a background of spectral-signature studies of terrain and water from multispectral systems. Large data return may complicate interpretation. Some experimental aircraft data available, primarily 9-lens photography. Much work has been done with the use of special film-filter combinations for specific purposes. Little work has been done on interpretation for hydrologic purposes.
Infrared Photography	Infrared photography is primarily of value in mapping drainage features and shorelines. The water is always black in a positive print. Some vegetation characteristics are discernible. Its most valuable use is as an adjunct to, but not a replacement for, standard aerial photography. Much aircraft data is available.
Color Photography	Color photography, in spite of its built-in spectral redundance, promises to be a major tool of the hydrologist in many special fields and is sufficiently better for recognition of significant hydrologic features that it may replace panchromatic photography for many uses. The interpretation capability of the potential operational hydrologic users of color photography must be greatly increased. Methods for spectral and density extraction of data are being developed. Much aircraft and Gemini spacecraft data is available.

Infrared-Color Photography

Color-infrared photography may be superior to standard photography in some respects. It shows differences in vegetation more clearly and provides a slightly higher contrast on water surfaces. Its general superiority to standard color photography has yet to be proved but it may be highly useful and is worthy of much additional research. Aircraft data is available.

Infrared Radiometry

Infrared radiometry is very useful for sequential measurements of changes in land and water surface temperatures because it is a simple measurement technique and data reduction simpler than for infrared imagery. Radiometry is routinely used for periodic surveys of near-shore oceanic areas. Data is available from aircraft and from Tiros and Nimbus Satellites.

Infrared Imagery

Infrared imagery has shown its value as a tool for measuring water-surface temperature and as a means of qualitatively differentiating some terrestrial features. The lack of a simple means of determining emissivity hampers its quantitative usefulness. Analytical techniques for proper use of the reduced data need to be developed. Data is available from aircraft and from Tiros and Nimbus Satellites.

Radar Imagery

Side-looking airborne radar has an all weather capability for coverage of large areas. Its ability to penetrate foliage and accentuate topographic features enhances its value. Water-surfaces are excellent reflectors of microwaves, resulting in a uniform black-tone image. For these reasons stream drainage systems and water surfaces are easy to identify. The black-tone precludes measuring the physical, chemical or biologic characteristics of water. Radar may be of value in terrain analysis for ground-water exploration. Aircraft data available for U.S., Brazil, Panama, and Venezuela.

Microwave radiometry and Imagery

Passive-microwave sensors measure the brightness and temperature of terrain and water surfaces. Spatial resolution is lower than infrared systems but radiance is directly proportional to temperature. Probably will find greatest application in oceanic and snow-field mapping. Aircraft data is available.

B. Application of Sensor Systems to Measure Physical, Chemical and Biological Water Properties

Remote-Sensor System	Measurement of Physical Characteristics of Water Surfaces	Measurement of Chemical and Biological Characteristics of Water
Panchromatic Photography	Largely unproved, with the exception of the ability to sense streamlines on water surfaces that may be indicative of movement of pollutants or other effluents. Small data use.	Useful only for assessing some vegetation types. Small data use.
Multispectral Photography	Largely unproved but may be useful in special situations Small data use.	May be valuable as a supplement to other photography but specific interpretation criteria have not been developed. Small data use.
Infrared Photography	Not usuable because water surfaces always appear black in infrared photography. No data use.	Not usable because water surfaces always appear black in infrared photography. No data use.
Color Photography	Of some value but rigorous evaluation has not been made. Small data use.	Probably a high potential for use but it must be supported by basic research in the spectral response of waters of various types. Small data use.
Infrared-Color Photography	May provide a higher contrast for mapping of discontinuities on water surfaces than any other type of photography. Small data use.	Probably not helpful in detection and identification of substances in water but may be useful in mapping their distribution. Small data use.

