The terrestrial hydrologic cycle: an historical sense of balance

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In this article, I explore the evolving historical views of the terrestrial hydrologic cycle through a lens that might be called ‘a model of balance.’ The notion of balance in western literature, seems to me to capture a central theme for how scholars of natural history, medieval mathematicians, designers of scientific instruments, and early waterworks engineers viewed the complexities and evaluated the evidence for how water moves in the terrestrial landscape. Using historical images and text, this study attempts to document how we arrived at the modern interpretation, its sources, origins, and relationships within the terrestrial earth. By comparing ancient models for the hydrologic cycle one can begin to construct a plausible story of its evolution as well as the important actors. I pay particular attention to the origins and sources of springs, rivers, and groundwater, the kinds of evidence proposed, and its relation to the sense of balance that emerges. Finally, I argue that at by the end of the 18th and into the early 19th century, the modern view of the terrestrial hydrologic cycle that emerged became a necessary foundation for the geophysical, ecological, and cultural Earth science themes that still flourish today. © 2017 The Authors. WIREs Water published by Wiley Periodicals, Inc.

INTRODUCTION

Today scientists have come to understand that the hydrologic cycle is a complex system with many interacting states, mostly unmeasured; and that these states drive the circulation of water within and among the ocean, atmosphere, land, soil, organic life, and the uppermost layer of the terrestrial earth. This complexity operates over many time- and space scales ranging from raindrops falling to earth to the slow wearing down and emergence of grand landscapes carved by water. In reality, the hydrologic cycle is hardly a cycle at all, because its revolutions are tied to other cycles, quasi-cycles, and random events of the earth system, including orbital earth and solar cycles, regular and irregular oscillations of the ocean–land–atmosphere climate system, and the organization of living things that utilize water in all its phases. In this study, I attempt to explore the evolving historical views of the terrestrial hydrologic cycle through a lens referred to as ‘a model of balance.’ The notion of balance in western literature, as proposed by Joel Kaye1 seems to me to capture a central theme for how scholars of natural history and early waterworks engineers viewed the complexities of the hydrologic cycle, its sources, origins, and relationships within the terrestrial earth; and further suggests that this sense of balance may have been an early foundation for the eventual discovery and application of mechanical laws to Earth system science.

Using a selection of historical texts and images, I attempt to document the changing views of the terrestrial hydrologic cycle, and how these views may have been used to unravel this complex system over time. Along the way, I pay particular attention to the origins and sources of springs, rivers, and groundwater, and their relation to the sense of balance that emerges. As a scientist, teacher, and water resource engineer, no attempt is made here to construct a
The geographer Yi-Fu Tuan's comprehensive history of the hydrologic cycle, a subject for historians, but rather to follow a thread that has for me created a plausible way to explain to students of hydrologic science how we may have arrived at our current thinking. I draw heavily from several modern authors who have provided different historical interpretations useful here. Asit Biswas and the History of Hydrology still offers one of the most complete chronologies of hydrologic science. The geographer Yi-Fu Tuan's The Hydrologic Cycle and the Wisdom of God, 3 explores the history of the idea of the hydrologic cycle, as it relates to the ‘philosophical, theological, and literary roots of the concept.’ Wilfried Brusaert’s 4, 5 historical perspective on the water cycle is especially important to the story of evaporation and transpiration. Joel Kaye’s A History of Balance, 1250–1375, 1 provides the fundamental theme of balance and its origins. Frank Adams’ The Birth and Development of the Geological Sciences, 6, James Dooge’s paper on the history of the hydrolcic cycle, 7 and Andre Guillerme’s The Age of Water, 8 and the historical development of urban waterworks in the basin of Paris, are all important references. I have also used original sources as they were available to me through my own collection and the recent trend in open electronic media.

