Global Change, A Catalyst for the Development of Hydrologic Science*

1. Introduction

The scientific origins of hydrology lie in the engineering problems of flood control, water supply, and sanitation. Thus the education and motivation of its practitioners has been oriented to problem solving. Over time, with development in the size and complexity of human society, there has been an evolutionary expansion in the scale of these problems, but until relatively recently, scientific understanding has not been an organizing principle of the accompanying hydrologic research and education. 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 many roles in the planetary mechanisms.

The issues of global change have served to catalyze our interest in hydrologic science by highlighting the centrality of water processes to the physical climate system and to the biogeochemical cycles. With this has come the realization that the comprehensive hydrologic science base for understanding and coping with these issues is missing. Hydrologic science has a natural place as a geoscience cutting across the established atmospheric, ocean, and (solid) earth geosciences (see Fig. 1), and its appropriate scientific research and educational infrastructure must be identified and established.

It is important to understand that what we propose here are not suggested as substitutes for or as pejorative reflections upon existing research or educational activities in the applied forecasting (i.e., engineering hydrology) and management (i.e., water resources) aspects of water. They are intended as needed complimentary, new initiatives.

2. Historical development of hydrologic science

Concern for water as both a necessity and a possible hazard has been with humans throughout their existence on earth, but not until the Hellenic civilization, about 600 B.C., did man attempt to understand nature just for the sake of understanding.

Precipitation was first measured in the fourth century B.C. by Kautilya of India and streamflow by Hero of Alexandria in the first century A.D. Little further advance in understanding occurred until the Renaissance when the work of Palissy (a French potter and naturalist), Perrault (a French lawyer), and Halley (English Astronomer Royal) collectively established the hydrologic cycle and marked the beginning of hydrologic science.

For the rest of the 17th and 18th centuries, Europe was transformed by the Industrial Revolution and its accompanying urbanization. Physicists and members of distinguished families lost interest in hydrology, and its development was left to civil engineers such as de Pitot, Chézy, and Venturi who were concerned with water supply and water power. The science developed spottily in response to the needs of engineering practice as water scientists and engineers focused their attention on drainage basins of characteristic dimension 10 to 100 km. Because the early foundations of hydrologic science were built upon experience

*This paper was presented as the Robert E. Horton Lecture in the Global Change Symposium at the AMS Annual Meeting in Anaheim, California on 7 February 1990.

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Vol. 72, No. 1, January 1991

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with middle latitudes, some inadvertent and long-lived biases were established. The catchments being studied were assumed to be passive participants in the hydrologic cycle producing no feedback to the atmospheric forcing, and the hydrologic processes peculiar to the nondeveloping desert, tropical, and cold regions received little or no attention.

In the United States, hydrologic research remained the province of enterprising inventors, prospectors, and wealthy amateurs until late in the 19th 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 United States Geological Survey (USGS) embodies the development of hydrologic science in the United States, particularly in sediment transport, groundwater, and water chemistry. (In surface water, however, private consulting engineers remained in the forefront of research well into the 20th century.) This period of federal and state agency dominance in the United States ended with the completion, in the 1950’s, 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 20th 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 (Whitten 1989).

In 1930, as AGU was transforming to an independent society, a Section of Hydrology was finally formed with O. E. Meinzer as chairman and R. E. Horton as vice-chairman. In 1931, Horton 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 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 underway 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 U.N.-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 landsurface 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 Fig. 2) 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. It is these dynamic interactions of the hydrologic cycle with major physical, chemical, and biological processes across a wide range of space-time scales that suggest hydrologic science as a central science of global change.

3. The geophysical basis of hydrologic science

The global reservoirs and fluxes of water are shown schematically in Fig. 3 in a representation of the hydro-
FIG. 4. The climatic hydrologic cycle at global scale (from NRC 1986).

FIG. 5. The tectonic hydrologic cycle (from Forster and Smith 1990).

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logic cycle as a fundamental geophysical process. Powered by the sun, the phase changes of water on earth involve storage and release of latent heat which helps drive the atmospheric circulation. Condensing in the atmosphere where it releases its latent heat, the liquid (or solid) water falls as precipitation, runs to the sea, and through evaporation regains its cargo of latent heat and returns through the atmosphere to wash the land again. This climatic hydrologic cycle is the framework of hydrologic science and occurs over a wide spectrum of space and time scales. It is usually referred to simply as "the hydrologic cycle" and is illustrated quantitatively at global scale in Fig. 4. It affects the global circulation of both atmosphere and ocean, and hence is instrumental in shaping weather and climate.

