HYDROLOGIC SCIENCE: A DISTINCT GEOSCIENCE

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Abstract. Hydrologic science deals with the occurrence, distribution, circulation, and properties of water on Earth. It is clearly a multidisciplinary science, as through the hydrologic cycle water is important to and affected by physical, chemical, and biological processes within all the compartments of the Earth system: atmosphere, glaciers and ice sheets, solid earth, rivers, lakes, and oceans. Because of this geophysical ubiquity, and because water is necessary and limiting for life, concern for issues of hydrologic science has been distributed among the traditional geoscience and engineering disciplines. As a result, an infrastructure of hydrologic science (i.e., a clear identity, with supporting educational programs, research grant programs, and research institutions) has not developed, and a coherent understanding of water's role in the planetary-scale behavior of the Earth system is missing. The supporting arguments, along with recommended scientific priorities are summarized here as proposed by the National Research Council Committee on Opportunities in the Hydrologic Sciences (see Table 1 for committee composition).

INTRODUCTION AND PROBLEM STATEMENT

Water moves through the Earth system in an endless cycle that forms the framework of hydrologic science. In so moving, it plays a central role in many of the physical, chemical, and biological processes regulating the Earth system making hydrologic science a unifying geoscience (see Figure 1).

Water vapor is the working fluid of the atmospheric heat engine where through evaporation and condensation it drives important atmospheric and oceanic circulations and redistributes absorbed solar energy. As the primary greenhouse gas it is instrumental in setting planetary temperature. Through fluvial erosion and sedimentation, water works to shape the land surface. Water is the "universal" solvent and the medium in which most changes of matter take place; hence it is the agent of element cycling. Finally, water is necessary and limiting for life.

Investments in water resource management over the last century have helped provide the remarkable levels of public health and safety enjoyed by the urban populations of the developed world. While we have spent lavishly to cope with the scarcities and excesses of water and to ensure its potability, we have invested relatively little in the basic science underlying water's other roles in the planetary mechanisms. This science, hydrologic science, has a natural place as a geoscience (see the appendix for definitions) alongside the atmospheric, ocean, and (solid) earth sciences; yet in the modern science establishment this niche is vacant.

Because of the pervasive role of water in human affairs the development of hydrologic science has followed rather than led the applications, primarily water supply and hazard reduction, under the leadership of civil and agricultural engineers. The elaboration of the field, the education of its practitioners, and the creation of its research culture have therefore been driven by narrowly focused issues of engineering hydrology. The scale of understanding has been modest, generally surface drainage basins with areas of 10,000 km^2 or less. One perception of the intellectual relationships among these water-relevant disciplines is that presented in Figure 2.

Hydrology has not been cultivated as a geoscience because until now there has been no practical need to build a comprehensive understanding of the global water cycle. The patches of scientific knowledge that support traditional small-scale engineering applications do not merge into the coherent whole needed to understand the geophysical and biogeochemical functioning of water at the regional and continental scales of many emerging problems. These problems include the possible geographical redistribution of water resources due to climate change, the ecological consequences of large-scale water transfers, widespread mining of fossil groundwater, the effect of land use changes on the regional hydrologic cycle, the effect of nonpoint sources of pollution on the quality of surface water and groundwater at regional scale, and the possibility of changing regimes of regional floods and droughts.

Furthermore, the training of hydrologic scientists cannot occur efficiently in educational programs dominated either by applications-oriented constraints or by predominant undergraduate preparation in engineering. A thorough background in mathematics, physics, chemistry, biology, and the geosciences is necessary. New institutional arrangements will be needed to allow student and faculty involvement in relevant field observations and to provide prompt access to the resulting data.

Reviews of Geophysics, 29, 2 / *May 1991*
pages 237-248
Paper number 90RG02615

8755-1209/91/90RG-02615 *$05.00*

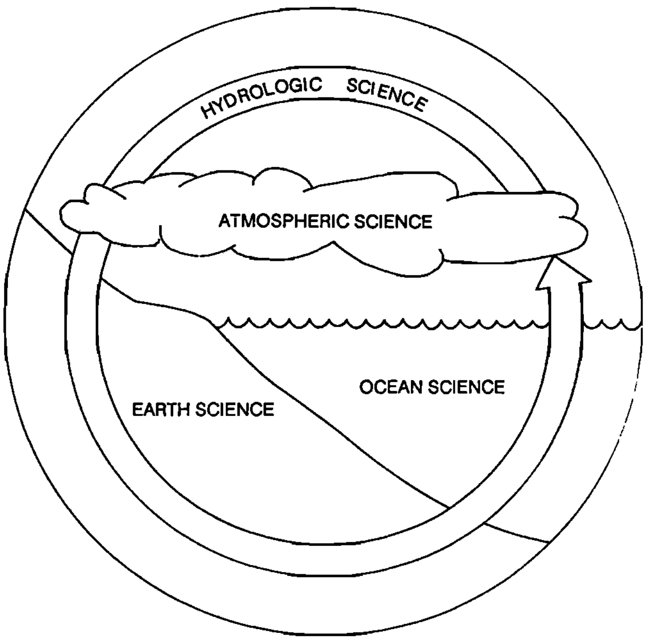

Figure 1. Hydrologic science: a unifying geoscience [from *NRC*, 1991].

MODERN HISTORICAL EVOLUTION OF HYDROLOGIC SCIENCE

The beginnings of modern hydrologic science may (arguably) be set in Renaissance Europe when the observations of physicists, naturalists and members of distinguished families such as Palissy, Perrault, and Halley collectively established the hydrologic cycle. With the coming of the Industrial Revolution and its accompanying urbanization, the amateurs lost interest in hydrology and its development shifted into the hands of engineers such as de Pitot, Chézy and Venturi who were concerned with water supply and water power. Thereafter, the science developed spottily in response to the needs of engineering practice.

In the United States, hydrologic research remained the province of enterprising inventors, prospectors and wealthy amateurs until late in the nineteenth century. At that time government became the prime mover in water research to support the practical needs of the proliferating water management projects on large rivers; new public agencies were formed such as the Weather Bureau and the Geological survey. The early history of the U.S. Geological Survey (USGS) embodies the development of hydrologic science in the United States, particularly in sediment transport, groundwater, and water chemistry [*Langbein*, 1981]. (In surface water, however, private consulting engineers remained in the forefront of research well into the twentieth century.) This period of federal and state agency dominance in the United States ended with the completion, in the 1950s, of the water projects delayed by World War II and with the concurrent rise of the environmental movement.

