THE HORTON LECTURE:
A BRIEF HISTORY OF HYDROLOGY

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I am grateful to the American Meteorological Society for bestowing me the honor of being the Horton Lecturer. The award honors a true polifacetic individual whose curiosity and genius led him to blaze the trails in hydrology and hydrometeorology that many of us have followed. Horton wrote about infiltration, runoff production, river basin response, erosion and fluvial geomorphology, evaporation and hydrometeorology. Everything he did was profound and thorough; setting standards, hypotheses and theories that are still debated. But Horton was not an ivory tower scientist. All his work was motivated by problems of society. For almost 30 years I have followed Horton's delight in the variety of challenges that hydrology poses. Like him I have dabbled in practically all elements of physical hydrology. And like him I have had a wonderful time! Hydrology has changed and evolved dramatically over my career.

The following will indeed be a short history of hydrology. It will also be a biased history, colored by my experiences, interests and work. I make no claim of completeness or of neutrality. I do claim pride on being a small part of what I think have been the best years of hydrologic science.

From the Greeks to Horton

My family and I returned to the USA after a year sabbatical in 1983. A not-so-friendly immigration officer in New York detained us for over forty minutes wondering what had we done over the past twelve months, suspicious of the trips to China, Europe and South America. I patiently explained that I was an hydrologist and lectured in all those places. A quizzical look was followed by the question: “What is a hydrologist?” After a carefully crafted explanation she gave me an incredulous look and asked: “Why would anybody care about that?”

Many have cared about hydrology, dating back to great civilizations in China, the Middle East, Greece and Rome. Early thinkers and philosophers did not understand three basic hydrologic principles (Eagleson [1970]):

1. conservation of mass,
2. evaporation and condensation, and
3. infiltration

They were worried about how water gets up to the mountains, flows down to the sea, and fails to raise the level of the latter. Because of what may be called limited spatial awareness, they could not see rainfall as a sufficient source of streamflow. To account for observed water behavior, underground reservoirs (beneath mountains) were hypothesized. Water was believed to be pushed up the mountains by vacuum forces, capillary action, or "rock pressure", surfacing as streamflow. These underground reservoirs were replenished by the sea.

Vitruvius, during the first century B.C., stated that the mountains received precipitation that then gave rise to streamflow. A filtration process by which water percolated into soil was also acknowledged by Vitruvius and later by da Vinci.

It was in the seventeenth century that Perrault proved by measurement that precipitation could account for streamflow in the

Seine River, France. Similar quantitative studies were made by Mariotte and Halley during this historical period. At this stage, the mass balance concept was pretty well established, although questioning of it continued well into the twentieth century.

The eighteenth century saw advances in hydraulics and the mechanics of water movement by Bernoulli, Chezy, and many others. The nineteenth century saw experimental work on water flow by people like Darcy and Manning. The above names are familiar to students of groundwater and surface-water movement.

Until the 1930s hydrology remained a science filled with empiricism, qualitative descriptions, and little overall understanding of ongoing processes. At that time, people such as Sherman [1932a] and Horton [1940] initiated a more theoretical, quantitative, approach. Sherman's unit hydrograph concept still remains with us as the most successful (but not necessarily the best) and most well-known explanation of river-basin behavior. Horton's ideas on infiltration, soil-moisture accounting, and runoff are still recognized by present-day hydrologists.

Thoughts on the Last 30 Years

By the time I arrived on the scene, as a student in 1968, generations of engineering hydrologists had been educated using the pioneering textbooks (1949 and 1958) of Linsley, Kohler and Paulhus. Their "Hydrology for Engineers" was one of the few, and overwhelmingly the dominant hydrology textbook in the United States. It is probably the historical best seller in the field, by far. Ven Te Chow's encyclopedic "Handbook of Applied Hydrology" of 1964 seemed to codify a "mature" field. To students like me, the field was lacking new ideas.

Luckily, my impressions were wrong, a revolution was brewing and it raised its head around 1970. Crawford's and Linsley's work on the Stanford Watershed Model (1966) and Harley's (1970) MIT Catchment Model showed that digital computers offered hydrologists the opportunity to integrate processes to simulate complicated behavior in a systematic, integrated fashion. Work at the Harvard water program and at Colorado State University by Yevjevich and students began viewing natural hydrologic processes as random phenomena and representing them in that fashion. The International Hydrologic Decade had been on-going for 5 years and a wealth of new data and group efforts were becoming available.

