OPPORTUNITIES TO IMPROVE HYDROLOGIC DATA

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Abstract. Hydrologic data collection over scales from centimeters to continents, from minutes to years is difficult and expensive, so hydrologic models usually conceptualize processes based on simple, often homogeneous, views of nature. This forced oversimplification impedes scientific understanding and management of water resources. As the focus of hydrologic research shifts to larger regional and global scales, the collection, management, distribution, and analysis of data will improve so that models and data can each drive and direct the other. Better models illuminate the type and quantity of data needed to test hypotheses. Better data permit development and validation of more complete models and new hypotheses. Coordinated hydrologic experiments (such as the Global Energy and Water Cycle Experiment) and remote sensing of hydrologic parameters examine hydrologic variables at these larger scales, and isotope geochemistry, paleohydrology, and biological methods allow analysis and retrieval of new kinds of information. Improvements in the management and accessibility of data will make them more easily available to hydrologic scientists.

INTRODUCTION

Hydrologic science deals with the occurrence, distribution, circulation, and properties of water on Earth. Because of water's importance to Earth and biological sciences and because water is necessary for all human activities, concerns for issues in hydrologic science have been distributed among traditional geosciences and engineering. Eagleson [1991] and the National Academy of Sciences' Committee on Opportunities in the Hydrologic Sciences, Water Science and Technology Board [1991] have argued that a coherent understanding of water's role in the planetary-scale behavior of the Earth system depends on the establishment of an infrastructure of hydrologic science. To support such an infrastructure, improvements are needed in the collection, management, distribution, and analysis of hydrologic data.

Hydrologic processes are highly variable in space and time, and this variability exists at all scales, from centimeters to continents, from minutes to years. Because comprehensive data collection over such a range of scales is difficult, hydrologic models, ranging from hydrologic components of climate models to models of water quality, usually conceptualize processes based on simple, often homogeneous, models of nature. Hence a 2000-km² river basin is commonly modeled as a lumped system that responds as a unit with average representative properties. Groundwater flow is rarely treated as three-dimensional. Rainfall is expressed as a mean over large areas and as depths over periods of a day. Snowmelt runoff volumes are forecast from averages of snow accumulation at a few index plots. These conceptualizations are caused by the common dearth of data, which lack the temporal and spatial resolution to support models that include processes and their interactions as they are truly distributed in space and time.

The pioneers of modern hydrology had to be active observers and measurers to answer their scientific questions. Most significant advances in the hydrologic sciences resulted from new measurements. Yet today there is a schism between data collectors and analysts. Some hydrologic researchers collect their own data, but the management of data for the broader enterprise, designing and executing data collection programs and archiving, managing, and distributing data, is too often viewed as mundane or routine. It is therefore difficult for agencies and individuals to assure continuity, accessibility, and consistency of hydrologic data sets. In the excitement over startling increases in our computational power and the scale of the problems we are able to compute, the scientific community tends to allow data programs to erode and only reluctantly to commit resources to improvements in managing data.

Reliable, consistent data are essential if our models are to best benefit from our technological prowess. Models and data together provide the basis to understand hydrologic systems and document changes in regional and global environments. Modeling and data collection each drive and direct the other. Better models illuminate the type and quantity of data that are required to test hypotheses. Better data, in turn, permit better and more complete models and new hypotheses.
If we accept this synergism, the hydrologic sciences are well situated for progress, because recently developed spatial and temporal models and new technology for data acquisition require a rethinking of traditional hydrologic problems.

Data are needed for multiple reasons in examination of the hydrologic cycle, and the choice of what, where, and when to measure influences what hydrologic questions we can investigate. Moreover, measurement of hydrologic variables is a scientific endeavor itself. In this paper I describe the needs and opportunities in the science of hydrologic measurement to develop and verify better methods of data collection. Future progress in hydrologic data collection should result from (1) coordinated experiments where diverse efforts are pooled; (2) technological advances in such fields as remote sensing and instrumentation; (3) new forms of analysis such as isotope geochemistry, paleohydrology, and improved models of spatial and temporal processes; (4) intensified efforts in design of monitoring networks and examination of data quality and compatibility; and (5) improved information systems that can engender new modes of research and foster interactions between observation and models.

CHARACTERISTICS OF HYDROLOGIC DATA

Hydrologic data are needed to measure fluxes and reservoirs in the hydrologic cycle and to monitor hydrologic change over a variety of temporal and spatial scales. Moreover, most hydrologic data have been collected to answer water resources questions rather than scientific ones. Progress in the hydrologic sciences therefore depends on improved methods for collecting hydrologic data, more complete and better organized archives of information, and better mechanisms for distribution and exchange of data.

Far more hydrologic data are obtained under field conditions than from the laboratory. The reason is that hydrologists are concerned with processes that only have meaning at the field scale or over long time scales, such as runoff and sediment yield from drainage basins or continental-scale drought. These requirements complicate hydrologic data collection. Despite large financial investments there remain important areas of ignorance about hydrologic storages and fluxes, which are unlikely to be removed by the incremental growth of existing instrumental networks. Technical and analytical innovations are necessary to overcome the paucity of useful hydrologic data now being assembled.

Figure 1 shows the global hydrologic cycle, with best estimates of volumes of water in the Earth’s reservoirs and fluxes of water between these reservoirs. Proper incorporation of hydrologic processes in climate models and an understanding of global hydrology require measurements of the patterns of surface wetness, temperature, reflectance, and vegetation, along with their effects on the formation of clouds and precipitation.

Range of Hydrologic Scales

Throughout the hydrologic sciences we encounter questions about the quantitative relationship between processes occurring at disparate spatial or temporal scales, from those of laboratory experiments to global transport of water, nutrients, and water vapor, from short-lived, transient phenomena to gradual long-term variations. Important questions exist at temporal scales from seconds to millennia and spatial scales from molecular to global.

A sample problem studied in the laboratory or a field plot involves interactions between solutes and water vapor, liquid water, and ice. The rate of elution of chemical impurities from an abating snow cover is faster than the melt rate; the major fraction of the impurities are released in the first states of melt, and some chemical species are released more rapidly than others [Davies et al., 1991]. Although we can calculate rates of snowmelt by monitoring energy exchange at the
surface, our knowledge of the chemical interactions is not yet good enough to allow us to calculate a "chemical hydrograph" [Bales et al., 1989].

At the same time, our current knowledge of some huge fluxes of water in the hydrologic cycle has large uncertainty. Earth's largest fresh water reservoirs are the ice sheets of Antarctica and Greenland, and the volume of water stored therein changes continuously. Assessing the rate of change is fundamental to developing scenarios for sea level change in the future, but little is known about the current state of balance. Only spot measurements of accumulation, melting, and iceberg production are available, along with a few altimeter data for southern Greenland, so the different estimates of the mass balance of the ice sheets encompass such a wide range of values that only qualitative assessments are possible [Van der Veen, 1991].

Data are needed at a variety of scales, and the spatial and temporal scales of available data restrict the questions that can be investigated. An important issue in the sampling of hydrologic processes is the structure of the statistical fluctuation that the processes have at different scales of measurement [Wood et al., 1990; Rodriguez-Iturbe et al., 1991]. How do the mean and variance of annual rainfall change as a function of the area over which the estimation takes place? How do the mean and variance of evapotranspiration depend on the time scale considered? How does soil moisture balance affect local recycling of precipitation? What is the combined effect of time and space scales in the statistical moments of hydrologic variables?

