The hydrologic cycle: a complex history with continuing pedagogical implications

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Abstract Historical papers relating to water often focus on a physical structure or archaeological artefact that is being investigated in order to achieve insight into the life, times or understanding of a historical culture or people. In this sense, the current paper is an anomaly in that the "artefact" motivating this historical review of the hydrological cycle was observed first in the classroom. More specifically, many years of teaching hydrology has highlighted the difficulty students often have in achieving a broad and deep understanding of hydrological processes. Several reasons could be proposed for the observed pedagogical difficulties, but what is of interest here is that a student's struggles are reminiscent of the historical ones relating to first deducing the hydrological cycle. Thus, a novel hypothesis is tentatively advanced: concepts that were tortuous or taxing to deduce historically often, and for quite similar reasons, are challenging to teach, and vice versa. While a comprehensive psychological exploration of this observation is beyond the scope of this article, a few broader connections are briefly explored.

Keywords History; hydrologic cycle; hydrologic processes; knowledge structures; learning strategies

Introduction

There is an inevitable historical component to learning: new understanding is never disembodied, but is built firmly on existing ideas and concepts. Mastery is established like a sequence of archaeological layers, with each new stratum laid on previous layers and supporting subsequent ones. Certainly there is an undeniable complexity to both learning and archaeology, for older layers are often reworked and then incorporated in ways defying tidy explanation. In this light, the current paper, limited by space constraints, imposes a pattern that is too simple and linear to elucidate the intricacy of either psychology or history. Yet, teaching experience continually suggests that many ideas that were difficult to establish historically remain challenging to teach, while difficult-to-teach subjects often turn out, on later examination, to have tortuous historical roots.

Perhaps there is no great surprise in this. Our brains were no doubt attuned over countless years to attend to certain consequences and relations, and to relegate others to subordinate positions. Our intuitive understanding of cause and effect has possibly changed less in the last 10,000 years than we might like to believe. Certainly, teachers of subjects like quantum mechanics or wave-particle duality sometimes despair that our common sense seems to have almost no rapport with the strange quantum world that is far removed from our day-to-day experience. Moreover, subtle mathematical ideas, like concepts of limits and convergence, are often found difficult by many students, and these same concepts caused many ancients to flounder in vexing conundrums, including Zeno's well known paradoxes. But how does all this relate to something as basic as hydrology?

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The hydrologic cycle

The global hydrological cycle is the set of processes that continually move water over and through the surface of the earth and both into and through the atmosphere. The cycle includes the evaporation of water from the land and oceans, the circulation of the atmosphere, the condensation of vapour into liquid, the formation of rainfall, the complex partition of precipitated water into surface and subsurface flow, the role of depression and detention storage, and the role of interception and stem flow. Such processes involve not only water and classical dynamics, but also thermodynamics, meteorology, chemistry, geology, oceanography and cosmology.

Consider first just one component, the apparently simple idea of “evaporation” from the oceans, and the traditional “start” of the hydrologic cycle. But what exactly is evaporation? We now know evaporation involves a phase change whose huge energy requirements originate primarily from the sun. High-energy solar photons impact and excite water molecules so that some achieve high enough velocities to escape the hydrogen bonds of the liquid state. Evaporation is a largely invisible process, whose mastery requires a subtle set of concepts, including conservation of molecular species, atomic theory, diffusion and transport, relative humidity, and temperature effects. Simply measuring something like evaporation is not a trivial challenge. How many modern students could propose a viable device for measuring global ocean evaporation? Without a great deal of support or training, the challenge might feel somewhat indeterminate, rather like the product of “an infinity of space” with a “vanishing of depth.” But, as humans gradually came to discover, the resolution of any indeterminacy can result in almost any value, depending on the details of the limiting process. But it is exactly in specifying such details that the global problem lies.

Taken together, it is not surprising that our current hydrological understanding was achieved slowly and painstakingly, with many false steps. If one imagines a modern undergrad being transported, equipped with a modern hydrological explanation, to the past, they’d be more likely to be met with ridicule and laughter than ready acceptance! And for them to prove the modern explanation in an ancient context, without practical and conceptual support, would not be easy.

