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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 Hydrologic Applications

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Contents

Abstract

Hydrologic instrumentation and methodology for assessing water-resource potentials have originated largely in the developed countries of the temperate zone. The developing countries lie largely in the tropic zone, which contains the full gamut of the earth's climatic environments, including most of those of the temperate zone. For this reason, most hydrologic techniques have world-wide applicability.

Techniques for assessing water-resource potentials for the high priority goals of economic growth are well established in the developing countries--but much more so in some than in others. Conventional techniques for measurement and evaluation of basic hydrologic parameters are now well-understood in the developing countries and are generally adequate for their current needs and those of the immediate future. Institutional and economic constraints, however, inhibit growth of sustained programs of hydrologic data collection and application of the data to problems in engineering technology.

Computer-based technology, including automatic processing of hydrologic data and mathematical modelling of hydrologic parameters is also well-begun in many developing countries and has much wider potential application. In some developing countries, however, there is a tendency to look on the computer as a panacea for deficiencies in basic hydrologic data collection programs. This fallacy must be discouraged, as the computer is a tool and not a

"magic box." There is no real substitute for sound programs of basic data collection.

Nuclear and isotopic techniques are being used increasingly in the developed countries in the measurement and evaluation of virtually all hydrologic parameters in which conventional techniques have been used traditionally. Even in the developed countries, however, many hydrologists are not using nuclear techniques, simply because they lack knowledge of the principles involved and of the potential benefits. Nuclear methodology in hydrologic applications is generally more complex than the conventional and hence requires a higher level of technical expertise for effective use. Application of nuclear techniques to hydrologic problems in the developing countries is likely to be marginal for some years to come, owing to the higher costs involved and expertise required. Nuclear techniques, however, would seem to have particular promise in studies of water movement in unsaturated soils and of erosion and sedimentation where conventional techniques are inadequate, inefficient and in some cases costly.

Remote sensing offers great promise for synoptic evaluations of water resources and hydrologic processes, including the transient phenomena of the hydrologic cycle. Remote sensing is not, however, a panacea for deficiencies in hydrologic data programs in the developing countries. Rather it is a means for extending and augmenting on-the-ground observations and surveys (ground truth) to evaluate water resources and hydrologic processes on a regional or even continental scale.

With respect to economic growth goals in developing countries, there are few indentifiable gaps in existing hydrologic instrumentation and methodology insofar as appraisal, development and management of available water resources are concerned. What is needed is acceleration of institutional development and professional motivation toward more effective use of existing and proven methodology. Moreover, much sophisticated methodology can be applied effectively in the developing countries only when adequate levels of indigeneous scientific skills have been reached and supportive institutional frameworks are evolved to viability.

Introduction

This position paper, prepared at the request of the Office of Science and Technology, Agency for International Development (PASA TA (IC) 9-72), Sept. 24, 1971), describes techniques for assessing water-resource potentials in the developing countries most of which lie in the tropics. This zone, however, contains the full gamut of the earth's climatic environments ranging, for example, from the rainless Atacama desert through the Amazonian rainforest to the Andean snowfields within the tropic zone of South America. Thus, hydrologic techniques, which have evolved in the developed countries of the temperate zone where similar climatic environments are found, can be applied wholly or in part in all the developing countries.

Although the earth is largely impregnated with or covered by water, relatively little of the total water volume is available for man's use given the present state of scientific knowledge and engineering technology related to discovery, control and management of water. Yet, ever-increasing demands are placed on available water resources by world-wide population growth and urbanization with attendant needs for greater food production through intensified irrigation and for control 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 more sophisticated understanding of the natural rôle of water in the earth's physical, chemical, and biological processes. Advances in hydrologic science have also stimulated engineering technology in devising more effective ways and means for utilizing available water resources as well as water heretofore not available, notably fossil ground water, sea water and polar ice.

All water for man's needs must be obtained from the natural environment, the hydrosphere. To use and control water effectively requires knowledge of its behavior in the environment and this knowledge is acquired through collection, analysis and interpretation of hydrologic data. Man's activities transect all phases of the water cycle. Therefore, hydrologic data are many facetted, including observations of precipitation, snow cover, stream flow, ground water, 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 great river from one drainage basin to another requires a high level of hydrologic knowledge and engineering technology.