There is an urgent need to characterize quantitatively the fluctuations of hydrologic variables at different time and space scales and to design data collection programs that will allow the study of theoretical constructs to structurally link the fluctuations at different scales.

Quality of Hydrologic Data Bases

Detection of hydrologic change requires a committed, international, long-term effort, and imposes rigorous standards of accuracy on the data. Most hydrologic data are collected by agencies for management of water resources, not for development of hydrologic understanding or examination of long-term trends, where more accurate data are needed. Changing priorities within agencies sometimes lead to modifications of hydrologic networks that result in discontinuities in time series, movement of measuring sites, or changes in accuracy of data. These modifications interfere with the suitability of the data for detecting subtle hydrologic changes that are superimposed on large interannual or interevent variation.

Synergism between models and data is necessary to design effective data collection efforts to answer scientific questions. Spatial and temporal scales of available data restrict the questions that can be investigated. Hydrologic parameters are measured most intensively over the humid-temperate, densely populated, industrialized regions; measurement networks are sparse over oceans and subhumid, tropical, high-altitude, or lightly populated regions.

Long-Term Data Needs

Long-term monitoring and the use of paleohydrologic records are fundamental to understand the role of extreme events in hydrologic systems [Jarrett, 1991]. The need for long-term measurements is becoming clearer in our investigations of hydrologic change. Some disciplines, such as paleontology and historical geology, have depended for their existence on the availability of data spanning periods as long as two billion years. Other disciplines that have traditionally focused research over shorter time frames, such as the environmental sciences, now stress the critical importance of long-term records. Tree ring data, for example, can aid the interpretation of modern records of precipitation and river flow, from rain gages and gaging stations, to see whether they represent the past several centuries.

Data for Global Hydrology

Sensitivity studies with global climate models have identified the important role played by surface hydrology. Subtle global hydrologic effects have important consequences for human affairs. Questions about the global water balance (the spatial and temporal characteristics of water in all compartments of the global system: atmosphere, oceans, and continents) have therefore become more important in modern hydrologic science [Eagleson, 1986]. However, useful hydrologic data at the global scale are sparse, because most hydrologic data have been collected with local-scale (or at best national-scale) questions in mind. The uneven distribution of hydrologic monitoring stations around the world makes it difficult to study the simultaneity of trends and the full extent of widespread changes that are suspected to be linked. For those hydrologic variables that translate into recognizable electromagnetic features that can be viewed from aircraft or satellite, remote sensing methods are used to fill in the vast areas between ground-based stations. Because it is not possible with foreseeable technology and resources to monitor hydrology over the entire Earth, a combination of global mapping and global sampling is necessary to answer hydrologic questions of global significance.

Spatial and Temporal Variability of Data Needs

A fundamental question faced by users of most hydrologic data is, "How do I interpolate between measurement points?" [Gupta and Waymire, 1990]. For example, depths and water equivalences of a snowpack are measured at many snow courses in cold regions, but it is only possible to use these data as crude estimates of the water content of a regional or basinwide snowpack. Strong spatial gradients caused by topography or vegetation on snowfall, interception, redistribution, and melt are not explicitly modeled in forecasting water supply, runoff rates, and soil moisture recharge, and in mountainous basins the distributions of rain gages often are skewed away from the higher elevations (Figure 2). Topographic influences on rainfall, evaporation, and soil moisture are poorly documented at scales varying from individual hillslopes to entire mountain ranges, and there is currently little understanding of the relationship between regional,
time-averaged rainfall rates and the frequency and magnitude of storms.

Large-scale hydrologic processes such as the coupling between global atmospheric circulation and the North American seasonal snowpack or regional droughts are not well understood or predictable [Walsh, 1987]. Understanding them requires simultaneous measurements of phenomena that have traditionally been within the purview of different disciplines.

Large-scale measurement programs such as Boreal Ecosystem-Atmosphere Study (BOREAS), Storm-Scale Operational and Research Meteorology (STORM), and Global Energy and Water Cycle Experiment (GEWEX) will address hypotheses about these couplings.

Important hydrologic changes may be subtle and difficult to detect because of large interannual or interevent variation. Recognition of such changes or their absence therefore requires carefully designed, long-term monitoring networks. The paucity of suitable long instrumental records requires the use of historical stratigraphic, botanical, and geochemical records of hydrologic change.

Some hydrologic events involve rare, short-lived, catastrophic processes, such as the influence of the eruption of Mount St. Helens on flooding and sedimentation along the Toutle and Cowlitz River valleys (Figure 3), the effects of intense forest fires on runoff and erosion during succeeding wet seasons, or the release of radionuclides after weapons testing or toxic chemicals after industrial accidents. The probability of an instrumental network being in place to record the event adequately is low. Therefore researchers and granting agencies need to be able to rapidly mount coordinated field studies to collect data when such transient processes occur.

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**Figure 2.** Raingages in the Eel River basin, northern California. At first glance the raingages appear to be well distributed, but almost all are in the river valleys, so precipitation is not measured in the higher elevations [Committee on Opportunities in the Hydrologic Sciences, Water Science and Technology Board, 1991].

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**Figure 3.** Accumulation of sediment on the Columbia and Cowlitz River beds after the eruption of Mount St. Helens on May 18, 1980 [Haeni, 1983].
Archival of Samples

Data needs are not only numerical. The archiving and rapid retrieval of samples for future analyses will be needed for the continuing analysis of environmental conditions in aquatic habitats. For example, an essential feature recommended for the National Science Foundation's Long Term Ecological Research Program is the archiving of chemical and biological samples. Established museums have served historically as repositories for biological materials. Unfortunately, such collections, although usually catalogued and curated well, have been disproportionately directed toward terrestrial organisms, or only the terrestrial life stages of aquatic species. Thus special initiatives will be necessary to insure that appropriate aquatic biological materials are archived and curated, and cryogenically or chemically stabilized water samples used for current scientific experiments should be archived for future analysis. If such samples were available today from past decades, they could be used to evaluate changes of chemical parameters in aquatic environments.

COORDINATED EXPERIMENTS

Evaporation of water from the Earth's land surface is a major component of the energy balance, and water vapor in the atmosphere absorbs infrared radiation and influences the climatic engine that drives atmospheric circulation. Therefore the balances of energy and water are intimately coupled, and the mathematical description of their interrelationship in time and space is an important unsolved problem in hydrologic science [Avissar and Verstraete, 1990]. The processes involved depend critically on such things as the physical properties of the soil, the type and density of vegetation cover, the climate, the season, and the weather. Observations are necessary to understand these complex phenomena, and they must be large enough in spatial scale to obtain useful averages of the Earth's naturally heterogeneous surface properties. Observations of both the land surface and atmosphere must be coordinated in time and space, to obtain a detailed understanding of the energy and water cycle at scales beyond that of the field plot. Large-scale field experiments combine observations of electromagnetic radiation from satellite and aircraft, measurements of wind, temperature, and humidity from sounding balloons, and fluxes of temperature, soil moisture, and energy at the surface.