Yet we can’t stop here. The hydrologic cycle is no less complex when it occurs at the level of a local watershed. Consider that the precipitation may be partially intercepted by vegetation or other structures and then later “removed” through evaporation. Water reaching the ground can be infiltrated, some of which later transpires while the remainder is either stored or slowly percolates through the subsurface. Such flows comprise the baseflow of rivers and streams. Ponding occurs when the rate of precipitation exceeds that of evaporation and infiltration and as depressions are filled, overland flow begins. This process is much quicker than its subsurface counterpart, usually forming the majority of streamflow during a rainfall event. Streams eventually find their way to bodies of water where evaporation returns water to the atmosphere, but at each stage conceptual complications, temporal delays, adjustments and hidden (e.g., groundwater) exchanges often occur.

Given all this it is not surprising that the discovery of the hydrologic cycle was infuriatingly slow. Although various hypotheses were proposed over time, development was highly constrained until well into the 16th century when Bernard Palissy finally integrated the various components into a coherent theory. Progress required coordination and integration of various abilities or “senses”:

(a) a sense of conservation – water molecules change phase, but remain as water;

(b) a sense of magnitude or quantification – to evaluate the relative contribution of terms; and a sense of time – virtually all the processes are unsteady, changing rapidly or slowly in time.

Though, say, the conservation of water perhaps seems trivial today, there are good reasons why this concept was elusive. Moreover, quantification of unsteady processes inevitably requires careful and sustained measurements along with excellent record keeping and analysis.

Consider the now obvious fact that streamflow ultimately originates from precipitation. Yet is it obvious water is conserved? There is certainly not a one-to-one relationship between rainfall and runoff. Two common observations greatly obscure the concept of conservation:

(a) The volume of streamflow is less than the volume of precipitation – so we must learn how to compute a complex set of "losses" or abstractions, terms that feel to many students even today like a poorly fitting patch on a bad job.

(b) Streams continue to flow even without recent rainfall – thus, much of the runoff water is not associated with the current rain, but with slow, and mostly invisible, subsurface processes. This reality requires more patches and more arm waving, otherwise known as "baseflow separation techniques." In fact, even today, it is not trivial to quantify or precisely separate surface from subsurface contributions to stream flow.

Thus, apparently obscure and difficult theories of evaporation losses and baseflow are necessary to complete the concept of conservation of water, even at the watershed scale. Humans tend to mistrust such long chains of cause and effect, wanting simpler and more emotionally satisfying explanations.

A sense of magnitude was also important to the development of hydrology. The contribution of infiltration to groundwater flow and groundwater flow to baseflow was long ignored because their role "seemed" insignificant. However infiltration over a large catchment can provide a significant volume of water to the subsurface; another computation leading to an apparent "zero-infinity" indeterminacy. Yet, quantification was critical if strict conservation was to be established. Ideas that appear fanciful today flourished without measurements to disprove them and modern understanding only gained acceptance when verified through experimentation (Adams, 1938). Thus hydrological understanding owes much to the development of time-keeping devices that made possible the precise measurement of dynamic parameters, not to mention subtle probes and devices to pick up vanishingly small changes.

Palissy's work helped remove various conceptual blocks. Subsequent experimentation led to (excuse the expression) a flood of material concerning the topic of the hydrologic cycle. Yet although relatively well understood, the hydrologic cycle in important ways can continue to challenge scientists and to confound students, at least at the level of application and prediction. Even if, for example, a consensus is eventually achieved about the basic mechanisms of global climate change, the implications of these events to the hydrological cycle are likely to remain vexing and controversial for some time.