In the present state of hydrologic knowledge, techniques for assessing water-resource potentials for high priority goals of economic growth are well-established in the developing countries--but much more so in some than in others. Whereas conventional techniques for measurement and evaluation of basic hydrologic parameters are now well-understood in most of the developing countries, institutional and economic constraints in many have inhibited growth of sustained programs of hydrologic data collection and application of the data to problems in engineering technology. Experience has proven, moreover, in the less-advanced developing countries 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 a viable level of institutional development and indigenous professional motivation has been attained. Consequently, the application of appropriate methodology must be geared to the needs of individual developing countries.

Hydrologic research in the developed countries although primarily directed toward domestic needs is nevertheless potentially applicable to the rest of the world owing to the universality of water problems. Such research can be grouped in three general categories as follows:

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

Environmental: Study of water behavior in various climatic, geographic and geologic environments such as limestone and volcanic terrains, lakes, reservoirs, coasts; hydrological aspects of pollution, irrigation, watershed management, floods, hydropower generation, etc.

Methodological: Mathematical analyses, 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, of course, place highest priority on research oriented toward water-resources development to meet pressing needs for economic growth. On the other hand, the developed countries give higher priority to research oriented to protection of known and utilized water resources and to control of deterioration in their quality.

Outstanding among efforts to advance and expand knowledge in scientific and applied hydrology during the past 10 years has been the International Hydrological Decade (IHD), initiated in early 1965 under the aegis of UNESCO with strong participation by UN specialized agencies and the national committees of 107 governments. The IHD has played a key rôle in fostering scientific and technical exchange among participating agencies and governments; in furthering establishment of national networks for collection of basic hydrological data; and in strengthening national programs of hydrologic research on a world-wide scale.

In following discussions, techniques or methodology for measuring or evaluating hydrologic parameters are described in the categories of streamflow, erosion and sedimentation, water movement in unsaturated soils, ground water and remote sensing in hydrologic applications. Established techniques and methodology are described in "state of the art" and those still under development in "current research." Where possible, instrument and survey costs have also been included. Research gaps and priorities, however, are discussed collectively as these are not strictly susceptible of separation into the above-mentioned categories.

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 stream flow 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 of the water mass in the hydrological cycle, methods and techniques of observation and measurement are highly evolved. Consequently, it is possible to measure stream flow 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 stream flow is the current meter with which it is possible 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 a gage observer who reads a calibrated staff gage at a selected station--usually daily at a specific time. Continuous observations of stage at selected stations can also be obtained by permanently installed clock-driven recorders with float and cable-driven drums on which continuous graphs of changing stream stage are registered by pen on a calibrated chart. Records of actual flow 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 for a calendar day. Daily discharge in the metric system is expressed in cubic meters or liters per second and cubic feet per second in the English system. 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 and 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. An adequate network of well-designed and well-planned stream-gaging stations is essential to the economy of any viable nation.

A most significant innovation in the collection of hydrologic data in the developed countries in the past two decades has been that of a digital recorder 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 records-processing program begins with a stage record obtained from a digital-recorder gage and ends with a computer print-out 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 entire processing procedure is called a "gage to page" plan, for almost the entire process is accomplished by the use of machines, the only human factor being the introduction of judgment factors into the programming of computer operations. 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 without the use of stilling wells and intake pipes, which are often expensive to construct and difficult to 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 $\pm$ 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 in the conventional current-meter measurement, the moving-boat technique requires information on the location of observation points, stream depth at each observation point, stream velocity perpendicular to the cross section at each section at each observation point. During the transverse 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 alines 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 req uires 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 mean 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 to 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 adequate networks for the collection of field measurements. Intuitive and judgment factors are utilized in beginning such networks. Appropriate weight is given to sampling areas having different terrains, 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 principal 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 in the responsibility of a government to furnish hydrologic data for its own use and that of its citizens 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. Even these relatively simple instruments, however, present maintenance problems in some of the more remote regions of developing countries as for example in Nepal, Afghanistan, Congo (Kinshasa), the interior of Brazil, Ethiopia and elsewhere. The digital recorder coupled with computer 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 might 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 instrumental and maintenance problems beyond the ken of the technical staff. The dye-dilution method for discharge measurement has been used occasionally for special hydraulics 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 in the 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 São Francisco Rivers in Brazil, the Paraná 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.