THE TERRESTRIAL HYDROLOGIC CYCLE AS A MODEL OF BALANCE

For most of the 20th century, accumulation of knowledge of the water cycle developed along disciplinary lines of inquiry, where the atmosphere, ocean, and terrestrial elements represented distinct specialties with a loosely shared scientific vision; where mathematics, mechanics, and technology of measurements and calculation, provided the tools for discovery and innovation. Fundamental to these advances were the discoveries of conservation laws in mechanics that laid the groundwork for present day role of water in Earth system sciences. Historically, many authors used the hydrologic cycle as a metaphor to explain or test contemporary theories and experiments as the field of mechanics developed during the 15th to 18th century renaissance. 9 In Joel Kaye’s A History of Balance, 1250–1375, 1 he makes the proposal that there was an earlier revolution in thinking during the 13th and 14th centuries of the medieval period when natural philosophy embraced what he refers to as ‘a sense of balance.’ In Kaye’s view, the new notion of balance was central to scholastic writing in disciplines of law, economics, medicine, mathematics, and natural history, even though the term balance or a sense of balance (aequalitas) was rarely stated explicitly. Balance was simply a ‘way of seeing,’ where objects and quantities in space and time were ordered and organized in natural ways constrained by logic, often authorized by divinity and most often motivated by practice. Kaye makes the claim that this new sense of balance was not an abstraction or idealized representation, but rather a concrete sense of the interaction of processes that might form the balance. By making the claim that balance has a history, he suggests how it may have laid the groundwork for later scientific discoveries of formal conservation laws in the 16th through the 19th centuries, as the balance of force, mass, and energy became mathematical. It is interesting to note that the famous physicist and philosopher Ernst Mach (1838–1916) in his treatise History and Root of the Principle of Conservation of Energy made a similar argument that followed from the theorem for conservation of mechanical energy (work) written in two parts (Ref 9, p. 19):

\[
\frac{1}{2} \sum m v^2 - \frac{1}{2} \sum m v_0^2 = \int (Xdx + Ydy + Zdz).
\]

1. It is impossible to create work out of nothing, or to construct a perpetuum mobile.

The first part of the theorem states the mechanics: the change in kinetic energy is balanced by the potential energy of the relative positions of the particles; while the second part is a generalization: the impossibility to do work indefinitely without an energy source. According to Mach, the second part of the theorem is ‘incomparably’ more general and has deeper roots in earlier natural history. In fact, Mach considers that (2) is a ‘foundation for some of the most important extensions of the physical sciences’ (p. 20). He describes these historical roots with examples such as:

Galileo, as we know, recognized the truth of the principle [2] in consideration of simple machines, and also deduced the laws of equilibrium of liquids (hydrostatic balance) from it.

He gives examples from the work of Huygens, Torricelli, Stevinus, Lagrange, and others, and finally complains without hyperbole: ‘The whole of mechanics is based upon the idea [2], which, though
unequivocal, is yet unwonted and not coequal with the other principles and axioms of mechanics’ (p. 32). The important point for the present paper is that something preceded mechanics, namely an implicit sense of balance as a frame on which we might comprehend the changing historical views of the physical world.

Using a selection of historical images and text that focus on evidence for the origin of springs, streams, rivers, and their sources allows me to illustrate how a sense of balance was necessary for the discovery and application of local conservation laws later in this period. I note the important role that images play in this story, with a quote by John Berger from his book A Way of Seeing:

Seeing comes before words. The child looks and recognizes before it can speak. But there is also another sense in which seeing comes before words. It is seeing which establishes our place in the surrounding world ... the relation between what we see and what we know is never settled.