Difficulties in discovering the hydrologic cycle

Early and classical ages

One of the earliest civilizations that dealt with the notion of the hydrologic cycle was the Chinese. The role of precipitation was discussed in several works from about the 9th century BC, while the dynamic concept of the hydrologic processes was recognized by the late 4th century or so (Ven Te Chow, 1976). Yet the most common explanation even up to the Middle Ages in Europe was based on the belief that all rivers issued from one or more subsurface caverns or lakes. The first known written evidence of this opinion is found in Homer's *Iliad*: 'the mighty deep-circling Oceanus, stream from whom all seas and rivers rise, all springs and bottomless wells' (Homer, 1977, p. 429).

The Ionic philosopher Anaximenes (585–525 BC) studied meteorological phenomena and presented reasonable explanations for the formation of clouds, hail and snow, and the cause of winds and rainbow. In the 5th century BC, the Pythagorean philosopher Hippon recognized that all waters originate from the sea (Koutsoyiannis and Angelakis, 2003, p. 2). At the same time, Anaxagoras (500-428 BC) and Plato (429-347 BC) were based on Homer's poetical view and developed erroneous theories, claiming again that a huge cavern inside the earth supplied all fluvial water.

Aristotle (384-323 BC), by contrast, correctly articulated the need for a continuous process. In *Meteorologica* Aristotle rejects the assumption of one large reservoir arguing that, if this were the case, it would have to be 'larger than the earth, or, at any rate, not much smaller' (Aristotle, 1984, p. 570). He was one of first to articulate the notion of a cycle for the hydrologic processes, by observing natural processes such as sunrise, and one of the first to relate not only water, air and the sun, but the phenomena of rainfall, evaporation and condensation; all these things he explained in a simplified yet innovative way. However, although his explanations were often reasonable, he found it impossible to believe that it was rain alone that fed the springs and supplied the rivers and he struggled with the difficult question of how streams can continue to flow for many weeks in the absence of rain (Deming, 2005).

The general understanding during the Roman Age is summarized by the philosopher and dramatist Seneca (3 BC-AD 65), who also considered rainfall inadequate to supply all rivers and springs:

> Rainfall may cause a torrent, but it cannot maintain the constant flow of a river. Rains cannot produce; they can only enlarge and quicken a river. (Adams, 1938, p. 431)

Seneca recognized the significant role of evaporation and believed that the co-existence of air and water is the main force that directs water to flow out of the earth and to form springs and rivers.

Marcus Vitruvius (1st century BC), a crucially important Roman writer, scientist and engineer, in his book *De Architectura* provided an explanation of precipitation and the processes that led to the formation of springs in the mountains based on evaporation mechanisms and landscape. Vitruvius's explanations are much closer to what is accepted today.

Middle ages and renaissance

Between the 1st and the 17th century AD most sciences were relatively inactive. Little attention was directed to the hydrologic cycle and the theory of the large subterranean reservoirs was prominent. However, the coming of the Middle Ages brought the subject again to the surface and new approaches were gradually developed. Historically the strongest intellectual influence was the teaching of the Christian church. The Bible was the main, if not the only, reference for most scientific reasoning. According to the book of Ecclesiastes the ocean was the source of all rivers and springs: "All rivers run into the sea, yet the sea is not full: unto the place from which the rivers come, thither they return again." Their conceptual model was built (correctly) on a cyclic understanding of the hydrologic cycle; however, its standard interpretation incorrectly assumed that the cyclic process was facilitated through holes in the sea bottom. Since most scholars were connected with the church, this belief was tiresomely quoted throughout the medieval period (Adams, 1938, p. 432).

A famous scholar of that age was the German Jesuit Athanasius Kircher (1602-1680), who dealt with the hydrologic cycle in his 1664 book, *Mundus Subterraneus*. According to his view, the earth's interior was penetrated by numerous subterranean passages that led water into great reservoirs within the mountains and then supply it to the surface as springs (Figure 1). *Mundus Subterraneus* is indicative of the medieval difficulty of perceiving the temporal discontinuity between rainfall and river flow, and why precipitation was discounted as a key source of river water.