The 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

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 behaviour 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
	$550
Simple gaging station with automatic graphic recorder	
Construction and material costs	$2,500
Instrumentation	1,000
Hydrologist services and maintenance per year	1,500
	$5,000
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
	$50,000
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 auxilary equipment	$1,500
One digital recorder with ancillary equipment	$700
Moving-boat technique:	
Instrumentation	$3,500
Boat and motor	5,000 to 10,000
	$8,500 to 13,500

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

Installation of 50 staff gages-------------------	$12,500
Observers 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 cost, however, would be in the order of $150,000 per year. For a large developing country, however, these costs might well be doubled or tripled.

Current research

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

With respect to the second category, much current 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 maintain 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 first 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, the most widely used of modelling approaches, usually requires input data with considerable detail in time and 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 stream-flow-aquifer relations, runoff prediction in various climatic and physiographic regimes, or ground-water basin modelling.

Conventional techniques for measuring discharge of streamflow by current meter 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 of 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 as for example in Brazil, Turkey, Kenya, Chad, Greece, Senegal and elsewhere. There is scope, however, for much wider application of these techniques in the developing world.

Erosion and sediment transport

Erosion and sediment transport phenomena, are operative in greater or less degree on most of the exposed surfaces of the earth. Erosion 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 wash load in natural stream channels and ends with deposition in 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--

How soon will this reservoir be filled with sediment?

What will happen to the stream (channel) below this dam when it is completed?

What will be the effect of these levees after their construction on this stream channel?

What will happen if this reach of the river is straightened?

What size of riprap is needed to prevent this river bank from eroding?

What depth of scour can be expected at this bridge pier?

To answer some of these questions 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 wash load is conventionally measured with a depth-integrating sampler, which typically consists of a stream-lined case carrying a standard 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 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-load sampling under flowing water is difficult because the finer particles are frequently lost in the sampling process. Clamshell (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 periodically determined 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 increasing for sediment studies such as determining the direction and velocity of sediment transport in streams; the stream-bed length effected 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 rôles played by splash or rain-drops and overland rill wash in the erosion of soil and the relation between erosion, 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 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

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. Practically oriented 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. It should, however, gain increasing favor in the near future because it is versatile and requires 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 two 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 application if initial costs can be reduced.

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 and including the water table. The hydrologic processes of infiltration, redistribution, percolation, drainage, and evaporation all occur in this zone. The water content of this 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. Study of water in this zone requires detailing mapping of water content and pressure-head distributions in space and time. What is needed is a method of 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 is, 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, with respect 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. 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 auxilary equipment--------- $1,000

One pressure-cell apparatus for laboratory use with auxilary equipment------------------- $1,000

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 principal 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 conductivity and diffusivity measurement in the unsaturated zone continues to be an important research need.

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 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 other phases of 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 hydrologic 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. Surface electrical-resistivity surveys 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 elastic properties of the two types of rock. Aeromagnetic and gravimetric methods are also used to locate buried bedrock surface where appreciable discontinuities in rock magnetism and density exist in two-layer systems. Aeromagnetic methods are particularly useful where rapid reconnaissance delineation 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 tool in distinguishing aquifer contacts. Formational 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 considerable antecedent 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 technique is fluid-conductivity logging which provides record or 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. Still more recently, compact television cameras with wide-angle lenses of short focal length are being designed for on-site inspection of well casings and examination of the lithologic character of borehole surfaces.

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-capacitor networks with analyzers can be constructed, with a degree of complexity depending on the nature of the ground-water system and the available basic data. In the model, the fundamental aquifer variable (transmissivity) is simulated electrically by capacitance. 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 inter-relationships such as streamflow-aquifer behaviour.

The chemical characteristics of ground water are very important with respect to its utilization as well as with respect to geochemical methods for analyzing ground-water systems. 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. Induced 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 developing areas such as the Chad Basin and Nile-Lake Victoria Basin of Africa, the Paraná Basin in Brazil, Cheju Island in Korea and elsewhere. Also radioisotopes, such as carbon-14 and 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 a transmission-conduit reservoir. As a conduit, 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. In its rôle as a storage reservoir the aquifer provides a reserve 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 behaviour of aquifers and ground-water systems, a considerable number of methods have been evolved for the mathematical analysis of problems in fluid mechanics as they apply to ground-water flow systems. To enumerate, well methods of aquifer evaluation 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 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 development programs begin with a light 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 are given in the estimates below.