The first formal recognition of the scientific status of hydrology was perhaps the formation of a Section of Scientific Hydrology within the International Union of Geodesy and Geophysics (IUGG) at its Rome assembly in 1922. At that time the U.S. National Research Council's Committee for the IUGG was called the American Geophysical Union (AGU) and it was asked to add a section of scientific hydrology to its growing set of geophysical specialties. The fate of this proposal illustrates the status of hydrologic science within the U.S. scientific community during the first half of the twentieth century. The leadership of AGU maintained for eight years that the level of active scientific interest (as opposed to consulting engineering interest) in the United States did not justify a separate section of scientific hydrology (Charles A. Whitten, personal communication, 1989).

In 1930 as AGU was transforming to an independent society, a Section of Hydrology was finally formed with O.

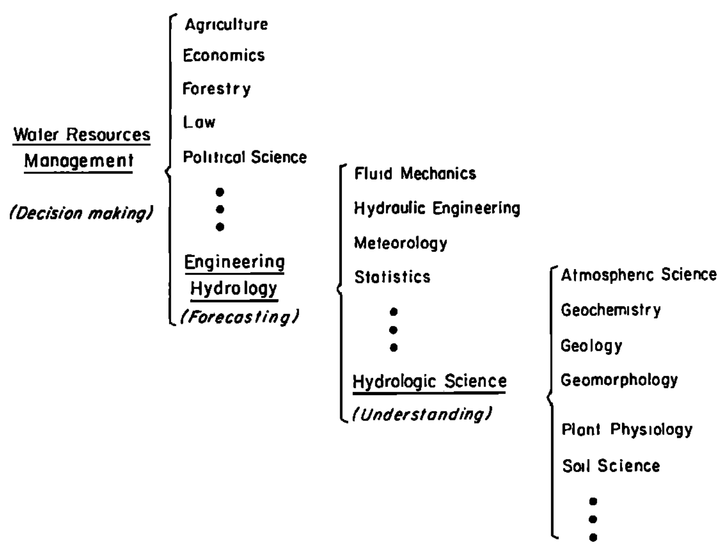

Figure 2. Water: the intellectual ingredients for its understanding, forecasting, and management [from *NRC*, 1991].

E. Meinzer as chairman and R. E. Horton as vice-chairman. *Horton* [1931] presented a comprehensive analysis of "the field, scope and status of the science of hydrology" in which (1) the central focus was on the conservation of water mass at river basin scale, (2) concern was principally with the physics of the hydrologic cycle omitting any mention of chemistry, and (3) the effects of man were excluded by implication. These restrictions reflect the continued dominance of the field in the United States at that time by the engineering concerns of nation building.

In the meantime, beginning in 1926, the National Research Council (NRC) had undertaken the preparation of a series of volumes on the physics of Earth intended "to give the reader, presumably a scientist but not a specialist in the subject, an idea of its present status, together with a forward-looking summary of its outstanding problems." In 1936, upon the recommendation of the AGU, the NRC appointed a subcommittee on hydrology with O. E. Meinzer (geologist in charge, Division of Ground Water, USGS) as chairman to prepare a volume on hydrology as a conclusion to this series. *Meinzer* [1942] opened that volume with a definition that somewhat tentatively proclaimed hydrology to be an earth science but one with traditional methods and problems that set it apart. His definition went beyond Horton's, however, to incorporate water-related chemical and biological activity.

By the mid-twentieth century, research on the scientific aspects of hydrology was well under way in university and government laboratories, focused on understanding laboratory-scale physical processes of the hydrologic cycle. Within the United States, concern was beginning to rise about the quality of our waters and about preservation of our natural environment. These enlarged interests found expression in an expanded definition of hydrology as a science put forward in 1962 by a committee chaired by Walter B. Langbein [*Ad Hoc Panel on Hydrology*, 1962]. This definition included the chemical constituents of water and the relation of water to living things. The Langbein Committee observed further that hydrology is an interdisciplinary science, involving an integration of other earth sciences to the extent that these help to explain the life history of water and its chemical, physical, and biological constituents. Missing here, however, is a sense of the interactive role of water in the Earth system.

The United Nations-sponsored International Hydrological Decade from 1965 to 1974 raised consciousness about regional and global problems and about man's impact upon the hydrologic cycle. It became clear that man's changes to the land surface were now affecting influential atmospheric processes and that the science base for understanding and assessing these interactions was missing. It was the dramatic color photographs of Earth in space, however, that crystallized active interest in the interconnectedness of nature and in the changes being wrought by man.

Contemporary views of hydrology accept that human activity has become an integral and inseparable part of the hydrologic cycle (see Figure 3) and that the quality of water is no less a concern than the quantity. Furthermore, these views stress the dynamic interaction of water with the other components of the Earth system (see Figure 4).

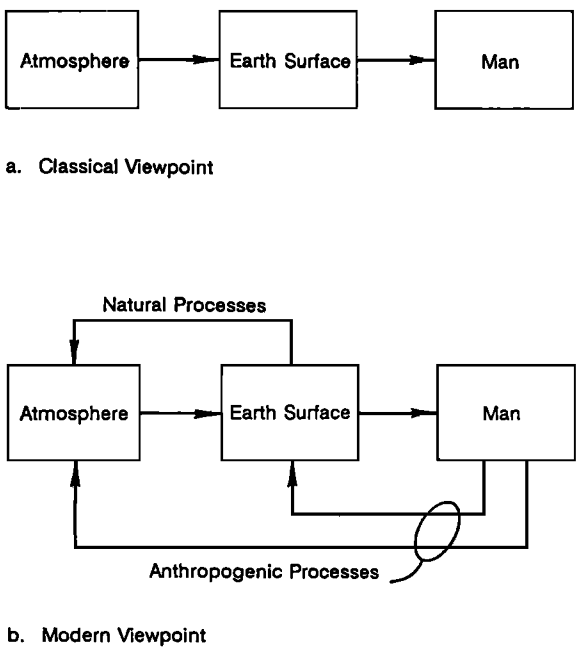

Figure 3. The role of humans in the hydrologic cycle [from *NRC*, 1982].