One such result, the "Handbook on the PRINCIPLES of Hydrology" (capitalization added by the author) , edited by Donald M. Gray (1970) stated in its foreword "... Hydrology is only an "infant" in growth in the modern-day family of sciences .... our ancient forebears, if they could but see us now, would be shocked to find how lax we have been in neglecting the study of water." It further claimed that "although empirical results or data may change regionally or geographically, the fundamental principles governing hydrologic processes, when defined in mathematical terms, do not vary, and therefore have general application. " The era of pure empiricism was over. Finally, in 1970 Peter Eagleson wrote "Dynamic Hydrology". A best seller it was not, but its impact on the generations of hydrologists to follow was enormous. Eagleson' work screamed science and emphasized that the hydrology of the land was intertwined with the atmospheric phenomena.

There were other key actors and other key events but to me the above were pivotal to launching the hydrologic revolution of the last 30 years. Things have changed so much that in a recent speech (1998) I joked that it seemed that all hydrology I learned at MIT was wrong. An exaggeration, but it gets the point across!

Several new principles, realizations, concepts, tools and methodologies that have their roots in this revolution have dominated hydrology over the last 30 years and will dominate it in the foreseeable future. These are:

- Hydrologic processes are not only incredibly variable in time and in space but the properties and parameters of the media in which they evolve are also extraordinarily variable. The old representations of hydrologic behavior within idealized homogeneous media, in 0 or 1 dimension, can lead to serious misconceptions and errors.
- Hydrologic phenomena can and should be represented, and interpreted, as products of stochastic dynamics. Uncertainty is inherent due to extreme variability and issues of scale (see below). This thinking goes way beyond traditional statistical analysis of data.
- Process representation and scale are inseparable. Some processes are scale dependent, measurements always are. Other processes are scale independent exhibiting various degrees of self-similarity.

- Complexity is the rule, not the exception. This complexity can be exhibited even in simple hydrologic systems as nonlinearities and feedbacks between inter-related phenomena are acknowledged or discovered.
- The atmosphere-biosphere and the hydrosphere, including the land hydrologic phenomena, are inseparable. Changes in one will affect the other.
- Hydrology is global. The river basin is no longer the only unit of interest. Acknowledging the close relationship between land hydrologic processes and the atmosphere is acknowledging that the important hydrologic cycle is the global cycle.
- The behavior and impact of plants on local, regional and global hydrology remains our largest unknown. Quantifying the relationship between the biosphere and the physical-chemical hydrology is our biggest challenge.
- Remote sensing must become the monitoring tool of choice. It is our only hope for viewing hydrology with the necessary time and space coverage to meet the challenges posed above.

Combined with remote sensing, advances in software and hardware demands a rethinking of our simulation, modeling and data gathering activities.

Examples of the Revolution

I was taught that surface runoff occurred when the intensity of rainfall exceeded the capacity of the soil to absorb it. We called it Hortonian runoff (R.E. Horton, the Role of infiltration in the Hydrologic Cycle, Trans. Am. Geophysical Union, Vol. 14, PP 446-460,1933). Now we know that other mechanisms exist; in fact, what I was taught practically never occurs in parts of the world. Dunne (1978) described a saturation from below mechanism for runoff production. Figure 1, from Freeze (1980), highlights the main differences in the runoff production processes when viewed from the perspective of behavior at a point. The fact, though, is that both mechanisms are valid and what is missing is proper accounting of the spatial variability of rainfall, soil properties, land cover and topography. The Horton versus Dunne debate in runoff production is an artifice of our 0 or 1 dimensional traditional thinking. This spatial component to basin infiltration was recognized even in the early digital watershed models. Figure 2 (Linsley, Kohler and

Paulhus, 1982) illustrates how the early Stanford Watershed Model attempted to account for variability in runoff production in the basin as a function of a surrogate of overall "wetness" over the region. The 0-dimensionality of the model did not allow it to account for one key element in the runoff production: basin topography. Topography plays a major role in the redistribution of moisture, with hollows in the basin becoming wetter and hence influencing the nature of runoff production. Figure 3 illustrates this redistribution. This spatial variability of soil moisture not only affects the mass balance in the basin but influences the energy balance through albedo effects and the partitioning of sensible and latent heat. The implications to sub-grid parameterization of models should be clear.