Light reconnaissance by one hydrogeologist of 1,000 square miles with minimum instrumentation and no test drilling for a 3-months term	$10,000
Moderately intensive reconnaissance by one hydrogeologist of 5,000 square miles with minimum instrumentation and no test drilling for a 1-year term	$25,000

Intensive investigation by 2 hydrogeologists of 10,000 square miles with full instrumentation, hydrogeologic mapping, aquifer testing, test drilling (excluding drilling rig) and report for a 3-year term	$150,000
One weekly graphic water-stage recorder with auxilary equipment for use in observation well	$250
One continuous graphic water-stage recorder with auxilary equipment for use in observation well	$700
One borehole geophysical logger, fully instrumented	$6,000
Test drilling:	
One combination percussion-rotary drilling rig	$80,000
Drilling costs, 8-inch hole, per foot	
Dolomite and limestone	$5
Unconsolidated sediments	$2
Sandstone	$4
Quartzite	$25
Basalt and granite	$15
Analog model of small ground-water basin	$15,000
Digital model of a stream-aquifer system	$25,000

Current research

There have probably been few major break-throughs in ground-water science since the work of C. V. Theis, who 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 of problems relating to two-phase fluid systems in heterogeneous porous media.

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

There are few if any identifiable research deficiencies in instrumentation and methodology insofar as needs for ground-water exploration, development and management in the developing countries are concerned. A number of developing 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 nurture, growth and support of scientifically based ground-water agencies; training and motivation of ground-water scientists; and administrative support of such agencies.

Remote sensing in hydrologic applications

Remote sensing has perhaps the greatest potential of all advanced techniques thus far evolved for evaluating the earth's mineral, land, and water resources and environmental processes, including the hydrologic cycle, on a regional or even continental scale. Water development and control has traditionally been undertaken on a local basis. This approach has frequently generated undesirable environmental costs which may be greater than the benefits of development. Remote sensing offers the opportunity for approaching water-resources appraisal, development and management on a more rational basis and regional scale, hopefully based on advance knowledge of the environmental implications of alternatives in development.

The state of the art, instrument and survey costs, and current research in remote sensing technology are thoroughly covered in a companion paper. (See, "The Application of Geochemical, Botanical, Geophysical and Remote Sensing Mineral Prospecting Techniques to Tropical Areas--State of the Art and Needed Research.") The discussion also applies wholly or in part to water resources and hydrology; hence there seems little point to repeating it here. For the interest, however, of the reader, present and potential uses of remote sensing in hydrologic applications, as identified by C. J. Robinove, are summarized in the following tabulation. This includes, of course, well-known conventional aerial photography as well as more recently evolved remote sensing techniques which are still in the experimental stage.

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.
Multispectral Photography	Multispectral photography interpretation requires a background of spectral-signature studies of terrain and water features that have not yet been made. Data returns from multispectral systems may be so voluminous that they cannot be readily interpreted. 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.
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.

Remote-Sensor System	General Comments on Potential Value and Use of Remote-Sensor System for Hydrologic Studies
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.
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.
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.
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.

Remote-Sensor System	General Comments on Potential Value and Use of Remote-Sensor System for Hydrologic Studies
Microwave radiometry and Imagery	Passive-microwave sensors measure the brightness 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.

Remote-Sensor System	Data Available from Remote-Sensor System	Measurement of Physical Characteristics of Water Surfaces
Panchromatic Photography	Much aircraft data taken for many purposes. Some special data. Some space data.	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.
Multispectral Photography	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.	Largely unproved but may be useful in special situations. Small data use.
Infrared Photography	Much aircraft data available	Not usable because water surfaces always appear black in infrared photography. No data use.
Color Photography	Much aircraft Gemini spacecraft data.	Of some value but rigorous evaluation has not been made. Small data use.
Infrared-Color Photography	Aircraft data available.	May provide a higher contrast for mapping of discontinuities on water surfaces than any other type of photography. Small data use.

Remote-Sensor System	Data Available from Remote-Sensor System	Measurement of Physical Characteristics of Water Surfaces
Infrared Radiometry	Data available from aircraft and from Tiros and Nimbus Satellites.	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 temperature. Moderate data use.
Infrared Imagery	Data available from aircraft and from Tiros and Numbus Satellites.	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 distribution within a water body as a function of the surface temperature. Small data use.
Radar Imagery	Aircraft data available.	Water is an excellent reflector of microwaves and, therefore, water surfaces show as a uniform black tone on radar imagery. Radar imagery, therefore, is of little value in measuring physical, chemical, or biological characteristics of water but is useful in locating and mapping areas of open water. Small data use.

