What Is a Hydrologist?

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For the first time in the history of the Athalie Richardson Irvine Clarke Prize, a hydrologist is being honored. In the name of my many colleagues, I thank you. I cannot help remembering an incident that occurred as my family returned from a year sabbatical in 1983. A not-so-friendly immigration officer in New York detained us for over 40 minutes, wondering what had we done over the past 12 months, suspicious of the trips to China, Europe, and South America. I patiently explained that I was a 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?" Right then, I decided to write my *Introduction to Hydrology* textbook!

As I said, for the first time, the Clarke Prize is going to a hydrologist. I am taking no chances! I will describe for you what is one of the most exciting, important, and fastest changing earth sciences.

Early thinkers and philosophers did not understand three basic hydrologic principles:

- Conservation of mass.
- Evaporation and condensation.
- 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," and surfaced as streamflow. The underground reservoirs were replenished by the sea.

As one of the leading hydrologists in the world, Dr. Bras has maintained an international consulting practice devoted to projects like radioactive waste removal. One of his greatest innovations was uniting hydrology with probability and statistics to improve forecasting and risk estimation; his rainfall models have significantly advanced river-flow forecasting and flood estimation. Other areas of groundbreaking research include irrigation control, urban storm water management, and water allocation. He is the author of two hydrology textbooks and has published over 100 papers.

At the Massachusetts Institute of Technology (MIT), Dr. Bras is the Bacardi and Stockholm Water Foundations Professor and head of the Civil Engineering and Environmental Department. He is also Associate Director of the Center of Global Change Science at MIT. Dr. Bras was also Assistant Professor at the University of Puerto Rico, and has held visiting appointments at Universidad Simon Bolivar (Venezuela), the International Institute for Applied Systems Analysis (Austria), and the University of Iowa.

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 and Horton initiated a more theoretical, quantitative approach. Sherman's unit hydrograph concept still remains with us as one of the most successful conceptualizations of river-basin behavior. Horton's ideas on infiltration, soil-moisture accounting, and runoff are still recognized by present-day hydrologists.

By the time I arrived on the scene, as a student in 1968, the knowledge base of hydrology was thought to be well developed. I was taught that surface runoff occurred when the intensity of rainfall exceeded the capacity of the soil to absorb it. Wrong! Now we know that other mechanisms exist; in fact, what I was taught practically never occurs in parts of the world.

I was led to believe that surface waters (like lakes and rivers) and groundwaters were practically independent systems, with weak links. Wrong again; 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.

Everything I ever did as a student was predicated on the idea that we could represent hydrologic properties like the ability of the soil to transfer water or inputs like the rainfall as spatially uniform quantities. Now we know that the variability in space and time of these and other quantities is so large that, in many cases, it is the most important element of the analysis.

Driven by the above belief in uniformity, hydrologists were happy with one rain-gauge every 2,000- to 10,000-square kilometers (km^2) over the United States. It looked strange then; it looks stupid now. Today, meteorological radar measures rainfall at resolutions of 2 km^2 all over the country, and sometimes that is not enough!

During my years as a student, society believed that disposing of contaminants in the subsoil 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 human health and the environment. We now know water does move through preferred high conductivity areas (or cracks and fractures) in soil and rock.

The hydrologic cycle is indeed massive, with hundreds of thousands of cubic kilometers of water exchanged every year between the atmosphere, oceans, and land masses. But it is a very sensitive, complicated, and fragile system, particularly relative to human needs. Only about three-tenths of a percent of all water is fresh and found in rivers and lake sources.

I was taught that the beautiful drainage patterns that river basins form were the product of randomness. I learned a beautiful mathematical theory of topologically random trees. Today, I 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. 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.

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 foreseeable beyond a certain horizon into the future. So predictability is very much limited.

For my bachelor and master theses, I found myself pushing the 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 1,000-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 and available for anybody, and it runs in seconds in any desktop 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 almost instantly obtain digitized elevation data of anywhere in the world: no time, no sweat, and practically no cost.

As a student, I was concerned only with local problems. My largest unit of study was the river basin and, for that matter, fairly small basins. I saw hydrology as a passive system driven by atmospheric input, precipitation, and evaporation. Again, we were very wrong. Today, my students learn that the atmosphere and the land masses are hydrologically linked. If I change the land surface, say by deforesting the Amazon basin, I will change the atmospheric circulations, the weather, and the climate of the region and the world. The land and the oceans are also linked. Freshwater from rivers play a crucial role in controlling ocean currents. The ocean and its currents, in turn, are key to world climate.

During my student years, men were walking on the moon, but we knew practically nothing of precipitation and weather over 70 percent of the planet, the oceans. Today, we have satellites that help us track hurricanes and are actively measuring precipitation, at 4-km^2 resolution, from space!

By now you may be asking yourselves: What did they teach him at the Massachusetts Institute of Technology (MIT) that was right? In a sense, nothing. All I do today I have learned since graduation. That to me is exciting! I did learn, very well, the concept of the hydrologic cycle. The concept is simply that water changes states and is transported in a reasonably closed system: the earth and the atmosphere. The cycle is closed only earthwide, each drop of water following a path from the ocean, to the atmosphere, back to the ocean or to the earth, where it moves back to the atmosphere or the ocean or remains in storage. Energy to keep this cycle going is provided by the sun. Processes involved include evaporation, condensation, precipitation, infiltration, and runoff.

I have learned that in a not too far-fetched analogy, water is the life blood and the lymphatic fluid of Earth. Globally, water mediates energy and mass transfers; it is largely responsible for global weather and climate; it carries waste and controls its degradation. Like our circulatory system, the hydrologic cycle moves water throughout the body: earth. The hydrologic cycle is an exquisitely intertwined and balanced interaction between atmosphere, oceans, and land to move mass and energy to where they are needed and to regulate the earth's temperature. Most solar energy is received in the tropics. The atmosphere responds with a very active cycle of evaporation and condensation. Evaporated water, largely from the tropical oceans, carries energy, which is transferred by atmospheric circulation to temperate regions where it is commonly released via condensation and precipitation. At the same time, warm tropical ocean currents move vast amounts of energy towards the energy poor poles. Water vapor, the most effective greenhouse gas, also regulates the Earth's temperature.

The hydrologic cycle is indeed massive, with hundreds of thousands of cubic kilometers of water exchanged every year between the atmosphere, oceans, and land masses. But it is a very sensitive, complicated, and fragile system, particularly relative to human needs. Only about three-tenths of a percent of all water is fresh and found in rivers and lake sources. That is, in fact, a lot of water, but its distribution is not coincident with the location of population needs. Atmospheric water vapor, which in many ways serves as our servomechanism of global temperature control, is recycled every 9 to 10 days. Any significant change in the nature of this very active element of the cycle will have a major impact on climate. Our activities over land have the potential to create major changes.

I hope I have been able to project the excitement, the fast pace, and the importance of hydrology. Let me end by quoting Albert Einstein:

"A hundred 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 who are also some of my very personal friends. Drs. Peter Eagleson, Ignacio Rodriguez-Iturbe, and Donald R.F. Harleman: Thank you for everything. 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, my wife, Pat, and two absolutely wonderful children: Rafael and Alejandro. Frankly, after them, the rest is icing on the cake.

Thank you.