At the outset, it is important to establish the possibilities for the hydrologic cycle as a model of balance. Yi-Fu Tuan and James Dooge suggest that there were at least three principal models that emerged over time. These are illustrated in Figure 1. First and the earliest is the ‘reverse hydrologic cycle,’ where springs and rivers are formed exclusively by a subsurface connection to the sea, and where it was understood that precipitation may have been adequate to support water for trees and plants but was not sufficient to explain the origin of springs and rivers. In this model, the vertical exchange of precipitation and evaporation is separate from the subsurface where the sea is the ultimate source with various ideas of how water might ascend from the abyss to form springs and rivers. Second, there is the ‘vertical hydrologic cycle’ which refutes the sea source for springs and rivers but argues that rainfall and atmospheric water vapor were responsible for both the necessary water to supply plants and living things and to provide an excess that was sufficient to explain springs and ultimately rivers without an explicit need for water from the abyss. The third is a more or less ‘modern view’ that illustrates how we understand the hydrologic cycle today where groundwater and vegetation are integral components of the terrestrial hydrologic cycle, an idea which, it turns out, was also held to various degrees by some of the ancient scholars as well.

It is interesting that more often than not, the ancient writers’ sense of balance included elements of all three models when trying to sort through the dominant sources. It also suggests that the ancients accepted a degree of uncertainty in the search for the ideal model of balance.

**EARLY MODELS OF THE TERRESTRIAL HYDROLOGIC CYCLE**

**A Balance of Land and Water: John Buridan (1295–1361)**

As a foundation for investigating the historical sense of balance in the hydrologic cycle, it is useful to consider a very early example of this thinking during the medieval period. John Buridan was a celebrated scholar at the University of Paris, who was responsible for one of the most important ideas in medieval physics. The *impetus theory of projectile motion* (Ref 11, p. 519), a foundational idea for the modern concept of inertia and conservation of momentum. Buridan also made original contributions to the application of physics to the earth sciences (Ref 11,
p. 594), during a period when rather few contributions to natural history can be found. As a student of Aristotle, he viewed the earth as spherical and of infinite age, which led him to some fundamental insights on the balance of land and water.\textsuperscript{1,5} His thinking went something like this. As water does not cover the earth in what might be the final stage of denudation and erosion, there must be a balance over infinite time that preserves the proportion of dry land to that of the sea. Buridan applies his sense of balance to the problem of the constancy in proportion of land and water in the following quote in Kaye (Ref 1, p. 449), ‘for each particle of dry earth that falls beneath the water another particle of equal measure, rises above the waters….’ Buridan goes on to explain his hydrogeological cycle as a dynamic condition driven by the relative difference between the center of gravity of the earth (centrum gravitas) and the center of magnitude of the earth (centrum magnitudinis), for which the difference continuously evolves over time (Ref 1, p. 444). Kaye further points out that similar reasoning led Buridan to speculate that earth had diurnal motion, another new idea. His geological cycle, driven by the variations in the center of gravity of dry land and water sustains an eternal yet dynamic balance in the growth and decay of continents and the revolution of the earth. It seems that Buridan was some centuries ahead of his time.


text

Early Arguments for the Balance of Sources
Since the pre-Socratic Greeks (600–300 BCE), there was speculation on the origin of springs and rivers.\textsuperscript{4,5} Aristotle (384–323 BC) in Meteorologica summarized a range of views on the subject that seemed to cover each of the prospects illustrated in Figure 1. He states that springs can be formed by rainfall condensed from air, with the excess of rain contributing to springs. Elsewhere he points to a complementary phenomenon where water is formed from air within the earth (Ref 6, p. 427).

It is unreasonable for anyone to refuse to admit that air becomes water in the earth for the same reason that it does [from] above it.

The Roman Pliny the Elder (23–79 AD) came squarely down on the side of the sea as the source of springs and rivers (Natural History\textsuperscript{12}) and the reverse hydrologic cycle, as did the Roman Seneca (3 BCE–65 CE) (Ref 6, p. 431). Unlike the changing conditions above the earth (i.e., seasonal climate and weather), the subterranean air within the earth is unchanging and constant, and could supply water for springs and rivers continuously. Tuan (Ref 3, p. 26) quoting the translation from Clarke (Ref 13, p. 117) tells us that Seneca also rejects rainfall as a source of springs from his own experience.

...as a diligent digger of vines, I can affirm from observation that no rain is ever so heavy as to wet the ground to a depth of more than 10 feet ... How then, can rain, ... store up a supply sufficient for rivers?