Remote-Sensor System	Data Available from Remote-Sensor System	Measurement of Physical Characteristics of Water Surfaces
Microwave radiometry and imagery	Aircraft data available	May be used for measurement of temperature. Small data use.

Remote-Sensor System	Measurement of Chemical and Biological Characteristics of Water	Snow Surveying and Mapping
Panchromatic Photography	Useful only for assessing some vegetation types. Small data use.	Useful for mapping snow-covered areas but does not indicate depth or water content of snow. Moderate data use.
Multispectral Photography	May be valuabel as a supplement to other photography but specific interpretation criteria have not been developed. Small data use.	May be useful but perhaps not superior to panchromatic photography. Small data use.
Infrared Photography	Not usable because water surfaces always appear black in infrared photography. No data use.	Not yet evaluated. Small data use.
Color Photography	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.	May not be significantly better than panchromatic photography. Small data use.
Infrared-Color Photography	Probably not helpful in detection and identification of substances in water but may be useful in mapping their distribution. Small data use.	Has been used to differentiate new snow from ice and firn. Small data use.

Remote-Sensor System	Measurement of Chemical and Biological Characteristics of Water	Snow Surveying and Mapping
Infrared Radiometry	Valuable only if the chemical or biological factors have an effect on the temperature or emissivity of the water surface. Small data use.	Not evaluated for this purpose. Small data use.
Infrared Imagery	Valuable only if the chemical or biological factors have an effect on the temperature or emissivity of the water surface. Small data use.	Of some use in sea-ice mapping but has not been evaluated for use in snow surveys for water-supply forecasting. Small data use.
Radar Imagery	Water is an excellent reflector of microwaves and, therefore, water surfaces show as a uniform black tone on radar imagery. Radar imagery, therefore, is of no value in measuring physical or chemical, or biological characteristics of water. No data use.	Has some value in mapping snow-covered areas but does not give data on the water content of snow. Small data use.
Microwave radiometry and imagery	Probably not useful. No data use.	May be capable of measuring temperature as a function of water content and density. Worthy of further research. Small data use.

Remote-Sensor System	Mapping and Description of Ground-Water Features	Glaciology
Panchromatic Photography	Highly useful for hydrogeologic mapping, drainage mapping, and identification of vegetation features associated with ground water. Large data use.	Moderate value in mapping snow and ice fields and surface structure of glaciers. Moderate data use.
Multispectral Photography	May be useful but perhaps not superior to panchromatic photography. May be useful in differentiating vegetation types as indicators of ground water.	May be useful but probably is not superior to panchromatic photography. Small data use.
Infrared Photography	Valuable as adjunct to panchromatic photography because some rock units have different contrasts and are, therefore, more recognizable. Moderate data use.	Now being evaluated. Small data use.
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 detection and identification.
Infrared-Color Photography	Probably superior to standard color photography in defining vegetation and soil characteristics. Small data use.	Has been used to differentiate new snow from ice and firn. Small data use.

Remote-Sensor System	Mapping and Description of Ground-Water Features	Glaciology
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.	Now being evaluated for its use in measuring temperature and radiative transfer of energy from snow and ice surfaces. Small data use.
Infrared Imagery	Now being evaluated as a tool for locating points of ground-water discharge to streams. Small data use.	Helpful in mapping ice and snow temperature and state. 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.	May prove to be highly useful for differentiation of snow and ice types and determination of energy budget. Small data use.

Remote-Sensor System	Geomorphology and Assessment of Changes in the Hydrologic Regimen	Measurement of Liquid-Vapor Transfer in Hydrologic Cycle
Panchromatic Photography	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	Not yet evaluated for this purpose.	Not applicable to this problem.
Infrared Photography	Helpful in addition to normal aerial photography but not normally used alone. Small data use.	Not applicable to this problem.
Color Photography	Helpful in determination of types and composition of surficial deposits. Small data use.	Not applicable to this problem.
Infrared-Color Photography	May be superior to standard photography. Small data use.	Not applicable to this problem.
Infrared Radiometry	Probably not useful for this purpose. Small data use.	Helpful in determining radiative transfer of energy from water and land surfaces to the atmosphere. Small data use.