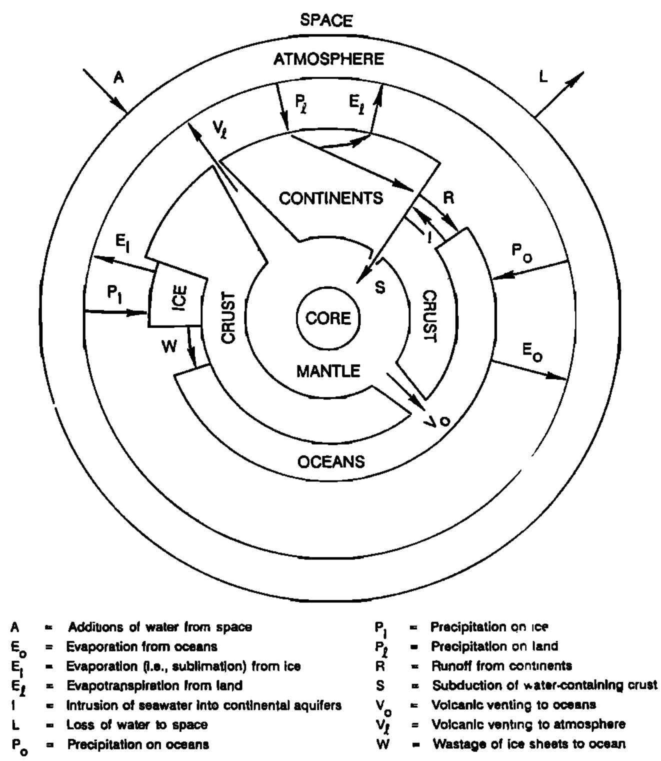

Figure 4. The hydrologic cycle as a global geophysical process [from *NRC*, 1991].

In response to these evolving perceptions and to the accompanying increase in the scale of hydrologic concern, the NRC established a panel in 1987 to conduct an assessment of the hydrologic sciences (Table 1). This paper is drawn from the report of that committee [*NRC*, 1991].

TABLE 1. Composition of the NRC Committee on Opportunities in the Hydrologic Sciences

Name	*Affiliation*
Peter S. Eagleson (chairman)	Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge
Wilfried H. Brutsaert	School of Civil and Environmental Engineering, Cornell University, Ithaca, N. Y.
Samuel C. Colbeck	U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H.
Kenneth W. Cummins	Pymatuning Laboratory of Ecology, Univesity of Pittsburg, Pa.
Jeff Dozier	Center for Remote Sensing and Enviornmental Optics, University of California, Santa Barbara
Thomas Dunne	Department of Geological Science, University of Washington, Seattle
John M. Edmond	Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge
Vijay K. Gupta	Department of Geological Sciences, University of Colorado, Boulder
Gordon C. Jacoby	Lamont-Doherty Geological Observatory, Palisades, N. Y.
Syukuro Manabe	National Oceanic and Atmospheric Administration, Princeton, N. J.
Sharon E. Nicholson	Department of Meteorology, Florida State University, Tallahassee
Donald R. Nielsen	Department of Agronomy and Range Science, University of California, Davis
Ignacio Rodriguez-Iturbe	Institute of Hydraulic Research, University of Iowa, Iowa City
Jacob Rubin	U.S. Geological Survey, Menlo Park, Calif.
J. Leslie Smith	Department of Geological Sciences, University of British Columbia, Vancouver
Garrison Sposito	Department of Soil Science, University of California, Berkeley
Wayne T. Swank	U.S. Department of Agriculture, Coweeta Hydrologic Laboratory, Otto, N.C.
Edward J. Zipser	Department of Meteorology, Texas A & M University, College Station

STATUS OF UNDERSTANDING

Reservoirs and Fluxes of Water

The global hydrologic cycle is illustrated as a global geophysical process in Figure 4. In this diagram the boxes represent storage reservoirs for Earth's waters and the arrows designate the transfer fluxes between them. This accompanying verbal description follows closely that given by the *U.S. Geological Survey* [1968].

Space and Mantle—Little is known about the amount of water in the two limiting reservoirs, space and Earth's mantle, but there is evidence that they both exchange water with the primary crustal, ice, atmospheric and oceanic reservoirs. The hydrogen in water is being lost to space very slowly through diffusion of water vapor and methane molecules into the upper atmosphere and the subsequent escape of hydrogen atoms freed from these molecules by photochemistry. This effective water loss is indicated by the symbol L in Figure 4 and the rate is probably of the order of 10^{-4} km^3 per year. Addition of water (A) from space is controversial; perhaps icy comets are a source. Without doubt however, volcanic activity continuously vents water vapor to the atmosphere (V_l) and liquid water to the oceans (V_o). Again, the rate is uncertain, perhaps less than 1 km^3 annually. Water also recirculates on a geological time scale by the subduction (S) of water-containing crustal material in a "tectonic hydrologic cycle" as illustrated in Figure 5.

Oceans and Atmosphere—More than 97% of all water in the land-ocean-atmosphere system is saline and resides in the oceans. This enormous reservoir is involved in processes of exchange with water on and under the land and in the atmosphere on many different space-time scales. The atmosphere, although it supports a global average precipitation (P) of the order of 1 m per year, contains only 0.001% of Earth's water at any moment. This is enough to cover the globe to a depth of about 2.7 cm. The atmospheric water storage is thus replenished once every 9 to 10 days on the average through evaporation (E). Evaporation, vapor transport in the atmosphere, condensation, and precipitation are the fundamental mechanisms for distillation and redistribution of Earth's fresh water in a climatic hydrologic cycle. This cycle, usually referred to simply as "the hydrologic cycle" plays a major role in the redistribution of incoming solar energy as well. It is illustrated quantitatively at global scale in Figure 6. About one-half of all solar energy reaching Earth's surface is used in evaporation, of which 90% comes from the ocean (E_o) and 10% from the land (E_l). The latent heat required for the phase change is carried with the resulting vapor by the wind until it is released when and where the vapor condenses. Water vapor is the most important of the greenhouse gases, acting to regulate Earth's surface temperature by absorbing and returning to Earth much of the thermal radiation emitted here.

Oceanic precipitation (P_o) and evaporation (E_o) have not been observed systematically because of obvious experimental difficulties. Their global average difference is usually estimated as the closure for a global water balance. Regional differences are important because they enhance or suppress thermohaline circulation. The space-time distribution of storm precipitation is poorly understood in