In the early middle ages, Isidore of Seville (560–636) expresses a view of the hydrologic cycle in his compendiums, Etymologiae.\textsuperscript{14} This popular tome was an encyclopedia that assembled and preserved extracts from ancient Greek and Roman manuscripts. He summarizes western knowledge of the terrestrial hydrologic cycle, and in the last sentence suggests a reverse model (p. 276, Book XIII; xi.21–xiii.11):

The reason why the sea has no increase in its size, even though it receives all the rivers and springs, is partly because its own huge size is not affected by the waters flowing in; then again, it is because the bitter water consumes the fresh water flowing in; or because the clouds themselves draw up and absorb a great deal of water; or because the winds carry away part of the sea, and the sun dries up part; finally, because it is percolated through certain hidden openings in the earth, and runs back again to the source of springs and fountains.

At the beginning of the Renaissance and the flourishing of western science, Leonardo da Vinci (1452–1519) also held a view in support of the reverse hydrologic cycle using an analogy for the balance of the human circulatory system\textsuperscript{15,16}:

It must be that the cause which keeps blood at the top of man’s head is the same as that which keeps water at the top of mountains.... There are veins which thread throughout the body of the earth. The heat of the earth, distributed throughout this continuous body, keeps the water raised in these veins even at the highest summits.

Yi-Fu Tuan (Ref 3, p. 29) summarizes the ancient microcosm–macrocosm theory of the cosmos where the human circulatory system (microcosm) is a representation of the hydrologic cycle (macrocosm). Tuan goes on to suggest that the idea may have influenced the prevalence of the argument for the reverse hydrologic cycle. It seems that the
microcosm–macrocosm notion had an ancient Greek origin first mentioned by Aristotle.

In 1678, the reverse cycle still had traction when Johann Herbinius (1632–1679) in his Dissertatio de Admirandis Mundi Cataractis Supra et Subterraneis, described the hydrologic cycle in two independent parts: one that operates above the land with rainfall enough to support plants and trees, and another supplied from below the land through the ‘subterranean abyss’ which is returned to the mountains to form springs and rivers. The frontispiece from the Herbinius manuscript (Figure 2) illustrates the notion. ‘The admirable cataracts’ [that originate] beneath the sea and descend to the abyss, that return as springs and form rivers ‘above the land and back to the sea.’ Rainfall, is apparently allocated the role of watering plants and trees mostly returning to the atmosphere as clouds, while springs, streams, and rivers are formed primarily by the separate and independent reverse hydrologic cycle. In the figure, we see Neptune, the Roman god of springs, lakes, rivers, and the sea playing an active role in the exchange, with the Great Lord (Domini in Magna) standing by as overseer. The river in question usually refers to the Nile in Egypt or perhaps the Tiber which rises in the Apennine mountains and flows through Rome.

**FIGURE 2** The ‘reverse hydrologic cycle’ as illustrated in the frontispiece of Johann Herbinius 1678, Dissertatio de Admirandis Mundi Cataractis Supra et Subterraneis.
Athanasius Kircher (1602–1680), a Jesuit scholar of natural history is more explicit in his spatial description of the subsurface origin of springs and rivers in *Mundus Subterraneus* published in 1641. The necessity to close the hydrologic balance (Figure 3) is accomplished by depicting subterranean channels, originating as whirlpools in the Mediterranean, driven by tides, and with the internal heat of the earth forming vapor that rises and ultimately condenses on the cold surface of mountain caverns (hydrophylacium).