The essence of physical science is experimentation. To describe a physical phenomenon, it must be considered at a given scale, the available (depending on the data) or the chosen (depending on the objectives of the study). Thus it is now generally accepted that further progress in the development of the needed parameterizations of land-surface processes in climate dynamics and in hydrology must be based on a new chosen scale, with comprehensive experiments and field data at larger scales than customary in the past. This recognition has led to cooperation at various national and international levels, resulting in several large-scale field experiments, either in progress or in the planning stages, to study atmospheric and land-surface processes and their interactions.

Only recently has it become possible to consider experiments at scales that were unthinkable only a decade ago. Opportunities have opened as a result of developments in low-cost electronic instrumentation, computer technology for handling large data sets, and remote sensing from satellites and aircraft for observations with appropriate spatial scales.

First ISLSCP Field Experiment (FIFE)

The International Satellite Surface Climatology Program (ISLSCP) was organized in response to the need to monitor variables that govern climate and its fluctuations at different regional and global scales. Satellites are eminently suited for this purpose. A first objective of ISLSCP is to develop and use relationships between current satellite measurements and hydrologic and other climatic and biophysical variables at the Earth's land surface. A second objective is to validate these measurements and relationships with ground data and also to validate surface parameterization methods for simulation models that describe surface processes from the scale of leaves of vegetation (1 to 10 cm) up to scales appropriate to satellite remote sensing (100 to 1000 m).

The First ISLSCP Field Experiment marked the initial phase of an experimental effort envisioned to accomplish these goals [Sellers et al., 1988]. FIFE took place during the summers and autumns of 1987 through 1989 near Manhattan, Kansas, over an area of about 15 x 15 km$^2$, which included the Konza Prairie Long-Term Ecological Reserve. The experimental area consists of rolling hills with about 50 m of relief between ridges and stream valleys, typically separated by distances of about 1 km. The FIFE study area roughly represents a much larger area, because it is surrounded by similar grasslands that are mainly used for grazing. This area of tall-grass prairie covers a strip 50 to 80 km wide that runs from Kansas to Nebraska to Oklahoma.

FIFE consisted of intensive field campaigns lasting 2 to 3 weeks each during the growing season of each year, and more than 100 scientists participated. The objectives imposed the need for simultaneous data acquisition and multiscale observation and modeling. As illustrated in Figure 4, this was done by acquisition of satellite data, together with simultaneous observations from aircraft and at numerous ground stations, and atmospheric soundings of different types. Scientific papers and presentations from these experiments are just beginning to emerge [Hall and Sellers, 1990; Sugita and Brutsaert, 1991]. A special issue of Journal of Geophysical Research is scheduled for publication in November 1992.

Boreal Ecosystem-Atmosphere Study (BOREAS)

The tall-grass prairie for the FIFE field site is one of Earth's simpler vegetated environments. As a next step in investigations of the interaction between land surface and the climate, a new study lasting from 1991 to 1996 will focus on the boreal forest biome. BOREAS (Boreal Ecosystem-Atmosphere Study) centers on a cooperative field experiment...
Satellite 10m-8km
Airborne Flux 15km

Airborne Radiometry 10m-15km
Flux Site 10m-1km
Canopy, Leaf Physiology 1cm-10m

Figure 4. Range of scales addressed in First ISLSCP Field Experiment. During the Intensive Field Campaigns, the various data sets associated with each scale were collected simultaneously whenever possible and with high time resolution over several diurnal cycles. These data are used to validate methodologies for integrating models at different scales over area to calculate fluxes at the scale of satellite data and global circulation models [Sellers et al., 1990].

integrating land-surface climatology, tropospheric chemistry, and terrestrial ecology [BOREAS Science Steering Committee, 1991]. The major field efforts will take place on two 20 x 20 km² sites located near the northern and southern limits of the boreal forest of North America.

BOREAS will explore the role of climate and atmospheric chemistry in controlling the extent and character of the biome. Observations from surface measurements, aircraft, and satellite aim to improve understanding of the processes that govern exchanges of energy, water, heat, carbon, and trace gases between the boreal forest ecosystem and the atmosphere. It will focus on those processes and states that may be sensitive to global change, particularly on the biome’s role in carbon cycling. Tans et al. [1990] present evidence that a large terrestrial sink of fossil fuel carbon exists in the temperature boreal zone, but the exact mechanisms and the location of the sink are unknown. Remote sensing will play a strong integrating role, and the study will develop techniques to extend understanding of exchange processes from the local to the regional scale.

Global Energy and Water Cycle Experiment (GEWEX)

GEWEX is designed to verify large-scale hydrologic models and validate global-scale satellite observations [Chahine, 1992]. The buildup phase will start in 1992, and a global observations phase will start in 1998 to coincide with the first deployments from space of platforms of the international Earth Observing System. This initiative of the World Climate Research Program addresses four scientific objectives: (1) to determine water and energy fluxes by global measurements of observable atmospheric and surface properties; (2) to model the hydrologic cycle and its effect on the atmosphere and ocean; (3) to develop the ability to predict variations of global and regional hydrologic processes and water resources and their response to environmental change; and (4) to foster the development of observing techniques and data management and assimilation systems suitable for operational applications to long-range weather forecasting and hydrologic and climatic predictions.

A central goal of the GEWEX program is to develop and improve modeling of hydrologic processes and to integrate
surface and groundwater processes on the catchment scale into fully interactive global land-atmosphere models. Inadequate representation of hydrology is a major weakness in present climate models. For example, a radical improvement is needed in the treatment of evapotranspiration, which dominates water and heat fluxes from the land surface.

The GEWEX program plans to support hydrologic modeling of continental-scale river catchments encompassing a diversity of terrain and climate conditions. The GEWEX field experiment program will systematically test these models on selected river basins for a minimum of 5 years, to provide the opportunity to compare detailed performances of alternative models under realistic conditions, to ascertain their sensitivity to different estimates of forcing fluxes and determine their agreement with observations. The experimental areas are large enough such that the hydrologic processes that contribute to global climate models and large-scale meteorological processes are apparent. The areas encompass a wide range of soil moisture conditions, vegetation types, and surface topographies. The first focused experiment planned is the GEWEX Continental-Scale International Project (GCIP), located in the Mississippi River basin.

Storm-Scale Operational and Research Meteorology (Project STORM)

FIFE and BOREAS as international efforts pose problems of logistics and coordination. One of their major accomplishments is that they serve as a means of attaining and sharpening the experimental technology and know-how for use in planning later experiments.

An essential component for future experiments that address the interaction between the surface hydrology and the atmosphere would increase the area examined to the regional scale. Possibilities under discussion for the 1990s include a combined experiment with Project STORM (storm-scale operational and research meteorology). The STORM project will be primarily a meteorological effort dealing with mesoscale storm-generating mechanisms, but it will have profound ramifications for hydrology as well. These future ISLSCP experiments are envisioned to involve scales of 200 to 300 km, the grid size of general circulation models, and would be best conducted along a gradient of different vegetation species. Because it will be impossible to measure all relevant variables over such large areas, several experiments of the spatial scale of FIFE will be nested within the larger area.