There is another hydrologic cycle important to global change, but at geologic time scales, in which movements of the earth's crust and mantle (rather than atmosphere and oceans) are the agents for water transport. In this cycle, water becomes incorporated chemically into rock (for example, by oceanic sedimentation of animal shells), subducted to the mantle through plate movement and returned to the atmosphere by volcanism. Here, we call this the "tectonic hydrologic cycle." We illustrate it in Fig. 5, but its characteristics are beyond the scope of this discussion. We focus here on those changes involving the earth's atmosphere and crust.

4. The Biogeochemical Basis of Hydrologic Science

Water has unique physical and chemical properties that enable it to play key roles in regulating the metabolism of our living planet:

- **Elixir of life** -- Water is practically a universal solvent. Because cell membranes are permeable only to dissolved substances, water is the elixir of life, essential both for the nourishment of cells and for the removal of their wastes. It plays this same role, both blood and lymph, at all higher levels of life's organization; the individual plant or animal, the household, city, civilization, and, apparently, for earth itself.

- **Climatic thermostat** -- Water's high specific heat gives it a large thermal inertia making it the flywheel of the global heat engine.

- **Global heat exchanger** -- Water's 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.

- **Insulator of life** -- Water is less dense in its solid state than in its liquid state making water bodies freeze from the top down. This maintains water temperatures conducive to many life forms.

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

5. Some global change issues in hydrologic science

Because of the interactive nature of water in the Earth system, hydrology is both actively and passively important in global change. 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 (Fig. 6). In the active sense, changes in landsurface properties and vegetation cover may, among other things, alter the long-term average runoff of water which would demand a corresponding change in the long-term average convergence of atmospheric moisture. This, in turn, would require a commensurate adjustment in atmospheric dynamics.

The historical evolution of hydrologic science has been in the direction of ever-increasing space and time scale, from small catchment to large river basin to earth system, and from storm event to seasonal cycle to climatic trend. Inevitably, increased scale brings in-
creased complexity and increased interaction with allied physical, chemical, biological, and mathematical sciences. New questions arise, many of which have implications for global change. We outline an eclectic subset of these here:

a. How do we aggregate the dynamics at various space-time scales in the presence of great heterogeneity?

This fundamental statistical-dynamical problem of hydrology remains unsolved and is crucial to the fidelity of atmospheric general circulation models (GCMs).

As far as global change is concerned, general circulation models are, for better or for worse, the only prognostic tool available. Furthermore, because of the complex interaction among the many physical, chemical, and biological components of the earth system, these models are a principal diagnostic tool in assessing system sensitivities. We must work to improve them.

The fluxes of moisture across the land surface boundary of GCMs depend upon the hydraulic conductivity (cm d$^{-1}$) of the soil. Such properties of natural soil formations are highly variable spatially as is seen by the observations plotted in Fig. 7. In this illustration, Plots 1 and 2 are separated by only 50 m, and we see that their conductivities, for common soil water content, may differ by a factor of 100. With the fluxes being complex, nonlinear functions of conductivity and of the similarly variable water content, the GCM requirement for $10^4$ km$^2$ gridsquare average fluxes is formidable. This problem occurs repeatedly in the parameterization of subgrid-scale processes for GCMs.

b. What are the feedback sensitivities of atmospheric dynamics and climate to changes in landsurface hydrology?

The fluxes of energy and water from landsurface to atmosphere are intimately linked and depend strongly upon the moisture state of the surface. The atmos-
pheric processes responsible for supplying this moisture are themselves sensitive to the moisture-driven fluxes in a feedback process of variable importance to weather and climate depending upon such factors as latitude and season. While we can reason from first principles as to the sense and conditional magnitude of each of these feedbacks considered independently, their complex coupling demands that we estimate the net effect of landsurface change using a model that incorporates all the essential interactions. This work is in its infancy.

It seems logical to expect the sensitivity of atmospheric dynamics to landsurface change to be largest where the primary atmospheric motions are vertical as a result of moist convection (e.g., tropical latitudes). Similar reasoning suggests that this sensitivity should decline wherever lateral atmospheric motions and large-scale condensation dominate (e.g., middle latitudes).