A fundamental question illustrated in these images and text is the balance of sources that was implied in their description. Each author applies his personnel notion of balance in arguing for how the hydrologic cycle works. It raises the question we want to explore here: *How did the modern view the hydrologic cycle come to be, what was the evidence for sources and how did it evolve with time?* The proposition is that the evolving ‘model of balance’ is an essential and unifying process for understanding and may even serve as a predecessor to later mathematical laws of conservation. As Kaye points out the great achievement of medieval scholarship was not in the growth of new science but rather in a new intellectual ‘model of balance’ expressed here as images and text that led to a new ‘way of seeing’ and laid important groundwork for future developments in science. Kaye refines his model of balance to mean ‘...a cluster of interlocking assumptions, both implicit and explicit, both conscious and unconscious, which together form a coherent and cohesive unity ... with structures which have a real existence and presence within the mind.’ He argues that the new model of balance ‘came to be seen as an aggregate product of the systematic interaction of multiple moving parts within the whole’ (Ref 1, p. 6). The new model was capable of ordering and regulating itself, with divine intelligence only in the sense of an overseer and not with any particular function in the system. The next section attempts to examine some early evidence in support of the evolving hydrologic model of balance.

A CONDITIONAL BALANCE

As noted above, proponents of the ‘reverse hydrologic cycle’ did not seem to preclude a pluvial influence on springflow and rivers, rather the precipitation theory, or rain-causes-rivers, was held to be insufficient as a source. So in many ways the three models of balance in Figure 1 were always proportional or conditional solutions to the problem each with a greater or lessor degree of certainty.

Stephen Switzer (1683–1745), famous for his water gardens, waterworks, and landscape designs, is an example of early 18th century thinking that summarizes contemporary understanding of the terrestrial water cycle as a theoretical and practical system. He appeals to a hydrostatic balance to argue for the importance of the reverse hydrologic cycle as the origin of springs but with some ideas about the temporal behavior of springs that goes beyond the simple model. In his book *An Introduction to the General System of Hydrostaticks and Hydraulics* (1729), Book I, Chapter II: Of the Origin and Rise of Springs, he surveys the ancient and contemporary schemes to arrive at his proposal for the true source. First, he rejects Aristotle’s idea that rising air from the abyss condensing on the cold wall of mountain caves, as unlikely based on a simple proportion. ‘How vast must those caves be ... [to] contrive air enough for the perennial streams of a large spring.’ He then promotes the microcosm-macrocosm analogy with a twist (p. 15): ‘...the circulation and ascension of waters in the bowels, and on the surface of the earth, as the blood does in the body, or rather as the sap does in a tree.’ Note that his hydrostatic balance includes a mechanism for the ascension of water from the deep, as a capillary siphon comparable to how trees take up water in their roots and discharge through their leaves.

...accounted for by the ... Laws of Pulsion, having its first source from the sea, and being arrived...
through all the permeable parts and subterraneous channels of the earth, ... til it breaks out on the sides of hills, and traverses its way, even to its return into the sea again....'

Switzer describes in some detail the experiments of Edme Mariotte (1686) in the Seine river catchment (more on this later) and who, along with earlier experiments by Pierre Perrault (1674), are generally credited with confirming the modern hydrologic model of balance. Switzer at first objects to 'hidden causes' as an explanation for the origin of springs (Ref 20, p. 16). The hidden causes of Mariotte are the excess of rain and snowmelt that infiltrate the earth and return to the surface as groundwater to form springs. Switzer accepts that this may occur in some parts of the world but rejects the idea as the main cause. Switzer does not quite object to the forward model of the 'curious' John Ray (1627–1705) either. In Ray's treatise, The Wisdom of God (1691, 1st ed. and 1709, 4th ed. used here) he observed great springs at the foot of the Alps that flow sparingly in the winter but upon dissolution of the snow, flow 'in a luxurious manner.' But again, he partly dismisses this proposal as having less consequence to the origin of springs in England. Nonetheless, Switzer has conditionally accepted (1) and (3) of the models of balance proposed in Figure 1.