Beven and Kirkby() must be credited for raising consciousness about the importance of topography in moisture redistribution and runoff production. Their TOPMODEL concept parameterized runoff in terms of basin areas more apt to saturate because of convergence of flow lines and small slopes. That idea is a long way from the "homogeneous", "equivalent" or "lumped" models that I learned as a student and that are still prevalent in operations, where a system of conceptual "buckets" are use to represent in an aggregate fashion the various storages and delays that lead to the basin response (Figure 4). Such approaches, were the result of difficulties obtaining spatially variable precipitation, topography and soil properties. Nowdays, though, we are quickly moving from a data poor to a data rich environment. We must substitute conceptualization with data. Digital Elevation Maps are readily available everywhere, and constantly improving in quality. Precipitation over the USA is now measured with digital Doppler radar at very high resolutions in time and space. Satellite remote sensing promises even more data on everything from soil moisture, to precipitation, to vegetation coverage. The bottom line is that distributed hydrologic models are the future and here to stay. Already we have systems that use digital elevation information and radar precipitation to drive distributed rainfall-runoff models that represent the basin at resolutions of tens of meters (figure 5). These models provide a wealth of information on basin behavior, from soil moisture distribution, to runoff distribution in space, to discharges at arbitrary locations. There are still challenges of calibration, but these I believe will be resolved as we insist on using remotely sensed data to drive the models of the future.

When I was a student we were happy if we found one raingage every 2000 to 10,000 km2 over the United States. It looked strange then; it looks stupid now. Today we can blanket the land with meteorological radar and measure rainfall at resolutions of two square kilometers and sometimes that is not enough! There is little question in my mind that errors in precipitation overwhelm other parameterization and model errors in flow and flood predictions (see figure 6). Equally important to all hydrologic applications is our increasing ability to utilize space-based remote sensing to obtain estimate of variables like soil moisture (Figure 7), snow depth and extent, surface fluxes and even precipitation. Many of us share the excitement produced by the successful Tropical Rainfall Measuring Mission which for over a year has produced impressive estimates of precipitation from space (Figure 7). This platform flies an active down-looking radar and passive microwave radiometers. The future of remote sensing of precipitation lies in a system wide integration of measurements from various space borne instruments and of ground observations a various types.

Predicting precipitation and floods was our Holy Grail. In some ways it still is, but today it is tempered by something called "chaos theory". In a nutshell, hydrologic phenomena are very non-linear. That means that a small change somewhere can lead to a very large change elsewhere in ways that are not fully foreseeable beyond a certain horizon in the future. So, predictability is very much limited. Figure 8 illustrates the enormous sensitivity on initial conditions of a model predicting precipitation.

Non linearities and feedbacks between states can occur in apparently simple hydrologic systems resulting in unusual, unexpected and unpredictable behavior. Back in my student years, if asked to guess at a representative soil moisture in a region I would argue for the climatic mean. I believed that the probability density function (pdf) of moisture, and most natural hydrologic variables, was a uni-modal function with clear central tendency. Nowadays I now that extremely simple representations of the land-atmosphere interaction leads to bi-modal pdfs of soil moisture, implying that the system has two preferred states and can oscillate between them, the biblical seven years of floods and seven years of drought (Figure 9)!

Back in the early 1970's we saw the land as the passive recipient of the atmospheric forcing, an interaction like the one described previously was never given serious consideration or at best was relegated to others to think about. Today the land masses play an important role in the climate change debate, not only as potential sinks or sources of carbon but as important factors in the physics and thermodynamics of the circulating atmosphere. It is no longer just oceans and atmosphere that matter, so does the land surface. This interaction clearly enhances or inhibits hydroclimatological anomalies like floods or droughts. Figure 10 illustrates that land surface conditions are as important as sea surface temperatures in defining weather and climate over the United States. At the local level, deforestation of relatively small areas of rain forest in the Amazon have the potential of producing mesoscale circulations with resulting impact on cloudiness, radiation and even precipitation (Figure 11).

This land-atmosphere interaction is not only local. We are now familiar with teleconnections triggered by sea surface anomalies like El Niño, but as Figure 12 shows, it is to be expected that large alterations of the land surface will have unpredictable impacts on global circulation and associated mass and energy balances.

Pauline Austin and Robert Houze ( )classified storm events in cells, small mesoscale, large mesoscale and synoptic scales. Indeed this useful taxonomy was the basis of many mathematical formulations for simulating rainfall (ref). As useful as that concept of dominant scales has proven to be, present thinking is that rainfall and other atmospheric phenomena exhibits scaling, that is scale independence, at least over some regimes ( ). Figure 13 illustrates that scale independence. The implications of those results to representations of atmospheric phenomena, to measuring of precipitation and other fields, and to predictabilty are significant. This scaling is suspected in both time and space. Our challenge remains to link such behavior to the dynamics of the atmosphere.