Infrared Radio-metry	Valuable for measurement of water-surface temperature but will not achieve its greatest potential until there is full development of analytical equations that express the temperature distribution within a water body as a function of the surface temp-erature. Moderate data use.	Valuable only if the chemical or biological factors have an effect on the temperature or emissivity of the water surface. Small data use.
Infrared Imagery	Valuable for measurement of water-surface temperature over large areas but will not achieve its greatest potential until there is full development of analytical equations that express the temperature dis-tribution within a water body as a function of the surface temperature. Small data use.	Valuable only if the chemical or biological factors have an effect on the temperature or emissivity of the water surface. Small data use.
Radar Imagery	Water is an excellent reflector of microwaves and, therefore, water surfaces show as a uniforn black tone on radar imagery. Radar imagery, therefore, is of little value in measuring physic chemical, or biological characte of water but is useful in locati and mapping areas of open water. Small data use.	Radar imagery is of no value in measuring physical or chemical, or biological characteristics of water. No data use.
Microwave radio-metry and imagery	May be used for measurement of temperature. Small data use.	Probably not useful. No data use.

C. Application of Sensor Systems to Assessment of Ground Water, Geomorphology And Liquid-Vapor Transfer

Remote-Sensor System	Mapping and Description of Ground-Water Features	Geomorphology and Assessment of Changes in the Hydrologic Regimen	Measurement of Liquid-Vapor Transfer in Hydrologic Cycle
Panchromatic	Highly useful for hydrogeologic mapping, drainage mapping, and identification of vegetation features associated with ground water. Large data use.	Excellent for measurement of geomorphic parameters. Small-scale photography allows systhesis of large features on a regional basis. Large data use.	Not applicable to this problem.
Multispectral Photography	May be useful but perhaps not superior to panchromatic photography. May be useful in differentiating vegetation types as indicators of ground water.	Not yet evaluated for this purpose.	Not applicable to this problem.
Infrared Photography	Valuable as adjunct to panchromatic photography because some rock units have different contrasts and are, therefore, more recognizable. Moderate data use.	Helpful in addition to normal aerial photography but not normally used alone. Small data use.	Not applicable to this problem.
Color Photography	High potential for hydrogeologic and aquifer mapping as an adjunct to the more readily available standard panchromatic photography. Small data use.	Helpful in determination of types and composition of surficial deposits. Small data use.	Not applicable to this problem.
	Probably superior to standard color photography in defining vegetation and soil characteristics. Small data use.	May be superior to standard photography. Small data use.	Not applicable to this problem.

Remote-Sensor System	Mapping and Description of Ground-Water Features	Geomorphology and Assessment of Changes in the Hydrologic Regimen	Measurement of Liquid-Vapor Transfer in Hydrologic Cycle
Infrared Radiometry	May be helpful in measurement of soil and ground-water discharge to streams but is less helpful than infrared imagery because of the small area covered and the difficulty of locating the trace of the radiometer on the ground. Small data use.	Probably not useful for this purpose. Small data use.	Helpful in determining radiative transfer of energy
Infrared Imagery	Now being evaluated as a tool for locating points of ground-water discharge to streams. Small data use.	Not yet evaluated. Small data use.	Useful in regional atmospheric physics but not used in small-scale studies. Small data use.
Radar Imagery	Moderately valuable in mapping geologic structure and in some lithologic differentiation for ground-water exploration. Small data use.	Now being evaluated. Small data use.	
Microwave radiometry and imagery	May not be useful because of coarse resolution. No data use.	Probably not useful for this surface. No data use.	Usable onl high altitu Doubtful us micro-clima No data use.

WATER DEVELOPMENT PRIORITIES

The focus of this report thus far has been on the assessment of hydrologic potential in developing countries. Inventorying and appraising the location, amount, quality and overall potential of the water which exists on or near the earth's surface is obviously but a precursor to development of the resource in the full sense of the term. Since water development programs in developing countries are limited by an inadequate capacity to actually obtain, utilize and conserve water, as well as by the aforementioned lack of assessment capabilities, it appears proper and useful to briefly acknowledge several potentially high-payoff research areas related to the developmental phase of water resources. These priorities include:

- --hydrological research re[illegible] to the use of brackish waters for irrigation;
- --desalination of seawater for urban supply in coastal zones;
- --evaporation suppression from relatively small open-water reservoirs;
- --artificial recharge of ground-water reservoirs (aquifers) with surplus or reconditioned surface water;
- --conjunctive use and management of surface and ground water in irrigation systems;
- --analog and digital computer modelling of alternatives in water development and management;
- --optimization of development and management of water resources of desert (non-renewable) aquifers; and
- --optimization of ground-water extraction from aquifers in crystalline and volcanic flow rocks.