Next Switzer introduces 'the ingenious' Dr. Edmund Halley, whose paper concerning the origin of springs was published in Transactions of the Royal Society (Halley, 1692). Switzer describes Halley's accounting of springs that owe their origin to that great quantity of vapors which are drawn out of the ocean by the heat of the sun, '...when the sun departs the horizon, [the vapour] descends again in the same great quantities ... on the tops of hills and mountains....' Switzer then goes on to say 'Although vapours have so great an effect, as to supply some of those parts of the [tropical] world, ... they have no occasion of rain itself, ... nor do vapours contribute much [if any at all] to furnishing of springs or brooks [in England]....' Figure 4 is Switzer's rendition of Halley's vertical hydrologic cycle published in Hydrostaticks.

The crux of Switzer's argument for the origin of springs is found in Hydrostaticks Chapter III (Ref 19, p. 32), where he sets conditions on the behavior of springs associated with different sources.

First. Springs which are temporary and do not flow continuously

- those which are certain and periodical [intermittent springs]
- those that are irregular which flow or are deficient septenially or decennially

Second. Those springs which are perennial and flow without ceasing or fluctuation

- those which are limpid pure and unmixed
- those which are mixed and abound in salt, and are warm as seen in hot baths
- those which are cold and mineral as in medicinal cold waters

Switzer has introduced a range of time scales into the hydrologic cycle, describing springs that respond rapidly to rain events; springs that respond to the annual cycle of dry [summer drought] and wet seasons [snowmelt or seasonal rain]; springs which vary on a 7- or 10-year cycle; and finally perennial springs of nearly constant flow with types that range from pure, to mineral and warm springs. It is only the Second type that he reserves for the reverse hydrologic cycle with the implied independence of springs to the fluctuations in weather and climate. The First type accepts the modern view and makes a clear proposal on how the time scales of precipitation, weather, and climate impact the origin of springs and rivers. Of course, the reverse model of balance would have been even more important to explaining rivers in arid regions where rainfall was scarce.

By the early 18th century, explanations of the terrestrial water cycle still called upon a vast subterranean conduit originating in the sea to explain the origin of springs and rivers but now with conditions and exceptions raised by the new science of Perrot, Marriotte, Ray, Halley, and others.
The Model of Balance Refined from Practice and Adaptation to Topo-climatic Conditions

There were notable exceptions to the ideas that rain-water could only penetrate the surface to a limited extent, and that the independent source of ground-water, springs, and rivers was the sea. In general, these views seem to emerge from practical concerns such as the understanding that might evolve from the practice of flood protection, water supply, irrigation, or from observations of regional topo-climatic conditions.

For example, there is ample evidence that China maintained a sophisticated network of measurements on rivers and rainfall from as early as the seventh century BCE.23 A recent translation of The annals of Lü Buwei [Lü shi chun qiu],24 compiled in 239 BC under the patronage of Lu Buwei, was referred to as an encyclopedia of world knowledge ‘…one of the great monuments of Chinese thinking, a work of originality and cohesion, inspired by a vision of a universal empire governed by harmony between man and nature.’24 Excerpts suggest a clear understanding of the regional geography of climate, terrain, and riverine networks, where the interior and western parts are dominated by the aridity and elevation of central Asia, while the coastal regions have strong monsoonal rainy seasons. The text shows a practical understanding of the geography of weather, rainfall, drought, and floods from earliest times. The following provides an example of a regional hydrologic cycle and the intimate relation among geography, climate, and rivers across China (Ref 25, p. 467):

The water flows eastward from their sources, resting neither by day or by night. Down they come inexhaustibly, yet the deeps are never full. The small [streams] become large and the heavy [waters of the sea] become light [and mount to the clouds]. This is [part of] the Rotation of the Tao.3 [water cycle]

In the fifth century, Li Dao Yuan (?–527 CE) compiled the Shui Jing Zhu (Notes on Water Classic), during the Northern Wei Dynasty (386–534 CE). This text builds on the theme of rivers, climate, and physiography. The book describes the source and course of major tributaries, along with cultural and historical information for some 1252 rivers from Mongolia to Cambodia and from East China to Iran and India.23,25 Nothing quite like this compendium exists in western literature for more than 1000 years.