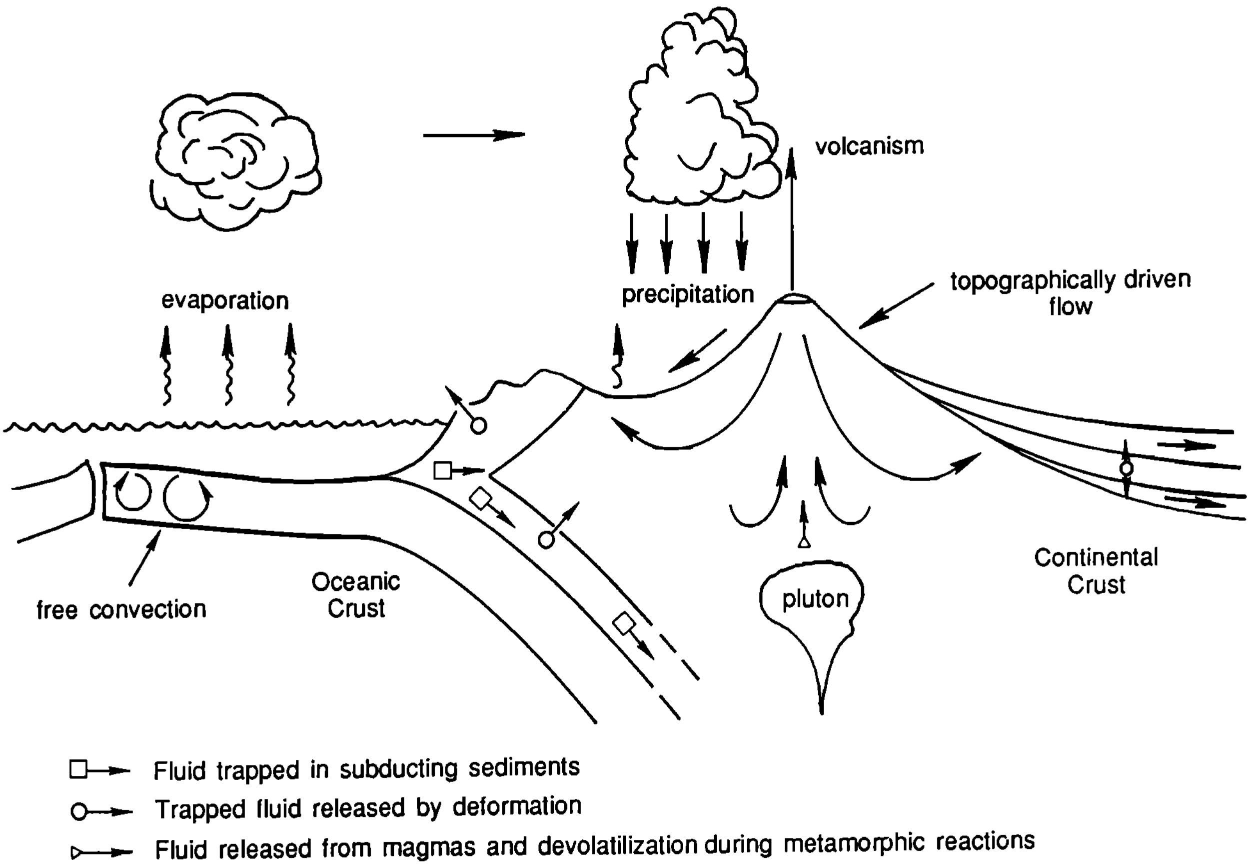

Figure 5. The tectonic hydrologic cycle [from *Forster and Smith*, 1990].

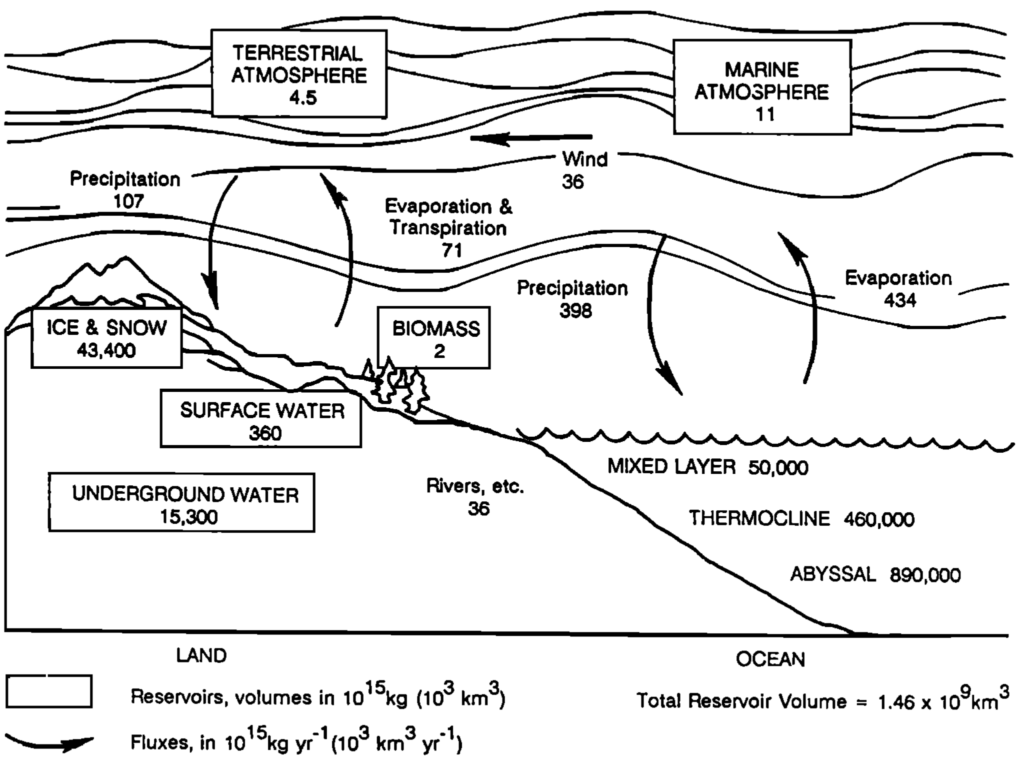

Figure 6. The climatic hydrologic cycle at global scale [from *NRC*, 1986].

relation to the mechanics of storm genesis even for storms over land where observation is much simpler.

The strength and horizontal scale of this evapoartion-precipitation cycle and associated energy redistribution are known to be highly variable with both season and geography but have not been well studied. In tropical regions where thermal convection is a dominant atmospheric mechanism as much as 50% of local precipitation may be derived from local evaporation. In the temperate latitudes with cyclonic atmospheric motions it may be only 10%. It is important to learn how patterns of surface wetness, temperature, reflectivity and vegetation influence the formation of clouds and precipitation on a wide range of space and time scales.

The Hydrologic Cycle—As a global average, only about 57% of the precipitation which falls on the land (P_l) returns directly to the atmosphere (E_l) without reaching the ocean. The remainder is runoff (R) which finds its way to the sea primarily by rivers but also through subsurface (groundwater) movement, and by the calving of icebergs from glaciers and ice shelves. In this gravitationally powered runoff process, the water may spend time in one or more natural storage reservoirs such as snowpack, glaciers, ice sheets, lakes, streams, soils and sediments, vegetation, and rock. Evaporation from these reservoirs short circuits the global hydrologic cycle into subcycles with a broad spectrum of scale. Runoff is perhaps the best known element of the global hydrologic cycle but even this is subject to significant uncertainty. For example, the direct groundwater flow to the sea is missing from streamflow observations and may be as much as 10% of total continental runoff.