Brackish water aquifers are widespread in arid and semiarid regions of the underdeveloped world as, for example, North Africa, southwest Asia and the arid coast of western South America. If strains of salt-tolerant food and fiber crops can be evolved by plant geneticists, such water could be used for extended irrigation in these regions. The disposal of saline waste water from such irrigation projects would constitute an area for applied research.

Desalination technology is rapidly approaching the stage where desalted ocean water may become economic for use in large urbanized and industrialized coastal zones of developing countries. In such situations, the concentration of population, user demand, water availability, and presumably financial resources should converge to offset high water costs. Such desalted water might even be blended with poorer quality water to obtain larger volumes of acceptable or potable quality.

Evaporation suppression is a promising research area which has important and immediate application in developing countries. Several techniques have been employed, mostly on an experimental basis, to reduce the water losses due to evaporation from the surfaces of ponds and reservoirs. The building of dikes to restrict the surface area of the water bodies has been used effectively. During the planning stage, the relationship between the incremental surface area and corresponding storage should be studied to evaluate the feasibility of diking shallow sections of the reservoir. And whenever an existing reservoir is evaluated, diking to reduce evaporation should likewise be considered. Large-scale tests have been carried out on the application of monomolecular films to the water surface to suppress evaporation. While this technique appears promising, there are many problems that must be solved before such films can be recommended for use on a practical basis.

Artificial recharge of ground-water reservoirs with reconditioned waste waters, or surpluses of natural surface runoff, is now practiced in Europe. Water-spreading and recharge wells are the two most common methods used in artificial recharge. Because of cost and the complexity of the required technology, recharge wells probably have limited applicability in developing countries in the near future. Water-spreading by flooding, basin, ditch or furrow, and natural channels is relatively nominal in cost, however, and has wide potential application. Strong emphasis is now being given to large-scale groundwater development for irrigation and other uses in developing countries such as India, Pakistan, Iran, Egypt, Turkey, Taiwan, Chile. As such development proceeds and intensifies, increased attention will need to be given to the technical feasibility of artificial recharge for replenishment of depleted ground-water storage and for control of water quality. In anticipation of such needs, applied research on artificial recharge methodologies appropriate to local hydrogeologic conditions needs to be undertaken in some of the more advanced developing countries.

In both developed and developing countries, surface-water and ground-water are often considered to be wholly independent resources and are frequently developed and managed by separate governmental agencies which have very little or no communication with one another. The fact is that streams and ground water are intimately inter-related and inter-dependent in many hydrologic environments. The development and use of one sooner or later affects the other. Disregard of this relationship can lead to disaster, particularly when withdrawals of substantial quantities of water are involved. For this reason, the concept of conjunctive use and management of all water resources in a given hydrologic basin is increasingly being implemented throughout the world, as for example in the Punjab region of West Pakistan, and in the lower Nile Valley and delta of Egypt. The concept needs to be extended, however, to other critical areas such as the Ganges Plains of India, and the river valleys of Chile, Argentina and Peru. Through conjunctive use, all the available water resources of a given valley or basin can be developed and managed optimally and equally, but much local research, hydrologic assessment, and water management planning (with special recognition of unique socio-economic conditions) is needed to achieve this goal.

Modelling of hydrologic systems through use of analog and digital computers is now well-established in the developed world, but is not widely practiced in the developing countries. There are, however, analog models of the Nubian aquifer system of the Western Desert of Egypt, the Punjab region of West Pakistan, and the Chad Basin of west-central Africa that are functional and that are used extensively for interpretative evaluation of the response of hydrologic systems to development stress. Digital modelling is being employed in Chile to study stream-aquifer relationships in the transverse valleys of the central part of the country and is being considered for use in Argentina and Brazil. Much wider application of modelling is potentially possible in most of the developing countries particularly for guidance of water managers in making optimum choices from among arrays of alternatives in water-resources development.