Water, Energy, and Biogeochemical Budgets (WEBB)

Part of the U.S. Geological Survey’s Global Change Hydrology Program, WEBB, will be a long-term program whose focus is the intensive field investigation of water, energy, and biogeochemical processes and interactions. Its objectives are to: (1) improve the understanding of the processes controlling water, energy, and biogeochemical fluxes of terrestrial and freshwater systems, the interactions of these processes, and their relation to climate; (2) improve the capability to predict water, energy, and biogeochemical fluxes of terrestrial and freshwater systems for a range of spatial and temporal scales.

A major component of WEBB will be an intensive data collection and analysis program to support the scientific objectives. Field studies will be conducted in basins located in a variety of climatic and physiographic regions; so far five sites have been selected. These basins will provide data for research on all aspects of balances of water, energy, major nutrients in water bodies, and greenhouse gases such as carbon dioxide and methane.

Water balance components of the program will consider such components of the hydrologic cycle as precipitation, runoff, evapotranspiration, soil moisture, and groundwater recharge. Energy balance aspects will address evapotranspiration, snowmelt, sublimation, glacier runoff and mass balance, river ice, and the response of permafrost to climate. Biogeochemical studies will consider the sources, sinks, residence times, and fluxes of major nutrients and of greenhouse gases.

REMOTE SENSING

Over the next decade and into the next century, advances in remote sensing (the inference of properties of the subsurface, surface, and the atmosphere made from measurements of reflection or emission of electromagnetic radiation, made from satellites, aircraft, or the surface) offer the possibility of obtaining frequent hydrologic measurements over wide spatial scales [Engman and Gurney, 1991]. To achieve the potential benefits of remote sensing, the data are converted from the raw electromagnetic measurements at the satellite, aircraft, or surface to hydrologic information that is made available to a wide spectrum of hydrologic scientists.

The hydrologic sciences, much like the rest of modern Earth science, are starting to examine interactions among the different terrestrial components at all temporal and spatial scales. Such an inclusive perspective requires an integrated data collection program, and remote sensing is an essential component. Instruments currently available on satellite, aircraft, or on the surface, along with those planned for the future, will make available measurements throughout the electromagnetic spectrum over a range of spatial and temporal scales.

The temporal variations of many hydrologic processes require global coverage every few days, so satellite instruments with broad swath widths and modest spatial and spectral resolutions are necessary. In addition, some hydrologic problems require analysis and interpretation of specific areas and detailed sampling within scenes produced by instruments with lower spatial or spectral resolutions. For these applications, data from satellite or aircraft instruments with higher spatial and, usually, spectral resolution are needed. Some processes that are important at the global scale are manifested in surface features with dimensions of tens of meters. Examples include anthropogenic damage to vegetation, which first appears in patches; forest clearing, which dramatically affects evaporation and carbon cycling, and in the tropics...
occurs in small, noncontiguous areas; land use change and desertification, where boundaries may move only short distances; alpine snow and ice, where spatial coverage may be small but where large volumes of water are stored; changes in permafrost and buried ice lenses caused by atmospheric warming; and changes in the extent of freshwater and saltwater marshes caused by changes in the water table height or sea level.

Remote Sensing of Hydrologic Parameters

Some important hydrologic variables can be measured by remote sensing. In the visible and near-infrared wavelengths, the source of energy is the Sun, and we can measure the radiation that is reflected by the surface or scattered by the atmosphere. In the infrared wavelengths, we measure radiation that is emitted by the Earth and its atmosphere. In the microwave part of the spectrum we measure either emitted radiation (passive microwave) or the backscattered response to a signal sent from the satellite or aircraft (active microwave). The visible, near-infrared, and thermal-infrared wavelengths can be used to measure many parameters of hydrologic interest [Kustas et al., 1989]: presence or absence of vegetation; structure of vegetation, including biomass and leaf density; stress in vegetation, including moisture content of leaves; soil type; snow cover and its rate of depletion.

For hydrology, the microwave region offers particular advantages, because the signal is integrated over some depth below the land surface, whereas reflectance of solar radiation and emission of thermal infrared radiation are determined by the characteristics of a much thinner surface layer [Elachi, 1987]. Clouds do not obscure the microwave signal over much of the wavelength range, so remote sensing from aircraft or satellite is possible even when cloud cover is present. Moreover, in the microwave frequencies the water molecule is resonant, and the electromagnetic properties of wet substances are much different from those of dry ones. Emitted (passive) or reflected (active) microwave radiation is especially suitable for measurement of properties that depend on water content: rain rate from ground-based radar [Georgakakos and Krajewski, 1991]; estimation of soil moisture [Owe et al., 1992]; hydrogeological properties from ground-penetrating radar; mapping of snow cover and estimate of snow water equivalence [Foster et al., 1984].

Many categories of hydrologic variables could be measured by remote sensing, because hydrologic processes modify the electromagnetic signal in some part of the spectrum. However, different hydrologic conditions may cause similar signals, so continued work is required to achieve unambiguous measurements. We need progress in two categories of problems:

1. We need to understand better the relationship between properties of the surface and its electromagnetic signature.
2. The model between the electromagnetic signature and the physical properties may be complicated, and the inversion of such a model to estimate hydrologic properties from the signal is often difficult.

New Systems in the 1990s

Operational systems. New satellite systems will open opportunities for hydrologic research in the coming decade. Among ongoing sensors are the DMSP special sensor microwave imager with 12.5–25 km resolution, the first launched in June 1987 and later launches continuing into the 1990s. NOAA polar orbiting satellites of the 1990s will have additional channels for the advanced very high resolution radiometer in the near-infrared and an advanced microwave sounder. Landsat and SPOT will continue to provide data with fine spatial resolution, needed for most studies of processes in vegetated areas.

Synthetic aperture radars. European and Japanese space agencies launched satellites with single-frequency, single-polarization synthetic aperture radars (SARs) in 1991 and 1992. Depending on the frequency and polarization, SARs can map sea ice [Leberl et al., 1983], estimate woody biomass and soil moisture, and map snow cover [Rott and Mätzler, 1987]. The SAR on the European ERS-1 (Earth Remote Sensing) satellite operates at 6 GHz and is especially suited for mapping sea ice and mapping snow cover. The SAR on JERS 1 (Japanese Earth Resources Satellite) operates at 1.4 GHz and penetrates more deeply into vegetation and soils, enabling the estimation of plant and soil moisture. The Canadian Radarsat, scheduled for launch in 1996, will operate at 6 GHz but will have a wide swath more suitable for global coverage.

Tropical Rainfall Measurement Mission (TRMM). The Tropical Rainfall Measurement Mission, scheduled for launch in 1997, is a rain radar that will improve the knowledge of rainfall over this important area of the Earth where data are scarce. It will also carry instruments to measure the Earth’s radiation balance. TRMM is expected to provide needed information about rainfall rates and associated tropospheric heating in the zone between 35°N and 35°S latitude.

Next-generation weather radar (NEXRAD). Most meteorologists and hydrologists who work with rainfall data have had little choice but to accept the deficiencies of data sets acquired for operational purposes. Recording rain gauges are often widely spaced and not placed optimally within watersheds. Use of operational radar network data for rainfall estimation has been severely limited. Although the technology dates from the 1950s, the radars are difficult to calibrate, the beam width is too large for quantitative use except at short range, and the data are archived at too coarse a resolution for most research uses. Dramatic changes are about to take place with the coming of the next-generation weather radar (NEXRAD) system [Hudlow, 1988].