Another explanation for the hydrologic cycle was provided by the theory of Alembics, which was first set forth in J. J. Becher's (1635-1682) book *Chemisches Laboratorium*. According to his observations, the earth resembles a giant alembic or distillation apparatus. The seawater that passes from the ocean bottom into the earth is heated by the underground fire and is vaporized. On its way to the surface, it easily enters the cavernous interior of the mountains. Since the mountains are covered with snow the temperature is significantly lower and therefore the vapor condenses to water, which forms springs that run down the mountain slopes and end again in the sea.

Two significant contradictions revealed the shortcomings of such theories:

a. The assumption that water rises up from the sea level to the mountains is against its nature, since it normally follows the reverse route, moving from high to low elevations.
b. If the ocean is connected with the mountains, then the fact that the water of the sea is salty, while the water of the rivers and the springs is fresh is a contradiction.

The efforts to address these issues were a mixture of arbitrary hypotheses, speculations and religious beliefs, generally lacking a scientific and observational basis. For example, several theories were developed claiming that the surface of the Ocean is higher than the Land, and therefore the movement of water to the mountains is reasonable; or that the reverse movement is in obedience to "the word of God"; or that fire from the earth's interior heats the groundwater and causes its evaporation to the surface. The change of salt water to fresh during its motion was often falsely attributed to "filtering" as water passed through geological layers of low porosity.

The Early Modern Ages and the elucidation of the hydrologic cycle

One of the first correct explanations of the hydrologic cycle was proposed by the Italian polymath Leonardo da Vinci (1452-1520), who recognized the role of pervious hydrogeological structures, especially those having a great slope and lying on impervious layers. Rain and melting snow from the top of mountain ranges can infiltrate through pervious

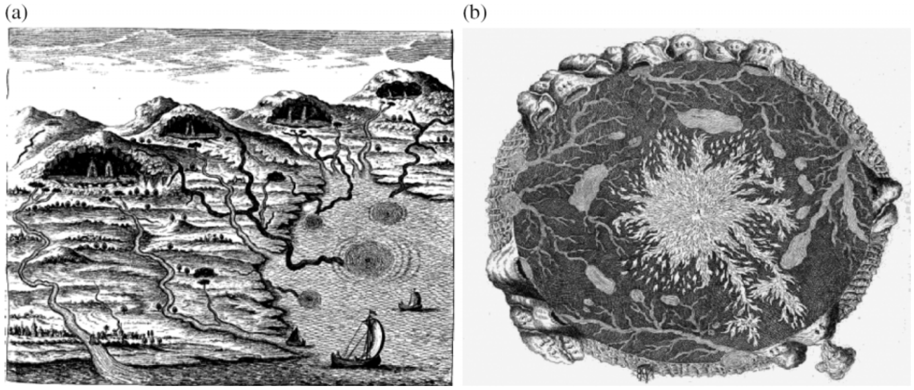

Figure 1 (a) The whirlpools in the sea represent the spots of the holes at the sea bottom from where water is transferred through passages to hydrophylacia (middle and top of the picture) within the mountains. (b) The complex of the subterranean passages described by Kircher (from http://kircher.stanford.edu/)

beds and then be carried for long distances below the surface, finally flowing out again either as springs or into the sea.

However, an integrated theory for the hydrologic cycle and a scientific explanation was at last provided in France by Bernard Palissy (c. 1510-1590). In his 1580 book *Admirable Discourses*, Palissy deftly cut through previous misunderstandings using sound arguments, stating convincingly that rain and melting snow were the only source from which springs and rivers derived their waters:

> When I had long and closely examined the source of the springs of natural fountains, and the place whence they could come, I finally understood that they could not come from or be produced by anything but rains. (Palissy, 1957, p. 48)

Palissy thoroughly defined the cyclical course of water, the role of processes such as precipitation, evaporation, condensation, infiltration, surface run-off and both groundwater storage and discharge.