Horton was no stranger to the concept of scaling and self-similarity. His description of the regularity of tree-like geometries has been proven to be consistent with a fractal, or self similar, description of the river basin (Figure 14, Tarboton and Bras, Barbera and Rosso). In fact Horton's classification of channel networks by stream orders, with the smallest tributary basins having order one and with order increasing with aggregation of tributaries dominated the field of fluvial geomorphology until the mid-1980's and it is still used by some. The "Horton numbers" : the bifurcation ratio describing the branching pattern, the length ratio stating the average length of streams are related to order and similarly the area ratio are still common in the literature, although we now know that they are poor discriminators of branching-tree structures, particularly when it comes to river basins.

The beautiful patterns of drainage that river basins form, I was taught, were the product of randomness. I learned a beautiful mathematical theory of topologically random trees (Shreve, 1969). Today we know that the tree-like organization of river basins and drainage results from well enunciated principles of energy expenditure and nature's desire to do its job efficiently. Through these ideas we relate the fractal nature of the basin to underlying physical principles (Figure 15). These principles and other work This is something to keep in mind every time we alter the landscape without heeding those principles. Ultimately nature will prevail: ask those who suffered the 1993 Mississippi floods.

We have learned that the topological, planar, description of the basin is not independent of the third dimension, the relief or energy in the system (Figure 16). We have also learned that the evolution of the river basin, its statistical characterization, is intimately related to the hydrologic processes that form it. Nowadays we have built numerical models that mimic the evolution of the basin. In a sense we can play creator and let our artificial nature evolve an organized structure from disorganized origins (Figure 17). The outcome of our experiments is very much a function of the processes in our artificial nature. Figure 18 shows how radically different basins result from experiments with or without mechanisms for hillslope erosion by landsliding.

Possibly one of the most important concepts we have learned in recent fluvial geomorphology work is that it is futile to think of the river channels independently of the hillslopes that feed them and vice-versa. Channel and hillslope are part of a whole and control and shape one another (Figure 19).

When I learned hydrology vegetation was treated almost as a nuisance term. For example, its effects on land-surface fluxes were lumped into a catch-all evapo-transpiration term, which was in turn crudely parameterized. In the late 1970 and early 1980's Pete Eagleson (ref) suggested the then radical idea that the biosphere, the climate, the hydrology and the soil were in a synergistic waltz trying to reach a point of "ecological optimality" (Figure 20). Hydrologists have certainly woken up to the realization that vegetation affects all we do and cannot be summarily treated. Some of the work in land-atmosphere interactions discussed previously certainly considers vegetation a key element of the analysis. In my opinion, though, we remain woefully ignorant and need to focus more on these issues.

The study of sub-surface flows and transport have been a dominant subject in hydrology over the last 30 years. I will do it injustice by limiting my comments. For one by "short history" is becoming too long and furthermore my own work in the field is far more limited. But do not be misled, advances in the analysis of subsurface flows have been extraordinary both from the science and the applications point of view. Years ago I was led to believe that surface waters like lakes and rivers and groundwaters were practically independent systems, with weak links. Now we know that ignoring the strong links is a recipe for disaster, evident as we seek to preserve the quality and quantity of our water resources.

We believed that disposing of contaminants in the sub-soil was safe, since flow in a homogeneous soil was so slow that contaminants could not possibly move too far. How wrong we were! Today we suffer the consequences of our ignorance with thousands of contaminated sites endangering humans' health and the environment because water does move through preferred high conductivity areas or cracks and fractures in soil and rock. Even Hollywood and John Travolta have discovered that excitement and mystery of the field!

Studies of groundwater hydrology led our forays into the impact of spatially variable medium properties on hydrologic behavior, particularly flow and transport. The work of Dagan, de Marsily, Gelhar and Neumann developed the tools presently used to study heterogeneity in subsurface and other hydrologic systems. The field also led in the solutions of inverse problems and parameter estimation, much of it presently re-appearing in the context of modern assimilation approaches in meteorology and surface hydrology.

I would be remiss if I ended this narrative without mentioning the impact that computers have had in the field. For my bachelor and master theses, I found myself pushing computer technology of the time to the limit. I developed a numerical model of water flow in an urbanized area. The best computer technology of the time took the whole night (and I had to be present!) to run the model. The computer took close to 1000 square feet of space and the instructions were written on cardboard cards (or even paper tape). Today cards are museum pieces; I believe my children have never seen one. The program I developed is surpassed by a 100-fold and available for anybody and it runs in seconds in any desk top personal computer.