Crust—The water in the uppermost meter or two of Earth's crust is known as soil moisture and is a key determinant of the state of the Earth system. With typical residence times of days to months, it provides the driving potential for moisture fluxes in the soil: upward as evaporation and as absorption by the roots of plants and downward in recharging groundwater. It serves the same storage and driving functions for dissolved chemical species. Both the carrier and the solutes interact with the soil medium. It is important to learn the rates and pathways of moisture through the soil in order to predict soil chemical reactions, solute responses and water quality changes. Soil moisture also plays an important role in soil formation, directly through chemical weathering of rock and indirectly through life support of soil biota. Soil moisture also is an active agent as well in the depletion of soil minerals through leaching, and it influences the resistance of soils to erosion. Finally, it also has an obvious and direct effect on the growth of vegetation, an aspect of the hydrologic cycle that has been intensively studied at the microscale because of its importance to agriculture. However, the heterogeneity of the subsurface medium presents many unsolved problems in understanding large-scale soil moisture behavior. For example, is it possible to infer the spatial structure of soil hydrologic properties from the large-scale geological processes responsible for rock and hence soil composition?

The porous earth and rock materials deep beneath the land surface and oceans constitute a great water reservoir. It has been estimated that some permeability must exist within the crust to depths of 13–20 km. Water filling these pores is called groundwater, the permeable strata are called aquifers, and the upper limit of the saturated zone approximates what is called the water table. Most movement of groundwater is the result of topographic relief and the rates of flow are slow, perhaps a few centimeters per day. Depending on how far the groundwater must travel to reach a surface discharge area, water in the shallow zone may remain underground from a few hours to more than 100 years. Among the important unsolved groundwater problems is the fate of toxic elements and compounds in these waters. We need to understand the advection and dispersion of solutes and their reaction with the porous medium as well as the transport of microparticles and their filtration by the medium. Water at great depth may take tens or even hundreds of thousands of years to pass through the subsurface and is often highly mineralized. Evidence exists for circulation of groundwater at depths of from 10 to 15 km, probably as a result of tectonically induced pressure gradients. We do not yet know how to measure and characterize the transport properties of these fractured rock masses.

The volume of groundwater in the upper kilometer of the continental crust is an order of magnitude larger than the combined volume of water in all rivers and lakes and is equivalent to the total of all groundwater recharge for about the last 150 years. The total volume of groundwater is almost one fourth of all nonoceanic water on Earth.

Groundwater discharges at topographically lower elevations of Earth's surface enable streams to flow even during prolonged rainless periods and after winter snows have melted. Coastal groundwater reservoirs may be recharged locally by saltwater intrusion (I) from the ocean.

A major problem that appears throughout geophysics is the representation of spatially aggregated nonlinear behavior in the presence of large spatial variability. In other words, given the dynamics at microscale, how do we represent the behavior at macroscale? This scale transfer problem arises in the hydrologic sciences when describing the coupled fluxes of heat and moisture across large land surface elements. It occurs when coupling the microscopic molecular processes of chemical reaction to the macroscopic averages of groundwater transport equations and in establishing appropriate dispersivities for use in describing the behavior of groundwater plumes at field scale.

Ice—The largest masses of freshwater exist as ice in the Antarctic and Greenland ice sheets. This ice, with an average residence time of about 10,000 years, participates very slowly in the hydrologic cycle. However, the reservoirs are so large that small percentage changes in ice volume can cause major changes in sea level on time scales of 100 to 10,000 years. Wastage (W) occurs primarily by melting or calving around the periphery. The Greenland Ice Sheet, if melted, would yield enough water to maintain the flow of the Mississippi River for more than 4,700 years, and this is only 10% of the total volume of ice caps and glaciers. The greatest single item in the water budget of Earth, aside from the oceans, is the Antarctic Ice Sheet. It contains about 64% of all nonoceanic waters. Melting of just the small West Antarctic Ice Sheet would raise global sea level by about 7 m. The stability of those portions of the Antarctic Ice Sheet that are grounded below sea level, such as the West Antarctic Ice Sheet, is a major unsolved problem.

The addition or subtraction of ice from smaller ice caps and mountain glaciers, reacting on time scales of 10 to 100 years, may appreciably affect the flow of certain rivers. The melting of ice in these glaciers appears to have caused a third to a half of the sea level rise observed in the past century. Snow cover on land and sea ice on the ocean vary rapidly and seasonally and exert a major influence on Earth's radiation budget and on the circulation of both atmosphere and ocean. We particularly need new observational techniques in order to study and monitor the rates of snow accumulation and melt over remote areas. Because of the sensitivity of snow and ice reservoirs to climate change it is important to monitor closely the extent of snow cover, the mass balances of mountain glaciers and ice sheets, and the West Antarctic ice sheet with its fringing ice shelves.

The magnitudes of these major water storages and fluxes are shown in the diagram of Figure 6.

Flux of Sediments

Water moves around on Earth's surface and, at large scale at least, gravity is the primary driver. In its relentless downhill course to the sea, water sculpts the landscape through the processes of erosion, transport, and deposition. In so doing, it is playing the key role in a geological-scale tectonic/climate feedback system. Tectonic and volcanic processes lift the crust creating the gradients that drive the erosion which gradually reduces the gradients. If the elevation changes are large enough they may affect climate, and the erosion may be self-limiting by precipitation reduction as well.

In the process of shaping the landscape, runoff forms a treelike network of channels into which the flow becomes concentrated. Although empirical "laws" describing the two-dimensional geometry of these networks have existed for almost half a century, there is little quantitative understanding of the dynamics of channel formation or of the causal relationship between the three-dimensional network structure and the precipitation driving the erosion. Such understanding would reveal fundamental scaling relationships of surface water hydrology over a broad range of spatial scales (i.e., 1 to 10^6 km^2) and would have immediate applicability to flash flood forecasting in ungaged watersheds and to parameterization of hydrologic processes in regional and global models. It would also help answer many fundamental geological questions about landscape formation.

In spite of decades of study, deficiencies in our understanding of fluid turbulence seriously impair our ability to specify the relative rate of transport of various sizes of grains and aggregates in streams and the duration of their storage at various locations within the channel system. This is important not only for its contribution to understanding erosion and deposition but also because many pollutants are moved through the system adsorbed on sediment particles.

Flux of Dissolved Solids

Water is the universal solvent and as it moves through the hydrologic cycle it dissolves and transports in solution solids as well as gases. Rain falling onto soil surfaces contains various gases and solids in solution. As some of the water infiltrates the soil and moves downward it picks up carbon dioxide from the soil, exchanges solutes with soil and rock particles, and becomes less acid. The percolating waters convey their solute load through the groundwater and into streams. This water has a dissolved mineral signature which is dependent upon the subsurface material properties, the flow path, and biological processes which recycle minerals. Knowledge of these solutes and their chemical kinetics can be used in tracer studies of subsurface water flow paths and in understanding the rates of continental degradation and soil formation.