Another interesting aspect of Palissy's work, indicative of his deep understanding of nature, is his sound explanation of the temporal discontinuity between rainfall and river flow, with which scholars from Aristotle to Kircher, had struggled:

> (…) rain water that falls on mountains, lands, and all places that slope towards rivers or fountains, do not get to them so very quickly. For if it were so, all fountains would go dry in summer: but because the waters that fell on the land in winter cannot flow quickly, but sink little by little until they have found the ground floored by something, and when they have found rock they follow its slope, going into the rivers. From this it follows that under these rivers there are many continual springs, and in this way, not being able to flow except little by little, all springs are fed from the end of one winter to the next. (Palissy, 1957, p. 68)

In the following years, as science gradually moved towards better understanding, numerous scholars examined the topic in depth. In 1674 Pierre Perrault presented his experimental efforts to quantify the hydrologic cycle. In his book *De l' Origine des Fontaines*, he considered a certain catchment area, calculated the average rainfall which fell upon the area using a rain gauge and then measured the amount of water passing through a certain canal. According to his findings, the ratio of the volume of rain to river flow was 6 to 1, proving that rainfall is more than adequate to supply springs and rivers; in fact, more than precipitation and run-off were required to complete the hydrologic budget. A similar experiment was carried out a few years later by the French physicist and priest Edme Mariotte (c.1620-1684) and provided an even greater ratio of approximately 8 to 1 (Adams, 1938).

The next significant step was taken by the Italian medical scientist and naturalist Antonio Vallisnieri (1661-1730), who spent long periods in the Alps considering the creation of springs and rivers. His greatest finding is the notion of infiltration. He observed that although the snowfields of Monte S. Pellegrino were extensive, the rivers near Modena were small and weak. A careful observation revealed that water produced by melting snow was flowing down from pervious layers below the earth surface and followed an invisible underground route for a long distance beneath Modena towards Bologna. As a result, the subterranean passages that were discussed during the Middle Ages existed, but their role was not to carry either seawater or fire from the ocean upwards to the mountain tops, but simply and quietly to transfer water down gradient (Adams, 1938). Thus, it was really only by 1715 or so that humanity finally achieved a complete picture of the hydrologic cycle.

In the decades that followed, the correct theory regarding the hydrologic cycle – based as it was on careful observation, experiment and quantification – gradually gained recognition. Nevertheless, traditional explanations, often supported by religious arguments, still received some support; indeed, many scientists, including Vallisnieri, were considered heretics. In fact, the true theory was not widely or broadly accepted until as late as the middle of the 18th century.

Difficulties in teaching the hydrologic cycle

Many academics have observed that hydrology can be difficult to teach. Although some students typically grasp all concepts well, many struggle with the relationships between hydrologic components, finding concepts of baseflow, abstractions, hydrographs, and cycles of storage and release counter-intuitive and confusing at the detailed level of calculation and application.

The difficulty for students to grasp the hydrologic cycle can perhaps partly be explained by recognizing that there are two parallel forms or learning (Vanderburg, 2000):

(a) knowledge embedded in experience (KEE) and
(b) knowledge separated from experience (KSE).

KEE is gained through direct experience and daily-life activities and is at work when, say, a child learns to speak. A functional grammatical understanding is learned informally and embodied in experience and memory. By contrast, KSE is gained primarily through school-based or book learning. These two forms of learning remain distinct as can be seen whenever a student recognizes a grammatical mistake without knowing what specific rule is being broken.

Prior to taking a course in hydrology, a student develops intuitive knowledge about the physical world through daily-life experiences. Rainfall intensity is felt when walking in a storm and an understanding of interception is displayed by running under a tree for shelter. This “intuitive physics” is developed by interacting with the world from the outside in (Vanderburg, 2005). Yet, many modern students have scant experience with rainfall or runoff, quite in contrast to students with, say, a farming or rural background. Yet direct experience is not complete or well suited to the challenges of hidden or invisible processes with long time delays.