Beginning in 1991, quantitative precipitation estimates from ground-based radar in digital form will be available both in real time and retrospectively for research. By the mid-1990s well over 100 NEXRAD stations will be in place, covering most of the U.S. NEXRAD data will greatly surpass current operational radar data in quality, areal coverage, and both spatial and temporal resolution.

Earth Observing System (EOS)

In the longer term, the Earth Observing System (EOS), whose first in a series of satellites is scheduled for launch in 1998, carries a full complement of instruments and has
ambitious plans for research across the Earth sciences, [Doez,
zier, 1990; Moore et al., 1991]. The EOS instruments will allow investigations of the hydrologic cycle through coordinated measurements of different instruments. Planned for a duration of 15 years, EOS will provide geophysical products from upgraded sensors, addressing among other issues the hydrologic cycle and its interaction with the physical climate and biochemical cycles. EOS supports these scientific investigations with three distinct goals: (1) establishment of long-term, reliable measurements from remote sensing of important geophysical and biological variables, so that global, regional, and local change can be documented; (2) use of remote sensing data, from the EOS platforms and from aircraft and other satellites, to identify and investigate the most important processes in Earth System Science; and (3) improvement of our predictive models, so that plausible changes over the next century can be better understood.

Along with TRMM, EOS will provide the first long-term, consistent global measurements of many key variables: precipitation, atmospheric water vapor, clouds, snow accumulation, sea ice, polar and alpine glaciers, soil moisture, vegetation, temperature, and winds. These will enable the investigation of processes that define interactions and feedbacks within the hydrologic cycle.

The instruments that are candidates for the EOS platforms are described in detail in the EOS Reference Handbook [NASA, 1991]. The possible complement includes many sensors important to the hydrologic sciences. Examples are: (1) infrared and microwave sounders for measuring profiles of atmospheric temperature, water vapor, and trace species; (2) microwave radiometers for atmospheric water vapor, precipitation, and snow and ice extent in all weather conditions; and (3) imaging spectroradiometers, one at high spatial resolution for detailed investigations, others at coarser resolution for global mapping, for measurements of nutrients in oceans and coastal and inland waters, optical properties of snow and ice, and tropospheric water vapor.

The EOS Data and Information System (EOSDIS) will provide timely data to investigators at the marginal cost of reproduction. Investigators with expertise in remote sensing will analyze the data to provide hydrological products, and these products will also be available in EOSDIS for use by other investigators. In this way, EOS will open remote sensing data to a broader range of scientists, because they will no longer need detailed knowledge of instrument characteristics and electromagnetic interactions at the surface.

Remote Sensing Below the Surface

Research frontiers in remote sensing of subsurface conditions promise important breakthroughs in our methods for mapping hydrogeological properties without the need of a dense network of boreholes. Of particular note are techniques based on ground-penetrating radar and tomographic reconstruction. Ground-penetrating radar can provide high-resolution maps of the subsurface stratigraphic profile to depths of tens of meters. Work is underway to determine how a radar profile can be interpreted to characterize the subsurface structure of hydraulic conductivity, the key physical property determining patterns and rates of fluid flux. Using ground-penetrating radar, it may also be possible to delineate plumes of contaminated groundwater. If so, immense benefits would result.

Borehole tomography is similar in concept to the familiar CAT-Scan equipment used in medical applications to obtain "pictures" of body organs without surgery. For applications in hydrogeology, multiple cross-hole signals are generated by moving a source along one borehole, while receivers are recording signal arrival at multiple depths in adjacent boreholes. Various source signals are being developed, including seismic, electromagnetic, and hydraulic. The cross-hole signals are processed to reconstruct a picture of hydrostratigraphic properties throughout the region between the source and receiver boreholes. Basic research is needed to better understand the relationship between the recorded signal and the hydrogeological properties of the subsurface. If the potential of these two methods is realized, they will herald a new era in detailed mapping of subsurface properties relevant to hydrologic processes.

At the local scale, remote sensing below the surface is useful for measurements of soil moisture profiles, which often vary greatly over scales of a few meters. Two common methods are portable dielectric probes and time domain reflectometry [Brisco et al., 1992]. Dielectric probes can resolve moisture in layers as thin as 1 cm, whereas time domain reflectometry can penetrate to deeper layers, integrating over resolutions about 5 cm thick.

ISOTOPE GEOCHEMISTRY

Natural Isotopes

Natural isotopes can be used as tracers to study residence times, mixing ratios, and flow velocities in the hydrologic cycle [Fritz and Fontes, 1989; Ingraham and Taylor, 1991]. Environmental isotopes are a key tool in studying the subsurface component of the hydrologic cycle. Their primary uses include identification and differentiation of water masses that have distinctive mixtures of different isotopes of hydrogen or oxygen in the water molecules, determination of the extent of mixing of two or more waters, estimation of residence time in hydrologic systems, and estimation of flow direction, travel time, and flow velocity.

The environmental isotopes in most common use today include the stable isotopes, deuterium (2H), oxygen 18 (18O), and carbon 13 (13C) and the radioisotopes, tritium (3H), carbon 14 (14C), and radon (222Rn).

Because the stable isotopes oxygen 18 and deuterium are part of the water molecule and are not significantly affected by chemical interaction with the rock or soil, they provide nearly ideal conservative tracers of water masses. Owing to differences of mass between hydrogen and deuterium, and between oxygen 16 and oxygen 18, one isotope is enriched (fractionated) compared to the other as water changes phase from liquid to vapor to liquid to ice and back. Isotopic fractionation is a function of temperature, and well-documented mechanisms cause enrichment or depletion of one isotope compared to the other, allowing quantitative evaluation of processes occurring within the hydrologic cycle. For ex-
ample, winter precipitation is depleted in $^{18}$O and $^2$H compared to summer precipitation. Distinct differences occur in the stable isotopic composition of precipitation with latitude and altitude, so changes in trajectory of storm tracks cause changes in the isotopic composition of precipitation. Meteoric water that has experienced evaporative processes is enriched in $^2$H compared to $^{18}$O in comparison to normal seasonal variations observed in precipitation. On a smaller scale, rain that falls in the beginning of a storm is often enriched in $^{18}$O and $^2$H compared to that falling at the end of a storm. Isotope hydrologists can take advantage of these differences in applications such as determination of the extent of leakage between aquifers, identification of recharge areas, determination of recharge rates or water age by counting annual cycles in $^2$H and $^{18}$O moisture in the unsaturated zone, application of isotope mass balances to determine the extent of interaction between rivers and aquifers, and investigation of paleoclimatic conditions.

Anthropogenic Isotopes

During the period from 1957 to 1964 massive amounts of tritium and $^{14}$C were introduced into the upper atmosphere from testing of thermonuclear weapons. The tritium and $^{14}$C content of precipitation reached as much as a thousand times natural background levels in 1963 and 1964 and established a unique tracer in groundwater systems. Recharge rates have been determined by locating the depth to the 1963 tritium spike. The simple presence of detectable tritium is an indication that a sample contains post-1957 recharge water. Tritium decays with a half-life of 12.3 years, and dating of shallow groundwater is possible if the tritium input to the hydrologic system can be defined (Figure 5). Comparison with anthropogenic but nonvolatile isotopes enable estimates of evaporation.