Involvement of Biota

Water supports a variety of living organisms and some have major interactions with the hydrologic cycle. The thin soil cover, for instance, is a result of physicochemical weathering by water and supports a vegetation cover which is about 99% of Earth's terrrestrial biomass. The vegetation is responsible through transpiration for most of the water returned directly to the atmosphere from the land, and the associated latent heat transfer is a major regulator of land surface temperature. Through photosynthesis the vegetation extracts carbon dioxide from the atmosphere. The removal of vegetation will modify runoff and, in certain climates, may reduce local precipitation due to Earth-atmosphere coupling.

The physical relationships among climate, soil, and vegetation that determine the dominance and stability of specific vegetation types at particular geographic locations are largely unknown and are important in anticipating the effects of climate change.

The soil also supports a variety of microorganisms which act upon complex organic materials and reduce them to simpler organic compounds and ultimately to mineral form. Bacteria and fungi are particularly important in the carbon cycle and in regulating the availability of phosphorus, nitrogen and sulfur. Their action results in the production of carbon dioxide and the development of humus, the organic detritus of decayed vegetation. Humus affects the infiltration and water-holding capacity of the soil and its resistance to erosion. Microorganisms are also responsible for transforming atmospheric nitrogen to a form usable by and essential to plants. While these well-known organisms are active near the soil surface, recent investigations have identified a great many of bacterial species up to 250 m below the surface. It is interesting to speculate on their natural role, if any, in the hydrologic cycle and on their possible use in the degradation of anthropogenic contaminants.

Oceanic microorganisms are responsible for roughly one-half of Earth's photosynthesis and therefore play a major role in atmospheric chemistry and the chemical quality of precipitation.

Wetlands are a primary source of atmospheric methane (another "greenhouse" gas) and perform a host of other hydrologic and biogeochemical functions. Serious scientific study of this complex biome is in its infancy, however.

In the last 500 years the hand of the human animal has been increasingly felt on the hydrologic cycle. The actions of man now extend to the "ends of Earth": high latitudes, deserts, and mountains, where they impact sensitive environments and about which hydrologic data and understanding are absent. We must learn to incorporate man as an active component of the hydrologic cycle in all environments.

A DISTINCT GEOSCIENCE

In its interactive role, water is both actively and passively important to the Earth system. In the passive sense, the occurrence and quality of water are sensitive to atmospheric dynamics and composition. In the short term the global distributions of rainfall, snowfall, evaporation and accumulated water, both surface and subsurface, affect the local extent and global distribution of biomass and biological productivity. Water movement couples the land with the oceans through the solution, entrainment, and transport of minerals and sediments; both liquid water and ice are powerful agents of erosion and, in the long term, they join with plate tectonics in shaping the land surface. In the active sense, changes in land surface properties and vegetation cover may, among other things, alter the long-term average runoff of water. This would demand a corresponding change in the long-term average convergence of atmospheric moisture and a commensurate adjustment in atmospheric dynamics.

In addition, water has unique physical and chemical properties that enable it to play key roles in regulating the metabolism of our living planet. Being practically a universal solvent it both nourishes and purges at all levels of life from cell to civilization. Water's high specific heat gives it a large thermal inertia making it the flywheel of the global heat engine. Its high latent heat makes it an efficient working fluid for the atmospheric heat engine converting solar energy into atmospheric and oceanic motions which act to redistribute both the energy and the water globally.

These properties mean that water-soluble elements will follow the hydrologic cycle at least part way. If they are in a chemical compound that is volatile as well as soluble, the elements will follow the hydrologic cycle all the way. The hydrologic cycle is thus the integrating process for the fluxes of water, energy and chemical elements. It is the fundamental biogeochemical cycle.

This realization of the importance of water to the Earth system at geophysical space and time scales has profound implications for the research and educational infrastructure of hydrologic science. We cannot build the necessary scientific understanding of hydrology at global scale from research and educational programs designed to serve the pragmatic needs of the engineering community. Hydrologic science must take its proper place as a geoscience alongside the atmospheric, oceanic, and solid earth sciences.

A new definition of hydrologic science has been proposed by the NRC Committee on Opportunities in the Hydrologic Sciences to reflect these evolving perceptions and to specify more clearly for programmatic purposes the current boundaries of the science. We limit the scope of hydrologic science to continental water processes and global water balance, which we delineate as follows:

1. Continental water processes refer to the physical and chemical processes characterizing or driven by the cycling of continental waters (solid, liquid and vapor) at all scales (from the microprocesses of soil water to the global processes of hydroclimatology) as well as the biological processes which interact significantly with the water cycle. (This restrictive treatment of biological processes is meant to include those which are an active part of the water cycle such as vegetal transpiration and many human activities, but to exclude those which merely respond to water such as the life cycle of aquatic organisms.)

2. Global water balance refers to the spatial and temporal characteristics of the water balance (solid, liquid and vapor) in all compartments of the global system: atmosphere, oceans, and continents. (This includes water masses, residence times, interfacial fluxes, and pathways between the compartments. Other than within continents, including their aquifers, rivers, lakes, and glaciers, this does not include processes internal to the compartments.)

These boundaries of the science are illustrated schematically in Figure 7.

EXAMPLES OF FRONTIER PROBLEMS

This enlarged scope of hydrologic science brings increased complexity and increased interaction with allied sciences. Important questions of physical behavior are identified. Examples are:

How do we aggregate the dynamic behavior of hydrologic processes at various space and time scales in the presence of great natural heterogeneity?

What are the feedback sensitivities of atmospheric dynamics and climate to changes in land surface hydrology, and how do these vary with season and geography?

What can the soil, sediment, vegetation, and stream network geometry tell us about river basin history and about the expected hydrologic response to future climate change?

What can we learn about the equilibrium and stability of moisture states and vegetation patterns? Is "chaotic" behavior a possibility?

How are water, sediment, and nutrients exchanged between river channels and their floodplains?

What are the states and the space-time variabilities of the global water reservoirs and their associated water fluxes?

How can the necessary and fundamental links between the deterministic and stochastic models of rainfall fields be established?

Fundamental chemical and biological questions are also identified; they are often soil-related and hence at the other extreme of scale. A few examples will give the flavor:

How can we employ modern geochemical techniques to trace water pathways, to understand the natural buffering of anthropogenic acids, and to reveal ancient hydroclimatology?

What is the nature of the feedback processes that occur between biochemical processes and the various physical transport mechanisms in the soil?

What is the relative importance of different flow paths and residence times to the chemistry of subsurface water?

How much transfer of adsorbed materials from one grain to another occurs during streambed storage?

How should we quantify the processes that determine the transport and fate of synthetic organic chemicals that enter the groundwater system?