Many productive aquifers in arid regions of the world contain large volumes of excellent water in storage which can be tapped by well-known deep well extractive techniques. The water in such aquifers is, however, non-renewable under prevailing climatic conditions. This water is not naturally replaced once it is withdrawn and hence must be considered a "wasting asset" just as any other mineral commodity. Aquifers of this type are wide-spread in North Africa beneath the Sahara and in the deserts of eastern Saudi Arabia and elsewhere in southwest Asia. Development of water from such aquifers must be undertaken with the full understanding that ultimately the supply will be depleted, usually within a term of a few decades, and that capital investments will have to be amortized within the life-span of economic withdrawal. Development of such aquifers is now proceeding apace in several parts of Algeria, Libya, Egypt and Saudi Arabia, but frequently with inadequate foresight and understanding of the hydrologic and socio-economic implications of ultimate depletion.

Many arid and semi-arid areas in the developing world are desperately short of water, yet lacking in perennial streams or productive aquifers that might be tapped for irrigation or public water supplies. Such areas which characterize large parts of sub-Saharan Africa, western Saudi Arabia, western India and elsewhere are commonly underlain by crystalline or volcanic flow rocks which form poor or mediocre aquifers. They could benefit substantially by creation of large subsurface cavities for water storage, possibly through underground nuclear explosions. Another possibility is explosive-induced fracturing in near-surface impermeable zones, and creation of shallow craters into which water could be accumulated for percolation and storage underground. Such techniques may be uneconomic at the moment and would have to take into account national and local political sensitivities involved in the utilization of explosives on a large scale, particularly those of a nuclear type. They have, however, considerable future promise and need to be fully evaluated.

The possibility of increasing atmospheric precipitation through weather modification has been the subject of much discussion, speculation, and research over the past decade. Studies have disclosed that under certain meterological conditions, precipitation may be measurably increased and, on occasions, decreased through seeding of clouds with silver iodide or potassium iodide. Dry ice has also been used but with anomalous results. The use of computerized cloud models has greatly improved the ability to predict seeding effects. However, despite certain technological advances, the state-of-the-art of weather modification is such that it is impractical to think in terms of its use for rainfall augmentation in developing countries in the foreseeable future. Cloud seeding experiments have generally yielded ambiguous results; cases have been noted where precipitation has occurred 200 kilometers from the "seeding zone". In addition, the technological and logistical backstopping requirements (e.g., specially stressed and equipped aircraft, sophisticated weather support services, advances aeronomy) simply are not available at realistic costs in most countries. Finally, the legal and political implications of man-induced changes in rainfall rates and distribution patterns are so uncertain and potentially severe that it is problematical if and when weather modification will become an important factor in water development planning.

CONCLUSIONS

Many conventional techniques for the measurement and evaluation of basic hydrologic parameters as well as for the assessment and monitoring of water resources potential are directly applicable to the needs of developing countries. In those countries with adequate manpower and institutional capabilities and with the necessary investment resources, approaches to water resources assessment and development can essentially parallel the approaches used in developed countries. Unfortunately, few developing countries have these characteristics, and therefore they have been obliged to attempt to utilize off-the-shelf technologies in an *ad hoc* and piecemeal fashion as the need for specific bits of data climbed higher on the overall development priority ladder. While the developed countries can be expected to continue to push the frontiers of the hydrological sciences, the developing nations will improve their capabilities to the extent that (1) they are able to select and apply well-established and proven methods to their particular mix of data requirements and institutional capacities; and (2) future research and development can be in part focused on particular needs and circumstances of the developing nations of non-temperate areas.

Clearly, a principal thrust of efforts to upgrade hydrological assessments in developing countries should be a strengthening of local capabilities to use the fruits of the decades of research directed to similar problems in developed countries. However, this will be a long and extensive effort and will always be faced with the need for foreign exchange investments to acquire the necessary equipment. Thus, a complementary approach should be undertaken in the field of adaptive research -- a type of research to which developed country specialists have devoted only minimal attention. This research should emphasize techniques which are capital-saving; which stress the importance of instrument durability and ease of operation and re-calibration rather than high precision; which address the need for improved network designs and minimum data requirements; and which provide data in a form easily usable by operating agencies.