Remote-Sensor System	Geomorphology and Assessment of Changes in the Hydrologic Regimen	Measurement of Liquid-Vapor Transfer in Hydrologic Cycle
Infrared Imagery	Not yet evaluated. Small data use.	Useful in regional atmospheric physics but not used in small-scale studies. Small data use.
Radar Imagery	Now being evaluated. Small data use.	Not applicable to this problem.
Microwave Radiometry and imagery	Probably not useful for this surface. No data use.	Usable only for high altitudes. Doubtful use for microclimate. No data use.

Approximate amount of data use:

Small - small number of interpreters evaluating techniques.
Moderate - a few persons using techniques in specialized studies.
Large - used by many hydrologists as a standard tool in hydrologic studies.

Research gaps and priorities

With respect to economic growth goals in developing countries, there are few identifiable gaps in existing hydrologic instrumentation and methodology insofar as appraisal, development and management of available water resources are concerned. Most of the gaps lie in the socio-economic realm and not strictly in the scientific or technical. What is needed is acceleration of institutional development and professional motivation toward more effective use of existing and proven methodology. Moreover, much sophisticated methodology can be applied effectively in the developing countries only when adequate levels of indigenous scientific skill have been reached and supportive institutional frameworks are evolved to viability.

Among areas of hydrologic research oriented to economic development the following would seem to merit priority attention for needs in the developing countries:

Hydrological research related to the use of brackish waters for irrigation

Desalination of sea water for urban water supply in coastal zones

Evaporation suppression from open-water surfaces of lakes and 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

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.

The technology of desalination of sea water is rapidly approaching the stage where desalted water may become economic for use in large urban and industrial nuclei of coastal zones of developing countries. In these situations there would be concentration of water use and demand and presumably financial resources to cover 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 area of research which has important and immediate application in developing countries. Numerous man-made reservoirs as for example, Lake Volta in Ghana, Lake Kariba in Zambia and Rhodesia, and Lake

Nassar in Egypt, have been created through large-dam construction in the developing countries during the past two decades. The water yield of these reservoirs could be markedly increased if it were possible to suppress effectively natural water losses by evaporation. Research in this area is still, however, in its infancy and much more work needs to be done before evaporation suppression techniques can be applied to large man-made reservoirs.

Artificial recharge of ground-water reservoirs with reconditioned waste waters or surpluses of natural surface runoff is now widely practiced in Europe and the United States. Water spreading and recharge wells are the two most common methods used in artificial recharge. Because of cost and the complex technology required, recharge wells probably have limited applicability in developing countries. Water spreading by flooding, basins, 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 ground-water development for irrigation and other uses in developing countries such as India, Pakistan, Iran, Egypt, Turkey, Taiwan, Chile, and elsewhere. As such development proceeds and intensifies, increasing attention will need to be given to artificial recharge for replenishment of depleted ground-water storage and for control of water quality. In anticipation of such needs, practically oriented research in artificial recharge methodology appropriate to local hydrogeologic conditions needs to be undertaken in many of the more advanced developing countries.

In most developing countries surface-water and ground-water resources are considered to be wholly independent of one another 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 in many hydrologic environments intimately inter-related and inter-dependent. The development and use of the one sooner or later effects 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 gaining increasing favor in the more advanced developing countries, 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, in other critical areas such as the Ganges Plains of India, the river valleys of Tunisia and Morocco, the river valleys and basins of Chile, Argentina and Peru, and elsewhere in the developing world. Through conjunctive use, all the available water resources of a given valley or basin can be developed and managed optimally and equably, but much local research on hydrologic as well as socio-economic constraints is needed to achieve this goal.

Modelling of hydrologic systems through use of analog and digital computers in now well-established in the developed world but is not widely practiced in the developing countries. There are, however, extant 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 interpretive evaluation of the response of hydrologic systems to development stress. Digital modelling also is being employed in Chile to study stream-aquifer relationships in the transverse valleys of the central part of the country and are also 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 not infrequently 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 storage of water through underground nuclear explosions. Also another possibility is nuclear 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 the local political sensibilities involved in the utilization of nuclear energy. They have, however, considerable future promise and need to be evaluated more fully.

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