Figure 8 illustrates the type of "experiment" needed. Here, using the GISS-II GCM is the simulated seasonal sensitivity of atmospheric moisture convergence to a drastic change in the soil moisture-holding capacity of the land surface, all else remaining constant. Note that the tropical climate (Fig. 8-b) exhibits sensitivity year-round, while in middle latitudes (Fig. 8-a) the sensitivity is confined to the growing season, at which time plants make deep soil moisture available to the atmosphere. This is also the season during which moist convection is important at these latitudes.

c. What are the sensitivities of the methane productivity of wetlands to climate change?

Methane gas follows water vapor and carbon dioxide in importance as a radiatively active "greenhouse" gas. Like carbon dioxide, its presence in the atmosphere is growing at well over 1% per year (see Fig. 9). The major sources are thought to include wet ecosystems such as rice paddies and natural wetlands, as well as fossil deposits, combustion, and the digestive systems of cattle. In wetlands, methane is produced in saturated environments where it is readily released to the nearby atmosphere. Vegetation and waterlogged organic sediment together create the oxygen-deficient environment that encourages methane-producing microbes. The sediment also plays a regulatory role in release of the methane, in part by supporting methane-consuming microbes near the surface.

Hydrologic activity influences each step of this process. Water table elevation fixes the fraction of the

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*Fig. 10. Forest formations of eastern North America (Map from Little 1971; boundaries from Eyre 1968; as presented by Arris and Eagleson 1989)*
organic sediment that is anoxic, and hence methane-producing, as opposed to the upper, unsaturated, methane-consuming sediment. To the extent that released methane may influence climate change, there is a potential for hydrologic feedback to the methane production.

d. What is the physical basis for the observed geographical distribution of the major vegetation types on earth’s continents?
The vegetation cover of earth’s continents is coupled physically to the climate system and to the soil by the fluxes of thermal energy, moisture, and nutrients. Different vegetation types have different physiological needs and tolerances which have developed over time in a process of co-evolution with their soil and climate partners. The current manifestation of this evolution and migration, as modified by human activity, is the observed distribution of vegetation formations such as is shown in Fig. 10 for eastern North America. What are the physical reasons for a particular formation being confined to a certain geographical zone? It is important to gain quantitative understanding of these boundaries if the effects of climate change are to be accurately forecast.

The transitions from one vegetation type to another are known as ecotones. Because they represent marginal conditions, ecotones will be sensitive to changing climate, and predicting their location is an important test of the GCMs on which our climate forecasts are based.

Hydrology plays a role in the location of these ecotones. In some cases (e.g., savannas), water availability controls the configuration of the formation. In others, where water is plentiful, dominance in a given environment may go to the vegetation type that produces the most biomass, and hence wins the race to reproduce. Biomass production is a function of carbon assimilation through the process of photosynthesis. Since both carbon dioxide and water vapor exchange occur through the open stomata, the evapotranspiration rate is often used as the basis for estimating productivity. Such an estimate (Arris and Eagleson 1989) apparently explains the transition between boreal and deciduous forest in eastern North America.

e. Can the dynamics of multistable nonlinear systems suggest new physical insights into the patterns of annual rainfall time series?
In now-classical work, E. N. Lorenz (1963) demonstrated that nonlinear phenomena can be the sources of intrinsically generated complex behavior. Although governed by well-defined deterministic equations, the dynamics may evolve into an aperiodic random-looking behavior called “deterministic chaos.” A characteristic of such systems is a multiplicity of simultaneously available states called “attractors” among which the system chooses according to the initial conditions. Since the initial conditions may be subject to external perturbations, a multi-stable nonlinear system exhibits an aperiodic series of jumps between attractors.

Figure 11 shows the normalized precipitation time series for the western Sahel which shows an apparent abrupt transition from one state to another. This behavior can be modeled (see Demaree and Nicolis 1990) as a bi-stable nonlinear dynamical system in which one stable state is quasi-normal rainfall and the other is low rainfall. The system is modeled as subjected to one stochastic perturbation such as would arise from the “normal” advective and convective processes and another of external origin such as sea surface temperature anomalies. The resulting behavior looks very much like Fig. 11.