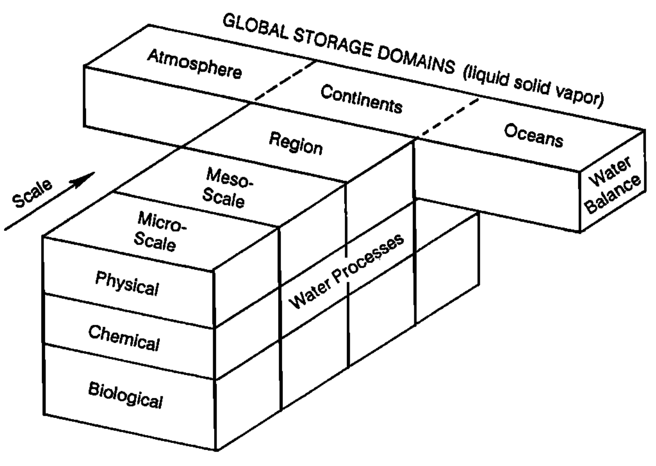

Figure 7. Hydrologic science: a distinctive definition [from *NRC*, 1991].

These and many other fundamental problems of hydrologic science must be addressed to provide the ingredients for solving the sharpening conflicts of humans and nature. They illuminate the multidisciplinary nature of hydrologic science and make clear the need for extensive cross-disciplinary interaction in education as well as in research, as is illustrated in Figure 8. The problems are not confined by the definitional constraints; thus there are major areas of overlapping interest with other sciences and frequent needs to violate the stated boundaries. Important in this regard are the issues of land surface–atmosphere interaction. Understanding the feedback effect of land surface moisture and energy fluxes on the formation of weather and climate is vital to progress in hydrologic science; more traditional concerns for generalization of the space-time variability of storm precipitation demand incorporation of considerable atmospheric dynamics and thermodynamics. Similar trespassing must occur in the areas of fluvial geomorphology, micrometeorology, and plant ecology (to name but a few) because of the importance to the hydrologic cycle of related processes such as erosion, energy flux, and transpiration.

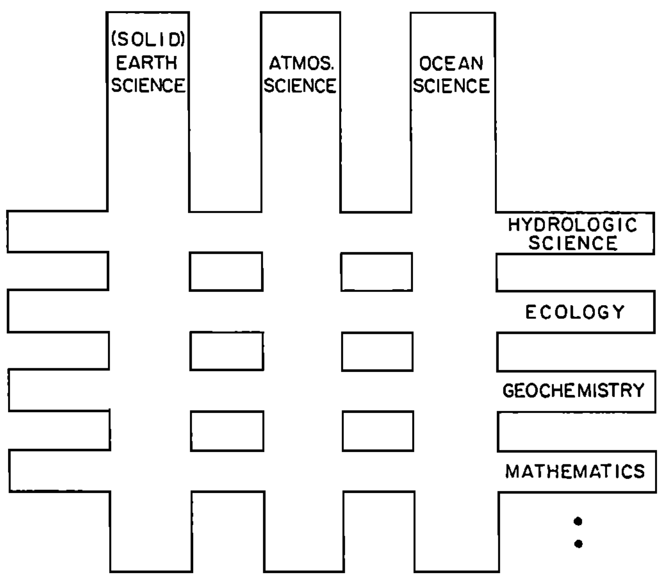

Figure 8. The intellectual fabric of Earth system science [from *NRC*, 1991].

DATA ISSUES

Hydrologic processes are highly variable in space and time, and this variability exists at all scales, from centimeters to the continents, from minutes to years. Data collection over such a range of scales is difficult and expensive, and so hydrologic models usually conceptualize processes based on simple, often homogeneous, models of nature. This forced oversimplification is impeding both scientific understanding and management of resources.

In the history of the hydrologic sciences, as in other sciences, most of the significant advances have resulted from new measurements; yet today there is a schism between data collectors and analysts. The pioneers of modern hydrology were active observers and measurers; yet now designing and executing data collection programs (as distinct from field experiments with a specific research objective) are too often viewed as mundane or routine. It is therefore difficult for agencies and individuals to be doggedly persistent about the continuity of high-quality hydrologic data sets. In the excitement about glamorous scientific and social issues, the scientific community tends to allow data programs to erode.

Data programs provide the basis for understanding hydrologic systems and documenting changes in the regional and global environments. Modeling and data collection are not independent processes. Ideally, each drives and directs 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. We must reemphasize the value and importance of observational and experimental skills.

EDUCATIONAL ISSUES

Higher education in hydrology at most universities, especially at the graduate level, has long been the province of applications-oriented departments such as engineering, agriculture and forestry. Doctoral and master's degree programs administered by these departments have been directed toward traditional "engineering" concerns such as water resources development, hazard mitigation, food supply, and water management as predicated on societal needs. The research focus in these departments has properly been the analysis and solution of practical problems, on the premise that these problems contribute palpably to the technical knowledge base required for water resources allocation, the management of floods and droughts, pollution control, etc. Current societal needs, as expressed through legislative action or executive orders, are as important to the choice of research problems and their methods of solution as are the flow of scientific ideas and technological breakthroughs.

This well-developed and successful line of inquiry differs markedly from that pursued in the pure sciences, such as chemistry. The difference, in fact, is exactly analogous to that between the disciplines of chemistry and chemical engineering. Chemistry is the science that deals with the composition, structure, and properties of substances and the reactions that they undergo. Chemical engineering deals with the design, development, and application of manufacturing processes in which materials undergo changes in their properties. The first discipline is a science, dealing with puzzle solving (i.e., motivated by the question), whereas the second is an application of science, dealing with problem solving (i.e., motivated by the answer). Hydrology has a long and distinguished history of problem solving, but where is the antecedent science of puzzle solving?

The education of hydrologic scientists offers challenges as great as those in engineering hydrology, but the spirit of the enterprise is different, just as it is between education in chemistry and in chemical engineering. The choice of research problem is occasioned by its level of development within the hierarchy of the science, by the availability of new methods with which to solve it, and by the desire to understand a hydrologic phenomenon more deeply. The solution of the problem advances the development of the science and expands the conceptual framework that gives it meaning. It is this kind of internally driven intellectual pursuit that motivates the pure scientists and that must be instilled by the educational process that forms their professional outlooks. That is the challenge to hydrologic science, and it differs from the challenge to engineering.

SCIENTIFIC PRIORITIES

Research

The following five research areas seem currently to offer the greatest expected contribution to the understanding of hydrologic science; they are not ranked by the Committee and are presented here in random order:

Chemical and Biological Components of the Hydrologic Cycle. In combination with components of the hydrologic cycle, aqueous geochemistry is the key to understanding many of the pathways of water through soil and rock, to revealing historical states having value in climate research, and to reconstructing the erosional history of continents. Together with the physics of flow in geologic media, aquatic chemistry and microbiology will reveal solute transformations, biogeochemical functioning, and the mechanisms for both contamination and purification of soils and water.