Many other environmental isotopes and transient atmospheric tracers are being studied to investigate their possible applications as dating tools and tags of water masses in hydrologic systems. For dating techniques, research is directed toward the use of chlorine 36 [Scanlon, 1992], silicon 32, argon 79, krypton 85, krypton 81, helium 3 [Solomon et al., 1992], helium 4, and fluorocarbon compounds. Heavy isotope ratios such as strontium 87/strontium 86 and uranium 234/uranium 238 can be applied as tracers of water masses. Stable isotope ratios of sulfur and nitrogen often show source material and currently are applied to studies of anthropogenic inputs of sulfur and nitrogen into shallow groundwater and surface water, such as from acid-rain deposition, agricultural runoff, fossil fuel combustion and sewage sources. These and other chemical and isotopic tracers open fruitful avenues of research.

PALEOHYDROLOGY AND LONG-TERM RECORDS

Paleohydrologic information can extend the time series of hydrologic data beyond the period of record and thereby give us a better picture of hydrologic trends and the statistical distribution of phenomena [Jarrett, 1991]. To understand hydrologic processes, one must know how the processes vary through time, from the minutes of a cloudburst and hours of a flash flood through to the variations in precipitation over decades, centuries, millennia and even longer. Neither means nor variations are necessarily constant over time. Within decades and centuries there can be extreme events, abnormal periods, and even climatic shifts. Detection and quantification of extreme events and climatic shifts are crucial for hydrologic evaluation. Traditional monitoring is useful in many applications, but new methodologies or increased efforts in established procedures are necessary to produce information about long-term effects of climatic variation on hydrology. A current opportunity to improve hydrologic data is the development of new long-term records of climatic-hydrologic variation for process modeling and making predictive or probabilistic estimates that may be beyond the range of recorded events. Important knowledge can be gained through intensive study of historical documentation and generation of new data using proxy climatic-hydrologic information, or "paleohydrology."

Physical Records

Paleohydrology can produce long-term information on means, extremes, trends, and variations of various hydrologic phenomena and probabilities of extreme events. For example, three-ring analysis has led to reconstruction of records of
Figure 6. Tree ring reconstruction of flow in the Colorado River. The top graph shows the measured average annual virgin flow, since 1915, plotted as a 9-year moving average, in the Colorado River at Lee Ferry. The bottom graph shows the reconstructed flow based on tree ring analysis, since 1520. The tree ring data show that the period from 1915 to 1925 was the wettest in the 400-year history [Committee on Opportunities in the Hydrologic Sciences, Water Science and Technology Board, 1991].
be deposited coherently by some continuous sedimentary process for best results. Tree ring sampling opportunities are widely distributed over land masses except for deserts and polar regions, but in tropical areas the deciphering of the tree ring record presents great opportunities. The geomorphic/geological sources of information, such as fluvial varved sediments, and paleolimnological opportunities. In flood deposits, are sporadic in distribution, as are paleosols, potentially determine sources, ages, and histories of geochemical indicators, including isotopic analyses, can potentially determine sources, ages, and histories of groundwater.

**Historical Records**

Long-term records can be developed also by the study of ancient documents that have only recently been appreciated for their scientific value. Increases in travel and communication are increasing the awareness of documentation relevant to climatic or hydrologic variation. From shipping transit times and sea ice conditions to descriptions of famine and even tax yields, one can glean information about effects of climate. These types of analyses call for linguistic and historical disciplines to be involved in hydrology.

Humans now may be on the threshold of causing climatic change, with attendant disturbances to the hydrologic cycle. Some of these modeled and projected shifts have analogs in the past. Precise knowledge of the analogous conditions aids in planning for future eventualities [Gleick, 1989]. The measured records do not extend back to these conditions, but through examination of the different types of climatically sensitive organisms or cyclical phenomena that have left measurable responses to climate, we can identify major past events and develop time series that are proxies for measured climate variations. Global patterns of warmer or colder, wetter or drier regions can be ascertained through study of biological and sedimentological indicators. Global circulation models, which can be run forward in time to produce estimates of future variations, can also be set back in time to compare to proxy data. Such exercises validate the model mechanisms and concepts and also estimate potential changes in the global hydrologic cycle. The extent of the normally recorded information is too limited in time and space for such validation.

**Prospect**

As a contributing discipline, paleohydrology is still in its early stage. Reconstructions have been published for streamflow of specific rivers in the southwestern and eastern United States and in Argentina based on tree ring analysis. This technique has also produced multicentury drought histories for certain regions along with calculations of return times for severe drought, at scales of major drainage basins. However, there are many key hydrologic uncertainties and data gaps throughout the world where tree ring analysis and other proxy studies could be applied. Sometimes they provide information where there are no instrumental records even today, for example in coral reefs and ice cores [e.g., Thompson et al., 1984]. To execute the application requires interdisciplinary science. There must be expertise in the particular proxy area, for example, palynology, dendrochronology, sedimentology, and expertise in hydrology itself to develop sensible and significant results. Although successful in many areas of the world, now there are more opportunities than accomplishments in paleohydrology.

**CHALLENGES IN WATER QUALITY**

Public concern with pollution of water resources, as well as its effects on human health and the environment, is widespread and occasionally intense. In response to public concern, many studies are being conducted to monitor and assess the amount and distribution of pollutants entering the hydrologic cycle. If these studies are to be useful to understand the causes of observed conditions and thus provide a foundation for cost-effective amelioration of water quality problems, they must address scientific principles as well as practical ones.

**Water Quality Monitoring and Assessment**

Data for water quality monitoring and assessment may be divided into three types: data collected to characterize ambient concentrations in lakes, rivers, and groundwater; data collected to monitor effluents; and data collected to monitor water quality for a specific use.

The remaining discussion focuses on ambient water quality data. However, managers of data collection programs for all three types of data need to become more aware of ways that data from individual programs can be made more useful for answering questions that are beyond the immediate pro-
program objectives. These include: (1) the need to collect important ancillary data, to place the water quality data in the context of the natural and cultural setting; (2) the need to carefully document sample collection and laboratory analysis procedures; and (3) the need to archive the raw data in easy-to-access computer data bases.

Scientific Issues and Challenges

Past experience shows that water quality data collected for utilitarian purposes are either difficult or impossible to use for scientific purposes. It is seldom appreciated that science-oriented designs not only contribute to advancing science but also significantly improve the process of attaining many practical goals.

Water quality is threatened by thousands of potentially harmful substances. Developing effective evaluations of water quality for so many chemicals is an imposing challenge, requiring continued development of screening techniques and broad-spectrum analytical procedures. We also need better ways to link contaminant selection to the physical-chemical properties of different substances, to the behavior of different substances in surface and groundwater, sediments, plant and animal tissues, to chemical usage estimates, and to the relative health and ecological risks associated with different pollutants.

A related issue has been the failure of traditional monitoring programs to identify emerging water quality problems, possibly because of the lack of a significant link between these programs and scientific inquiry. For example, most water quality sampling in the United States has been targeted exclusively at substances for which regulations already exist, leading to a focus of effort on selected constituents ("priority pollutants") that occur infrequently while ignoring more important contaminants.