The following are areas in which successful research could have a major impact on upgrading present capabilities to carry out efficient and effective hydrological assessments in developing countries:

- Instrumentation development: including low-cost instruments which are durable and easy to operate and maintain under harsh environmental conditions; expendable varieties that can be disposed of after use; and automated instruments and systems which can record and transmit data from remote, unattended stations, with adequate precision at acceptable cost.

- Data Network Design: design of low-cost networks of data collection stations for rainfall-runoff measurements, streamflow, groundwater sampling, etc., that would optimize use of existing equipment and manpower by identifying minimum sampling requirements for meeting desired objectives.

- Stochastic Methods: improvement of the statistical methods for extrapolating from point source data to areas where data is unavailable, thus obtaining greater value from the existing scattered data and assisting in the design of new data networks.

- Remote Sensing: testing and evaluation of the utility of satellite-based sensor systems, particularly those employing multi-spectral techniques, for measuring and monitoring such phenomena as precipitation rates and frequency, evaporation from lakes and reservoirs and groundwater occurrences in semi-arid and arid regions.

The impetus for greater investment of talent, time, and financial resources in adaptive research will require action at a number of levels. Expanding the awareness of research opportunities and technology needs in this field among the scientific and development assistance communities is a prerequisite. Hopefully, this report will contribute toward that objective. Increased attention to the freer and more rapid dissemination of the results of water research investigations throughout the international scientific community is also required.

Although scientists and technologists in the advanced countries can, with proper direction and support, be expected to pay greater attention to the particular needs of the developing countries, significant improvement will probably be made only through the initiative of the developing countries themselves. The continuing evaluation and articulation by these countries of constraints and requirements they face with respect to water resources development is of fundamental importance. Ultimately, however, the degree of improvement will hinge on the capacity of the developing countries to build indigenous capabilities which will allow them to address their own particular problems with R & D programs, and to adapt foreign technologies as required. Consequently, institution building and manpower training should be viewed by both developing countries and assistance agencies as key components of development planning in the water resources field. As such, the strengthening of existing facilities or the establishment of new institutions, and the training of professional and sub-professionals, warrant priority attention both through the pursuit of specially designed projects, and also through their inclusion as basic components of all water research and development projects in developing countries.

Finally, water assessment is but one aspect of water resources development. Attention must be paid concurrently to requirements for improved methods and techniques for harvesting, controlling, conserving, and protecting the resource; an increased effort in one area should not be at the expense of the others. Effective use and management of water resources requires a strong, balanced, across-the-board supportive infrastructure of research workers, planners and managers, institutions, and laws. This particular report has focused, by design, on a single section of a spectrum of requirements -- the assessment of hydrological potential -- not because it is the most important aspect, but because it is an important aspect, and by virtue of its current relative neglect, an area in which additional research can have significant payoffs.

SELECTED BIBLIOGRAPHY

Streamflow

Barron, E. G. New instruments of the Surface Water Branch, U.S. Geological Survey: Western Snow Conference, Proc., 28th Annual Meeting, 1960.

Corbett, D. M. and others. Stream-gaging procedure. U.S. Geological Survey Water-Supply Paper 888 (reprinted), 245 p., 1962.

Dawdy, D. R. Mathematical modelling in hydrology. Proc. First Inter. Seminar for Professors, Urbana, Ill., July 13-25, 1969, vol. 1, p. 346-361, UNESCO/IHD, Paris, 1970.

Fuerstein, D. L. and R. E. Selleck. Tracers for dispersion measurements in surface waters. Calif. Univ., SERL Rept. 63-1, 69 p., 1963.

Guizerix, J. M. V. "Measurements of rate of flow:" Guidebook on Nuclear Techniques in Hydrology, IAEA/IHD Techn. Reports Series no. 91, p. 32-42, Vienna, 1968.