Only a few years ago, if I wanted to get the topography of a region, I had to obtain a map on paper and with some luck and a lot of effort digitize it to make it useable in the computer. Today my students go into the worldwide web and practically instantly obtain digitized elevation data of anywhere in the world: no time, no sweat, and practically no cost.

The Next 30 Years

Water and the water environment is quickly becoming a global and political issue, with implications to the security of nations and human health, development and sustainability world-wide. As the science of water Hydrology has a bright and exciting future. But I believe we are at a threshold, one similar to the one I encountered in 1968. A major push is needed and more bright young minds most come into the field to create new paradigms and new knowledge. A group of us (see references), led by my younger colleague, Prof. Dara Entekhabi have produced a document entitled "An Agenda for Land-Surface Hydrology Research and a Call for the Second International Hydrologic Decade" presently available at http:web.mit.edu/darae/WWW/Hydro.html and hopefully in the Bulletin of the American Meteorological Society Bulletin, where it has been submitted for publication.

The time is ripe for a new Hydrologic Decade. The last one, 1965-1975, was a major element in launching the exciting developments that I have summarized previously. It created a revolution of thought. It was the seed on which many of us have tried to build a new science from a mature engineering discipline. The time is ripe because we have identified many avenues of inquiries, because the outstanding questions are important to society and because technology, particularly in computation, communications, and remote sensing is ready and capable to help us through the outstanding obstacles. It is ripe because in the era of interdisciplinarity we are ready and eager to find new partners, to create new alliances and to continue the evolution of new models for the education of the hydrologist of the future. Finally, what could be more exciting than to launch such global effort with a promising new millennium?

The "Agenda" presented is limited to land-surface hydrology, we are confident that complementary documents will come forth to complete our vision of the future. I would like to take the opportunity to summarize the science priority questions that the document poses. I urge you to read the complete document for detail. The science questions are:

- What are the physical mechanisms and process-pathways by which the coupling between surface hydrologic systems and the overlying atmosphere modulate regional weather and climate variability?

- What are the mechanisms and the time-scales of interactions between the formation of terrain, soils, vegetation ecotones, and hydrologic response?
- Are there critical scales at which spatial variations in surface properties should be explicitly represented in models of land-atmosphere exchange?
- Under what conditions can effective parameters be used to represent macroscale hydrologic processes and does the upscaling of microscale processes depend on the process and lead to changes in the form of the governing equations?
- Does lateral soil water redistribution significantly affect large-scale soil-vegetation-atmosphere exchange processes?
- How can the effects of human activity on hydrologic response be distinguished from natural climate variability in a range of physiographic environments?

The Agenda goes onto develop the need for research in monitoring systems and their integration with the science questions and modeling needs. I want to emphasize the requirements for fulfilling the promise of remote sensing that the document identifies:

- Classical ideas and associated existing models that are optimized to function with sparse in situ observations of precipitation accumulation, stream discharge, and surface air micrometeorology should be replaced with reformulated hydrologic models that are forced with spectral observations or retrieved fields of spatial data.
- Hydrologists need to evolve from passive recipients of limited remote-sensing observations to acting as a unified scientific community that is engaged in supporting the definition, design, and implementation of sub-orbital and space-borne instruments.
- Validation data bases (over regions or basins) consisting of in situ and remote sensing measurements need to be established so that instruments and retrieval algorithms may be quantitatively and definitely evaluated.

To Conclude

I hope I have been able to project the excitement, the fast pace, and the importance of hydrology. To me the last 30 years have been extraordinarily rewarding professionally and personally. Let me quote Albert Einstein:

> "A hundred of times every day I remind myself that my inner and outer life are based on the labors of other men [and women', living and dead, and that I must exert myself in order to give in the same measure as I have received and am still receiving".

I have benefited tremendously from my association with MIT and the its Department of Civil and Environmental Engineering. I have been mentored and tutored by giants in the field that are also some of my very personal friends. Drs. Peter Eagleson, Ignacio Rodriguez-Iturbe, and Donald R.F. Harleman: Thank you for everything.

Standing on the shoulders of giants was not enough, I also built, and continue to do so, on the sweat of an extraordinary group of students. They are, after all, my most important professional legacy. I thank them all. (their names are provided with the references)

I want to thank my parents, Amalia and Rafael: What can I say, they gave me all. Last but not least, I am blessed with a wonderful partner and friend, Pat, and two absolutely wonderful children: Rafael and Alejandro. Frankly, after them the rest is icing on the cake. Thank you.