Future data collection programs need to provide explicit flexibility to adjust to changing environmental concerns and to incorporate exploratory aspects with the design. Frequent interpretation of data also is required to identify emerging issues; the data should not be simply collected and archived for future analysis. The integration of biological measurements with physical and chemical measurements also can significantly strengthen the utility of a data collection program to help identify emerging problems. For example, biological properties may be more sensitive to water quality than chemical or physical measurements. Too often chemical and biological measurements are considered competitive rather than complementary aspects of water quality characterization.

BIOLOGICAL METHODS IN WATER QUALITY ANALYSIS

Biological information can complement chemical analysis to improve measurement of water quality. Physical and chemical properties of water may vary rapidly, and intermittent or infrequent grab samples may give misleading indications of prevailing water quality. The native biota may be better indicators of water quality and human effects because of their prolonged exposure, integrated response, and differing sensitivity to all the varying conditions of their environment. Indeed, organisms provide the only direct measure from which ecologically significant impacts can be deduced. All levels of biological organization, molecular, cellular, tissue, organ, individual, population, and community, have been used or proposed for water quality interpretation. The methods may or may not identify a particular cause of change, but a measurable biological response may help to identify physical or chemical tests to be used in the search for cause.

The first biological methods used in a water quality context were based on presence or absence of species. Characteristic native species were used to demarcate zones of decreasing concentrations downstream from a point of heavy organic loading. Particular species were thought to show the pollution condition in each zone. However, the supposed indicator species also occurred in unpolluted environments, and the zonation varied with type and intensity of pollution and other hydrologic properties. Further work on human effects resulted in methods based on analysis of assemblages of species. The relative dominance of tolerant and intolerant species or of functional feeding groups in a biotic community is sensitive to water quality. These methods are successful when enough ecological knowledge exists about the species used, the case with most fish (but fish may be impractical to sample). They are less successful when ecological requirements of the species are poorly known, as is usually true for algae and benthic invertebrates. In the absence of detailed information about a particular species, effective ecological methods are available based on resemblance between biotic communities in hydrologically similar streams, with and without human impacts. Selection of suitable reference streams is crucial to the success of this approach.

The occurrence of one type of effect, sewage contamination, has traditionally been determined using microorganisms indigenous to the gut of man and warm-blooded animals as tracers. Bacterial density in laboratory cultures inoculated with water samples is interpreted to show the degree of fecal contamination and the potential occurrence of associated human pathogens. Escherichia coli is replacing fecal coliform and fecal streptococcus in these tests as a more specific indicator of human effect.

The sensitivity of organisms to target contaminants or the concentration of contaminants in living tissues can be used to detect spatial distribution or biological availability of contaminants. The method samples native species or introduced, caged species. It is limited by differences in sensitivity or uptake of contaminants among species, by lack of suitable widely distributed sentinel species in continental waters, and by effects of enclosure on caged organisms.

Laboratory bioassays using sensitive organisms are performed to determine biological effects of specific environmental events. Responses, usually from short-term tests, are measured as bioaccumulation or changes in behavior or physiology. Although test conditions are standardized, thus far the results cannot be extrapolated to other test conditions or species. In particular, bioassay results do not directly provide adequate information about an effect on the long-term structure and functioning of ecosystems.
Limitations of single-species bioassays have led to the use of laboratory or field-emplaced microcosms to determine effects or the fate of contaminants. Sizes of microcosms range from less than a liter to many cubic meters, and typically consist of plants and soils with carefully monitored inputs and outputs of moisture, energy, and chemical species from the system. Microcosms contain important components and exhibit important processes of natural ecosystems. They simplify environmental variability while exhibiting multispecies phenomena under controlled and replicable conditions. Results are empirical analogues of whole ecosystem functioning, but require great care in broad extrapolation to the field.

Methods based on levels of organization below the individual are applied in the field or laboratory to detect, quantify, or determine human effects. Techniques based on enzymes, antibodies, tissue cultures, and gene probes are being used or actively developed. The degree of sensitivity and specificity possible with these methods suggests their use in water quality analysis will increase.

Clearly, biological data can supplement physical and chemical data to provide more holistic understanding of functioning and natural evolutionary trends of hydrologic systems, as well as human effects on such systems. To accomplish this in detail, major advances are needed for determining hydrologic implications of ecological results. Improvements also are needed aimed at increasing sensitivity, simplicity, and uniformity of biological methods and decreasing costs and analytical time. To date, only for indicator bacteria have procedures been adequately standardized and the results made accessible in water quality data banks. Other biological data relevant to water quality are scattered and are based on diverse methods of sampling and analysis. Standardized methods would enhance the scientific value of biological information by providing a reliable baseline for making temporal and spatial comparisons. Improved communication of ecological results and their significance is also needed, in forms useful to other scientists and the public.

Biology can furnish uncommon insights for hydrology, insights not possible solely from a knowledge of physics and chemistry. For example, organisms are involved in the transport and cycling of elements in water and sediments. Organisms are targets of scientific efforts to preserve rare and endangered species. Populations of organisms are intentionally affected by management programs and unintentionally affected by natural and anthropogenic environmental effects. These and other issues often require studies on large spatial and temporal scales. Such studies should be incorporated into national and international water quality monitoring systems to provide the means to evaluate and improve incompletely developed, but potentially valuable biological methods for understanding the organization and functioning of hydrologic systems.

**DATA ACCESSIBILITY AND MANAGEMENT**

Advances in the hydrologic sciences depend on how well investigators can integrate reliable, large-scale, long-term data sets. Storms, floods, and droughts are natural events that can be measured just once, whereas laboratory experiments can be repeated. Instruments used in hydrology must be reliable and operated such that data captured are of known standards and precision.

On rivers, measured stage data (height of the water surface above reference datum) are transformed to discharge. The stage/discharge relationships, commonly called "rating curves," typically are extrapolated to extreme stage values and may require adjustment as new gagings at the extremes become available. This adjustment may apply retrospectively for rating curves that have been used for many years, so a data archive should store original stage measurements and rating curves separately, to allow this retrospective examination and adjustment.

The data sets required to answer many of the open research questions in hydrology will be complex. Inevitably, many scientists from a variety of disciplines and backgrounds will be involved in data collection and analysis, over a significant period of time. How can diverse investigators and investigations produce compatible data sets, assure their quality, and confidently assemble them for larger, indeed public use and access? Creating effective data systems for assembling and distributing scientific data sets is not trivial and depends heavily on the personal efforts of active scientists. If the data system is constructed within the scientific community by scientists working in concert with computer scientists rather than by independent experts working without scientific interaction, there are many scientific opportunities as well as technical and political challenges.

**Information Management**

Advances in the hydrologic sciences require data and information systems that will provide the infrastructure to enable scientific interaction between researchers of different disciplines and employing different methodologies; they must be information systems, not just data systems. They provide hydrological information, not just raw data from spaceborne instruments or in situ sensors. They allow researchers to collate and cross-correlate data sets. The output of large-scale hydrologic and climate models also generate huge "data" sets that need to be analyzed, compared, and validated. Serious problems in the data systems now available impede hydrologists’ access to needed data and thereby to their productivity. In particular, four shortcomings in current systems have been identified [Stonebraker and Dozier, 1991]:

1. Current storage management technology is inadequate to store and access the massive volumes of data generated by satellite systems or large-scale models. While it is possible to store a Terabyte ($10^{12}$ bytes) of data on magnetic disk at high cost, this approach will not scale when experiments and the data generated per experiment increase. Instead, multilevel hierarchies that use magnetic disk and tertiary media are needed; current file systems and data base management systems offer no support for this type of multilevel storage. Moreover, current tertiary memory devices, such as tape and optical disk, are too slow, and hardware and software must mask these long access delays through sophisticated caching.
2. Current input/output and networking technologies do not support the data rates needed for browsing and visualization. Examination of data from satellites or large-scale hydrologic models require that we visualize in various ways, such as rapid viewing of time sequences. Such visualization places severe demands on input/output systems to generate the required data fast enough, and severe networking problems arise when scientists are remote from the data server.