Langbein, W. B. and W. G. Hoyt. Water Facts for the Nation's Future. Ronald Press, New York, 288 p., 1959.

McCall, J. E. Stream-gaging network in the United States. Amer. Soc. Civil Engineers Proc., 87, no HY2, Paper 2776, P. 79-95, March 1961.

Smoot, G. R. and C. E. Novak."Measurement of discharge by the moving-boat method:" U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chap. A11, 1969.

Water Measurement Procedures--Irrigation Operators' Workshop, J. C. Schuster, ed., U.S. Bureau of Reclamation Publication REC-OCE-70-38, September 1970.

Wilson, J. R., Jr. "Flurometric procedures for dye tracing:" U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chap. A11, 1969.

World Meterological Organization Technical Note #117. Use of flumes in stream gauging.

World Meterological Organization Technical Note #115. Machine processing of hydrometerological data.

World Meterological Organization Publication #324. Casebook on hydrological network design practice.

Erosion and Sediment Transport

Chang, F. M., D. B. Simons and E. V. Richardson. Total bed-material discharge in alluvial channels. U.S. Geological Survey Water-Supply Paper 1498-I, 23 p., 1965 (1966).

Colby, B. R. and E. W. Hubbell. Simplified methods for computing total sediment discharge with the modified Einstein procedure. U.S. Geological Survey Water-Supply Paper 1593, 17 p., 8 pls., 1961.

Colby, B. R. Discharge of sands and mean-velocity relationships in sand-bed streams. U.S. Geological Survey Professional Paper 462-A, 47 p., 1964.

Courtois, G. Sediment movement and transport: in Guidebook on Nuclear Techniques in Hydrology, IAEA/IHD Techn. Reports Series no. 91, p. 55-66, Vienna, Austria, 1968.

Courtois, G. Erosion studies: in Guidebook on Nuclear Techniques in Hydrology, IAEA/IHD Techn. Reports Series no. 91, p. 67-69, Vienna, Austria, 1968.

Florkowski, T. Suspended load: in Guidebook on Nuclear Techniques in Hydrology, IAEA/IHD Techn. Reports Series no. 91, p. 51-54, Vienna, Austria, 1968.

Hubbell, D. W. Apparatus and techniques for measuring bedload: U.S. Geological Survey Water-Supply Paper 1748, 74 p., 1964.

Larsen, E. M. Sedimentation processes as part of hydrology. Proc. First Int. Seminar for Professors, Urbana, Ill., July 13-25, 1969, vol. 2, p. 737-743, UNESCO/IHD, Paris, 1970.

Perkins, D. C. and J. K. Culbertson. Hydrographic and sedimentation survey of Kajakai Reservoir, Afghanistan: U.S. Geological Survey Water-Supply Paper 1608-M, 43 p., 1970.

Water Movement in Unsaturated Soils

Black, C. A., editor. Methods of soil analysis, Monograph no. 9, Amer. Soc. of Agronomy, 1965.

Bruce, R, R, and A. Klute. The measurement of soil moisture diffusivity. Soil Sci. Soc. Amer. Proc. 20, p. 458-564, 1956.

Childs, E. C. "The non-steady state of the water table in drained land." Journ. Geophys. Research, Vol. 65, p. 780-782, 1960.

Davidson, J. M., J. W. Biggar and D. R. Nielson. "Gamma-radiation attenuation for measuring bulk density and transient water flow in porous materials." Journ. Geophys. Research, vol. 68, p. 4777-4783, 1963.

Freeze, R. A. "The mechanism of natural ground-water recharge and discharge. L. One-dimensional, vertical, unsteady, unsaturated flow above a recharging or discharging ground-water flow system." Water Resources Research, vol. 5, p. 153-171, 1969.

Hagan, R. M., H. R. Haise, T. W. Edminister, editors. Irrigation in agricultural lands. Monograph no. 11, Amer. Soc. of Agronomy, 1967.

Jackson, R. D., R. J. Reginato and C. H. M. van Bavel, "Comparison of measured and calculated hydraulic conductivities of unsaturated soils", Water Resources Research, vol. 1, p. 375-380, 1965.