Such modeling exercises provide valuable new insights into hitherto perplexing observations. Estimating the model parameters from the data will, of course, allow potentially useful statistical predictions of such practical quantities as the residence times in the separate states.

These and many other fundamental problems of hydrology must be addressed in order to provide the ingredients for solving the sharpening conflicts of man and nature. Many, if not most, of them will require coordinated multidisciplinary field studies of the appropriate scale. Others, such as the measurement of unknown oceanic precipitation and evaporation, will require sensors, often satellite-borne, that are still undeveloped. Progress in many areas of the science is currently data-limited.

6. Hydrologic science is a distinct geoscience

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 is needed and has been proposed recently (NRC 1990) to reflect these evolving perceptions and to specify more clearly for programmatic purposes the current boundaries of the science.

First, the new perceptions: We add that hydrologic science is a geoscience interactive with the ocean, atmospheric, and (solid) earth sciences as well as with plant and animal ecologies and with human activities on a wide range of space/time scales. The new perceptions are the interaction of the components and the range of scales.

Second, the practical boundaries: The ubiquity of water on earth and its indispensability to life do not make hydrologic science out of all geoscience and biology. To form a separate identity we must specify and claim the central elements of our science and locate its administrative boundaries as an adjustable compromise between completeness and precedent. Here we disclaim any implied responsibility of hydrologic science for developing understanding of the physics, chemistry, and biology of water within the ocean and atmosphere reservoirs, for these processes lie firmly in the recognized domains of our sibling geosciences. We do include the study of snow, ice, and lakes within our definition of hydrologic science, however.

To establish and retain our individuality as a separate geoscience, we limit the scope of hydrologic science to the following:

**Continental Water Processes** -- the physical and chemical processes characterizing or driven by the cycling of continental waters (solid, liquid, and vapor) at all scales (from the micro-processes 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.)

**Global Water Balance** -- 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 for 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 Fig. 12.

The complex problems of global change illuminate the multi-disciplinary nature of hydrologic science and make clear the need for extensive cross-discipline interaction in education as well as in research. The problems pay no attention to organizational boundaries; thus, there are major areas of overlapping interest with other sciences and frequent needs to violate the stated boundaries. This is both inevitable and desirable. Primary in this regard is the case of landsur-
face-atmosphere interaction. Understanding the feedback effect of landsurface moisture and energy fluxes on the formation of weather and climate is vital; 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) due to the importance to the hydrologic cycle of such related processes as erosion, energy flux, and transpiration.

7. Needed actions

Development of hydrology as a science is important to the current effort to understand the interactive behavior of the earth system because of the key role that the hydrologic cycle is now known to play therein. Achieving this comprehensive understanding will require the kind of long-term disciplinary and multidisciplinary effort that can only be sustained by a vigorous scientific infrastructure. To advance the science of hydrology resources will be needed:

- Separate research grant programs should be established in hydrologic science to help create and maintain a cadre of hydrologic scientists and to provide a focused image and identity for the science.
- Coordinated, multi-disciplinary field experiments should be increased in number particularly at the mesoscale and in a variety of climates.
- Long-term hydrologic observations should be given renewed attention.
- Graduate education in hydrologic science should be pursued independently of engineering in new programs based within the geosciences.

8. Summary

The scientific issues of global change have highlighted the importance and scale of the role of water in the earth system. A case is made for the need to recognize and pursue hydrologic science as a separate and distinct geoscience that cuts across the traditional atmospheric, oceanic, and solid earth sciences (Fig. 13).

Acknowledgments. This material has been drawn in large part from the collective work of the NRC Committee on Opportunities in the Hydrologic Sciences (P. S. Eagleson, Chairman; W. H. Brutsaert; S. C. Colbeck; K. W. Cummins; J. Dozier; T. Dunne; J. M. Edmond; V. K. Gupta; G. C. Jacoby; S. Manabe; S. E. Nicholson; D. R. Nielsen; I. Rodríguez-Iturbe; J. Rubin; J. L. Smith; G. Sposito; W. T. Swank; E. J. Zipse), including contributions from outside the committee. Of the latter, particular credit is given here to H. F. Hemond for the material on methane, and to C. Nicolis for that on chaos. The opinions expressed are those of the author, however, and do not necessarily reflect those of the committee or of the NRC.


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