Hydrology courses too often maroon a student in a mathematically abstract world. This artificial world contrasts to the “real world” because mathematical expressions cannot be experienced (Vanderburg, 2005). Furthermore simplifying assumptions dilute reality to a point where a student cannot recognize the physical world an equation approximates. Even basic concepts, such as the fact that runoff can continue to increase after a storm, are often surprising and confusing to students who have not experienced this reality, and who perhaps have been overly influenced by an instant gratification paradigm. Thus, the KEE and KSE worlds are not just separate as they usually are, but actually in conflict, without crossover of ideas or intellectual reassurance.

A typical confusion might arise when determining what components of the hydrologic cycle to include under various circumstances, such as when to ignore groundwater flow or evaporation in the analysis of runoff. Experience with a backyard garden can guide a student in choosing to water plants a bit more on bright days because the plants almost dried out on the last sunny day. However, mathematical expressions divorced from context cannot guide a student in determining when certain terms become important or what kind of accuracy is reasonable to expect or require.

Hubert Dreyfus in his book *What Computers Still Can't Do* (1994) gives insight to this problem. Daily experiences develop assumptions of the world that are stored in the metaconscious. These assumptions form the background of perception and help interpret new information and current experiences. The metaconscious makes decision making efficient by focusing the conscious on a narrowed set of relevant choices based on past experiences. On the other hand, mathematical equations, devoid of context, must treat all relationships as possibly relevant (Dreyfus, 1994). Without physical experience to guide and with no direction from equations, students are usually confused and overwhelmed by the information that needs processing.

Links between historical and teaching difficulties

The slow development of the current understanding of the hydrologic cycle and the difficulty of modern students to grasp the concepts is by no means a coincidence. Both problems are linked (literally and metaphorically) by what occurs under the surface. For ancient civilizations the phrase "what occurs under the surface" referred to a component hidden from human observation. Temporal and spatial variations in the subsurface further removed this component of the hydrologic cycle from their experience. The ancients resorted to what Kahneman and Tversky (1982) might term their "perceptual best bet." Visual experience of above ground phenomena almost certainly shaped their expectation of the hidden processes. History overflows with related examples. Aristotle argued that groundwater formed from the condensation of air to water in the coldness of the earth much like above ground air condensed into water (McCulloch and Robinson, 1993). In the 17th century Athanasius Kircher proposed that the earth was crisscrossed with passageways in the same way the human body comprises a network of veins and arteries (Adams, 1938). These misunderstandings are congruent with Vanderburg's analysis of knowledge embedded in experience (2005). Such knowledge is limited when what can be experienced does not co-relate well with what is happening and when outcomes are the result of gradual processes.

Since KEE was insufficient to advance the field of hydrology, science and experimentation (KSE) were needed to determine "what happens when it rains." This body of knowledge still challenges modern students. Students and others are deeply guided by KEE but their intuition can conflict with the logic of mathematical expressions. This is one reason why laboratories and practical component of courses are integral to the development of a strong and integrated understanding. Practical work also encourages students to gain visual and physical experience and to correlate "reality" to the abstract and often context-less world of theory.

Conclusions

Hydrology and hydraulics, like all human knowledge, inevitably enfold cultural understanding. The historical review shows how human understanding, influenced by the conditions of each age, may have been grounded by direct observation of the natural phenomena, but was also strongly influenced by speculation and human creativity, often mixed with mythology, literary and religious considerations. What makes such flights of imagination so understandable is that large components of the hydrologic cycle, including groundwater flow and evaporation, are essentially invisible, possibly spatially distributed over large areas, and sometimes significantly delayed in time. The net result is that a full understanding and wide acceptance was achieved no earlier than three centuries ago, when humanity finally managed to obtain sufficient background and quantitative data to establish a correct and complete explanation.

A somewhat analogous process takes place in a classroom, where students struggle with the various hydrologic concepts and try to obtain a sense of time and magnitude in order to translate experience into knowledge. Systematic knowledge, as an outcome of a long and often mathematically intensive procedure, needs the contribution of intuition, while experience alone can disorient a student, or even a researcher, when it lacks a sound scientific basis or a holistic sense of system behaviour.

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