Klute, A. "The movement of water in unsaturated soils." Proc. First Inter. Seminar for Professors, Urbana, Ill., July 13-25, 1969, vol. 2, p. 821-883, UNESCO/IHD paris, 1970.

Stallman, R. W. Relation between storage changes at the water table and observed water-level changes. U.S. Geological Survey Prof. Paper 424-B, p. 39-40, 1961.

Vachaud, G. "Determination of the hydraulic conductivity of unsaturated soils from an analysis of transient flow data." Water Resources Research, vol. 3, p. 697-705, 1967.

Youngs, E. G. "The drainage of liquids form porous materials." Journ. Geophys. Research, vol. 65, p. 4025-4030, 1960.

Ground Water

Back, William and B. B. Hanshaw, Chemical geohydrology: in Advances in Hydroscience, vol. 2, edited by Ven Te Chow, p. 49-109, Academic Press, New York, 1960.

Davis, S. N. and DeWiest, R. J. M. Hydrogeology. John Wiley and Sons, New York, 463 p., 1966.

De Wiest, R. J. M. Geohydrology. John Wiley and Sons, New York 366 p., 1965.

Ferris, J. G. and A. M. Sayre. "The quantitative approach to ground-water investigations. Economic Geology. 50th Anniv. Vol., p. 714-747, 1955.

Ferris, J. G., D. B. Knowles, R. H. Brown, R. H. Stallman. Theory of aquifer tests. U.S. Geological Survey Water-Supply Paper 1536-E, 1962.

Hubbert, M. K., The theory of ground-water motion. Jour. Geol., Vol. 48, no. 8, p. 785-944, 1940.

Meinzer, O. E. Outline of methods for estimating ground-water supplies, U. S. Geol. Survey Water-Supply Paper 638-C, 1932.

Patten, E. P., Jr. and G. D. Bennett. Application of electrical and radioactive well logging to ground-water hydrology. U. S. Geol. Survey Water-Supply Paper 1544-D, p., 1963.

Payne, B. R. and T. Dinger. Nuclear techniques in hydrology. Proc. First Inter. Seminar for Professors, Urbana, Ill., July 13-25, 1969, vol. 1, p. 126-148, UNESCO/IHD, Paris, 1970.

Pinder, G. F. and Bredehoeft, J. D. Application of the digital computer for aquifer evaluation. Water Resources Research, Vol. 4, p. 1069-1093, 1968.

Skibitske, H. E. Electronic computers as an aid to the analysis of hydrologic problems. Bull. Intern. Assoc. Sci. Hydrol., Publ. 52, p. 347-358, 1961.

Stallman, R. W. Electric analog of three-dimensional flow to wells and its publication to unconfined aquifers. U.S. Geol. Survey Water-Supply Paper 1536-H, p. 205-242, 1963.

Thatcher, L. L. Principles of the application of nuclear techniques in hydrologic investigations. Proc. First Inter. Seminar for Professors, Urbana, Ill., July 13-25, 1969, vol.1, p. 149-193, UNESCO/IHD, Paris, 1970

Precipitation

Bissell, V. C. and Peck, E. L. Unmanned Measurement of Snow Water equivalent using natural soil radioactivity. Paper presented at 53rd Annual Meeting of American Geophysical Union, Washington, D. C. April 1, 1972.

Kahan, A. M. "Status of Cloud Seeding-1972", Proceedings of American Water Resources Association Symposium, Watersheds in Transition, Fort Collins, Colorado, June 1972.

Kessler, E., and Wilk, R. W. Radar measurement of precipitation for hydrological purposes. WMO/IHD Report No. 5.

Peck, E. L. Review of methods of measuring snow cover, snowmelt and steamflow under winter conditions, International Symposia on the role of snow and ice in Hydrology.

Peck, E. L. and Bissel. Aerial Measurement of Snow Water Equivalent by Terrestrial Gamma Radiation Survey, Paper presented at the XV General Assembly of the IUGG, Moscow, August 1971.