3. Current commercial relational data base systems are inadequate to store and manage the diverse types of data required. Hydrologic scientists need access to disparate kinds of data: (1) point data for specific geographic locations; (2) vector data, like topographic maps, whereby data are organized as polygons or directed graphs; (3) raster data, such as satellite and aircraft remote sensing data, organized as arrays or two to five dimensions; and (4) text data, including computer programs, descriptions of data sets, etc. that need to be organized for easy retrieval.

4. Current visualization software is too primitive to allow hydrologic scientists to render data returned for useful interactive analysis. Just as commercial relational data base systems are not good at managing diverse kinds of data, commercial visualization tools and subroutine packages have the same faults. Improved visualization is needed for two purposes in hydrologic science: (1) visualization of data sets (remote sending data, in situ data, maps, and model outputs must be interpreted and compared); and (2) visualization of the data base (input and output to the data base management system, queries and answers, would benefit from visualization).

For programs to usefully access the widespread data bases coming on line, and new paradigm for a "data base centric" view is needed. In the future, scientists will interact with a logical view of their data, rather than directly with files containing data (Figure 8).

**Data Distribution on Inexpensive Media**

Optical disks and compact disks have become attractive alternatives to traditional magnetic tape or disk storage media, because they offer the capacity and security necessary for hydrologic archives, and because multiple copies of large archives can be made cheaply. For example, the entire daily stream gaging record of all gaging stations for 1 year are stored on optical disks for such countries as the United States and New Zealand. Wallis et al., [1991] have assembled a long-term hydroclimatological data set, which includes precipitation, temperature, streamflow, and made it available on CD-ROM. The need to publish expensive yearbooks of data disappears.

**Responsiveness to Scientific Needs**

The evolving requirements characteristic of active research demand a data system with real-time adaptability. This can be achieved by a scientifically involved data system team that puts a priority on service. This is no small effort: it requires direction on a day-to-day basis by active scientists. In particular, for large projects such as FIFE or GEWEX the role of a "project information scientist" is recognized as critical and rewarded appropriately.

In addition to personnel issues, there are several political aspects. Three legal categories of data can be defined: data that are acquired from public sources with no distribution restrictions, data that are collected by publicly funded principal investigators, and data that are acquired with public funds from private sources, corporations, or individuals, with specific legal rights to restrict their distribution. The FIFE approach was to recognize a data collection and analysis phase in which data sets were exchanged, quality controlled, and revised, but general access was restricted [Strebel et al., 1990]. However, in larger, more costly programs, demand for access to the data by the scientific community and the tax payers deems a restricted-access period almost intolerable.

The EOS Data and Information System (EOSDIS) will therefore operate more openly [Dozier and Ramapriyan, 1991]. NASA policy specifies that all EOS data and derived products be available to all users, with no preference given to EOS investigators and no proprietary period. Research users in the United States and participating countries will pay only the marginal costs for data reproduction and distribution; they will have to agree to publish their results and to make available supporting information, including methods of analysis and code implementing the algorithms. Research users in other countries may have the same access to EOS data by proposing cooperative projects and associated contributions—similar access to their satellite, aircraft, and surface data. For all data products the documented scientific software that produced them will also be available.

To the extent possible, the same policy should be applied to all hydrologic data. For surface data, prices are usually cheap enough to enable science. However, currently, data from commercial satellite systems (Landsat and SPOT) are expensive enough to make their usage for examining time sequences of drainage basins impractical for all but well-funded, established investigators.
EDUCATION AND HYDROLOGIC DATA

The Committee on Opportunities in the Hydrologic Sciences, Water Science and Technology Board [1991] addressed educational issues and recommended interdisciplinary programs at the graduate and undergraduate levels. Included in their topics for university programs are several that relate to data collection, management, and analysis.

Chief among these are that students must measure natural phenomena, preferably in field situations as well as in controlled laboratory settings, and programs include experience in writing short research papers that require analysis of data as well as familiarity with the published literature. At the undergraduate level, field and laboratory experience are particularly important.

Universities must recognize that students in the diverse array of disciplines that analyze the Earth’s hydrologic processes will need to be trained in techniques of hydrologic data collection, management, and analysis (field research methods, remote sensing, software development, data base management, statistical inference) as well as in the conventional supporting subjects of physics, chemistry, mathematics, and computer science (beyond computer programming). Departments that offer courses and degrees in hydrologic sciences will need to incorporate such training into their curriculum.

CONCLUSION

Four recommendations, if followed, would enhance the collection, distribution, management, and analysis of data to support the hydrologic sciences [Eagleson, 1991].

Maintenance of Continuous Long-Term Data Sets

The hydrologic sciences use data that are collected for operational purposes as well as those collected specifically for science. Improvements in the use of operational data require that special attention be given to the maintenance of continuous long-term data sets of established quality and reliability. Experience has shown that exciting scientific and social issues often lead to an erosion in the data collection programs that provide a basis for much of our understanding of hydrologic systems and that document changes in regional and global environments.

Improved Information Management

The increasing emphasis on global-scale hydrology and the increasing importance of satellite and ground-based remote sensing lead to use of large volumes of data that are collected by many different agencies. Information management systems are needed that allow searching many data bases and integrating data collected at different scales and by different agencies.

Interpretation of Remote Sensing Data

Effective use of remote sensing data is now too difficult for many hydrologic scientists, because the interpretation often depends on a detailed knowledge of sensor character-istics and electromagnetic properties of the surface and atmosphere. Hydrologic data products should be made available in a form such that scientists who are not remote sensing experts can easily use the information derived.

Dissemination of Data From Coordinated Experiments

Special integrated studies, such as FIFE, BOREAS, GEWEX, and WEBB that involve intensive data collection and investigation of the fluxes of water, energy, sediment, and various chemical species produce high-quality data sets that have value lasting far beyond the duration of the experiment. Optimal use of these data requires broad and timely distribution beyond the community of scientists who are involved in the experiments.

ACKNOWLEDGMENTS. My review of issues about collection, distribution, and analysis of hydrologic data began as part of my service on the National Academy of Science’s Committee on Opportunities in the Hydrologic Sciences. Their book, Opportunities in the Hydrologic Sciences, is available from the National Academy Press, 2101 Constitution Avenue, N.W., Washington, D. C. 20418 as ISBN 0–309–04244–5. Robert E. Davis made comments on the manuscript, and I received correspondence and preprints from Robert Jarrett and George Leavesley.

Garrison Sposito was the editor in charge of this paper. He thanks Peter S. Eagleson, Keith Loague, Ronald G. Amundson, and an anonymous referee for their reviews of the technical content of the manuscript.

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