Water is the basis for much ecosystem structure, and many ecosystems are active participants in the hydrologic cycle. Understanding these interactions between ecosystems and the hydrologic cycle is essential to interpreting, forecasting, and even ameliorating global climate change.

Scaling of Dynamic Behavior. In varied guises throughout hydrologic science we encounter questions concerning the quantitative relationship between the same process occurring at disparate spatial or temporal scales. Most frequently perhaps, these are problems of complex aggregation that are confounding our attempts to quantify predictions of large-scale hydrologic processes. The physics of a nonlinear process is well known under idealized, one-dimensional laboratory conditions, and we wish to quantify the process under the three-dimensional heterogeneity of natural systems, which are orders of magnitude larger in scale. This occurs in estimating the fluxes of moisture and heat across mesoscale land surfaces and in predicting the fluvial transport of a mixture of sediment grains in river valleys. It arises in attempting to extend tracer tests, carried out over distances of 10 to 50 m in an aquifer, to prediction of solute transport over distances of hundreds of meters to kilometers. It occurs in extrapolating measurements of medium properties in a small number of deep boreholes to characterize fluid fluxes at crustal depth.

The inverse problem, disaggregating conditions at large scale to obtain small-scale information, arises commonly in the parameterization of subgrid-scale processes in climate models and in inferring the subpixel properties of remote sensor images.

Solving these problems will require well-conceived field data collection programs in concert with analysis directed toward "renormalization" of the underlying dynamics. Success will bring to hydrologic science the power of generalization, with its dividends of insight and economy of effort.

Land Surface–Atmosphere Interactions. Understanding the reciprocal influences between land surface processes and weather and climate is more than an interesting basic research question; it has become especially urgent because of accelerating human-induced changes in land surface characteristics in the United States and globally. The issues are important from the mesoscale upward to continental scales. Our knowledge of the time and space distributions of rainfall, soil moisture, groundwater recharge, and evapotranspiration is remarkably inadequate, in part because historical data bases are point measurements from which we have attempted extrapolation to large-scale fields. Our knowledge of their variability, and of the sensitivity of local and regional climates to alterations in land surface properties, is especially poor.

The opportunity now exists for great progress on these issues through a combination of multidisciplinary field experiments (such as the completed First International Field Experiment (FIFE) of the International Satellite Land Surface Climatology Project (ISLSCP) and the completed Hydrologic Atmospheric Pilot Experiment–Modélisation du Bilan Hidrique (HAPEX-MOBILHY)) and numerical modeling.

Coordinated Global-Scale Observation of Water Reservoirs and the Fluxes of Water and Energy. Regional-scale and continental-scale water resources forecasts and many issues of global change depend for their resolution on a detailed understanding of the state and variability of the global water balance. Our current knowledge is spotty in its areal coverage; highly uneven in its quality; limited in character to the quantities of primary historical interest (namely precipitation, streamflow, and surface water reservoirs); and largely unavailable still as homogeneous, coordinated, global data sets.

Hydrologic Effects of Human Activity. For at least two decades hydrologists have acknowledged that humans are an active and increasingly significant component of the hydrologic cycle. Quantitative forecasts of anthropogenic hydrologic change are hampered, however, by their being largely indistinguishable from the temporal variability of the "natural" system.

Experiment and analysis need to be focused on this question. Identification of the signal of change within the background noise of spatial and temporal variability will require observations at regional scale and over many annual cycles. Forecasting the course of future change will be eased by understanding what changes have already occurred.

Data Requirements

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. An information management system is needed that would 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 characteristics 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 Multidisciplinary Experiments. Special integrated studies, such as HAPEX, FIFE, and the Global Energy and Water Experiment (GEWEX), 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 broader and more timely distribution beyond the community of scientists who are involved in the experiment.

Educational Requirements

Multidisciplinary Graduate Education Program. The broad range of education inputs to graduate study in hydrologic science necessitates the formation of a multidisciplinary program in the hydrologic sciences. This program should be either a department unit or a confederation of faculty from host departments that is assured of autonomy and resources by upper level administration. The program would educate graduate students who are considered first and foremost as hydrologists, not geologists, geographers, or engineers who have some background in hydrology.

Experience With Observation and Experimentation. The changing nature of hydrologic science requires the development of coordinated, multidisciplinary, large-scale field experiments. Graduate students should be given experience with modern observational equipment and technologies within their university programs, and mechanisms should be developed to facilitate their participation in these experiments, irrespective of their university of study. When the experiments are planned, the inclusion of a diverse array of studies should be an integral part of the plan. Undergraduate students of science should have experience with measurement of natural phenomena, preferably in field situations as well as in controlled laboratory settings.

Visibility to Undergraduate Students. Programs should be developed to make hydrologic science more visible as a scientific discipline to undergraduate students. These programs should include such elements as research participation, internships at laboratories and institutes, curricula that introduce the latest innovations, visiting distinguished lecturers, media development, and in-service institutes for teachers.

CONCLUSION

To meet emerging challenges to our environment we must devote more attention to the hydrologic science underlying water's geophysical and biogeochemical role in supporting life on Earth. The needed understanding will be built from long-term, large-scale coordinated data sets and, in a departure from current practices, it will be founded on a multidisciplinary educational base emphasizing the basic sciences.

A case is made for the need to recognize and pursue hydrologic science as a distinct geoscience that cuts across the traditional atmospheric, ocean and solid earth sciences. The supporting educational and research infrastructure must be put in place.

APPENDIX: DEFINITIONS

It is important to understand our use of the term "geoscience" vis-à-vis "earth science" and the more recently coined "Earth system science." We follow the National Science Foundation (NSF) and use "geoscience" to include atmospheric science, ocean science, earth science, glaciology, and, as we argue herein, hydrologic science. As does the NSF, we interpret "earth science" as the solid earth sciences including geology, petrology, seismology, volcanology, etc. "Earth system science" includes all sciences relevant to the functioning of planet Earth as a set of interacting physical, chemical, and biological mechanisms. It differs from geoscience in its inclusion of important terrestrial biota and certain solar and other space physics effects on Earth, and in its emphasis on integrated planetary behavior.

ACKNOWLEDGMENTS. This material has been drawn primarily from the collective work of the NRC Committee on Opportunities in the Hydrologic Sciences. Their report entitled "Opportunities in the Hydrologic Sciences" is available from the National Research Council, National Academy Press, 2101 Constitution Avenue, N.W., Washington, D. C. 20418, as ISBN 0-309-04244-5.

Garrison Sposito was the Editor in charge of this paper. He thanks George M. Hornberger and an anonymous referee for their assistance in evaluating its technical and explicative features.

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