Rainbird, A. F. Methods of estimating areal average precipitation, WMO/IHD Report No. 3.

Report on the Alaska Ten Year Comprehensive Plan for Climatologic and Hydrologic Data. Interagency Technical Committee for Alaska, Third Edition, November 1970.

Rodda, J. C. The precipitation measurement paradox, the insturment accuracy problem. WMO/IHD Report No. 16.

WMO Guide to Hydrometeorological Practices, 2nd ed. 1970.

Remote Sensing Applications in Hydrology

Bock, Paul. Concepts of a global water information system. Proc. Second Amer. Water Resources Conference, Univ. of Chicago, Chicago, Ill., Nov. 20-22, 1966, Amer. Water Resources Assoc. p. 405-415, 1967.

Bock, Paul. Remote sensing in space technology in hydrology. Proc. First Inter. Seminar for Professors, Urbana, Ill., July 13-25, 1969, vol. 1, p. 61-87, UNESCO/IHD, Paris, 1970.

Castruccio, Peter A. Remote Sensing and Data Handling - Their Application to Water Resources - 13th Meeting of the Panel on Science and Technology, 1972.

Colwell, Robert N. Monitoring Earth Resources from Aircraft and Spacecraft, National Aeronautics and Space Administration, 1971, U.S.G.P.O.

International Workshop on Earth Resources Survey Systems, May 3-14, 1971, Vol. II, U. S. Government Sponsors, U.S.G.P.O.

Pophem, R. W. Satellite applications to snow hydrology, WMO/IHD Report #7, 1968.

Robinove, C. J. Space applications in water-resources development. United Nations Conference on Exploration and Peaceful Uses of Outer Space, Vienna, Austria, Aug. 14-27, 1968.

Robinove, C. J. Space technology in hydrologic applications. Proc. First Inter. Seminar for Professors, Urbana, Ill., July 13-25, 1969, vol. 1, p. 88-107, UNESCO/IHD, Paris, 1970.

Technical Conference of Hydrological and Meteorological Services (Proceedings), WMO No. 30Y, pp. 3-25, WMO, Geneva 1970.

Water Quality

"Automated Water-quality monitoring." Environmental Science and Technology, Vol. 2, August 1968.

Ballinger, D. G. "Instruments for Water quality monitoring", Environmental Science and Technology, Vol. 2, No. 2, Feb. 1972.

Handbook for Analytical quality control in water and wastewater laboratories, U. S. Environmental Protection Agency, June 1972.

Methods for Chemical Analysis of Water and Wastes, U. S. Environmental Protection Agency, 1971.

Methods for Organic Pesticides in Water and Wastewater. U. S. Environmental Protection Agency, 1971.

Ward, J. C. and Karaki, S. Evaluation of the Effect of Impoundment on Water Quality in Cheney Reservoir, U.S. Dept. of the Interior, Bureau of Reclamation Research Report # 25, September 1969.

Weber, C. I. Methods of Collection and Analysis of Plankton and Periphyton Samples in the Water Pollution Surveillance System, U. S. Dept. of the Interior publication, June 1970.

Evaporation - Evapotranspiration

Blaney, H. F. and Criddle, W. D. Determining Consumptive Use and Irrigation Water Requirements, USDA Technical Bulletin #1275, December 1962.

Erie, L. J., French, O. F., and Harris, K. Consumptive Use of Water by Crops in Arizona, University of Arizona Technical Bulletin #169, August 1968.

Hounam, C. E. Problems of evaporation assessment in the water balance, WMO/IHD Report no. 13.

Mustonen, S. E. and McGuinnes, J. L. Estimating Evapotranspiration in a Humid Region, USDA Technical Bulletin # 1389, July 1968.

Schwab, G. O., Fevert, R. K., Edminster, T. W., and Burns, K. K. Soil and Water Conservation Engineering, John Wiley and Sons, 1968.

USDA Soil Conservation Service National Engineering Handbook, Section 15, Irrigation, Chapter 1, "Soil-Plant-Water Relationships", March 1964.

World Meteorological Organization Technical Note. # 83, Measurement and estimation of evaporation and evapotranspiration.