The 8th to the 13th century saw a golden age of science, mathematics, and engineering in the Islamic world, with the growth of cities such as Merv in the desert oasis along the Silk Road, to Baghdad on the Tigris river in Mesopotamia, to Cordoba and the Al-Andulus territory of present day Spain. Unlike the well-watered lands of northern Europe, these arid regions would have required a practical knowledge of the water cycle just to sustain these large population centers. In 1972, Nadji and Voigt26 published a paper introducing a little known 11th century text devoted to the construction and maintenance of qanats in Persia titled, ‘The Extraction of Hidden Waters’ by Mohammed ibn al-Kiraji. Abigail Schade27 provides the first English translation of the text in her dissertation Hidden Waters: Groundwater Histories of Iran and the Mediterranean. In that, she discusses how qanat construction throughout the region was adapted to various topo-climatic conditions, citing qanat construction in the mountain basins of Persia and the oasis topographic depressions of Egypt. Paul Ward English28 discusses the origin of qanat technology and its spread from Persia, Egypt, the Levant, Arabia, and across North Africa into Spain. Figure 528 illustrates a typical qanat, a perfectly adapted ancient artifact for water supply in arid desert basins where large rivers are rare and groundwater is often deep.

From Schades’ translation,27 al-Karaji portrays a deep understanding of the hydrologic cycle as indicated in the following passages:

On the water cycle. ‘The great water courses are born in the … regions where the permanent glaciers remain for the whole year, without diminishing. These regions themselves are not cultivable; but in summer the scorching sun there melts the snows, the soil dries out, and the water becomes held and metamorphoses into pure air, but Providence makes it so that all these snows and ice, melting little by little, feed the currents of water which flow toward the cultivated regions. And once the soil is deprived of the abundant humidity accumulated during the winter, the earth is greedy again for the rains until then, with the approach of winter, the snows begin to fall again. If the wintry humidity continued the whole year, the soil would risk a disparity under the mass of flood waters. What is essential in all this is the metamorphosis, during winter, of pure air, turned dense (katif), into water, and in summer, become more held [raqiq], the water again becomes pure air. So the survival of cultivation and of livestock depends straight away on a double metamorphosis: that of pure air into water, and that of pure water into air.’

On plants as indicators of groundwater (p. 212). ‘a very trustworthy man he told me once he had dug a well in a steppe where they had been growing alhagi [cemethorn (Alhagi Maurorum)], and having observed that the roots of this plant descended
the entire length of the well—which measured 50 cubits (~25m)—finally reaching the subterranean water. Almost everywhere, the Alhagi sends its roots to draw water from the depths. Anyway, the better watermelons are the ones that have been planted atop the roots of the Alhagi. To do this, one lightly splits the roots of the Alhagi, close to the ground, and there plants, next to it, the seeds of the watermelon and covers them back up with soil. The watermelons that grow there are absolutely superb, very superior compared to the melon that comes from seeds being sown.

On hydrostatics (p. 222). ‘[One knows] that left to its own devices, far from seeking to ascend, water always flows down toward the center of the Earth ... It is the same with water that rises in the tube of a curved glass [a siphon] as it is sucked through one end, to flow out the other end. Here again, water descends from one level that is higher flowing into a lower level. It is thus normally impossible that the water would rise on its own and gush ... except when the origin of the source is higher up...’

On hydrostatics of artesian or confining conditions. ‘In principal water does not raise itself up from the depth of a well, and does not gush to the surface unless the source is situated very high up...’ ‘Thus, if you see a source spurting out of soft rock this is because this is only a surface layer of rock, but in the depth the water is necessarily continuing in a girdle of hard rock. If you drill the soil below such a source, you can reckon that it will have a much greater flow, than the source of a fountain [or spring from soft rock].’

By modern standards, these are amazing descriptions that portray a deep understanding of the general terrestrial water cycle and certainly show that ‘hidden waters’ or groundwater was no mystery at all. Taking only the second example, al-Karaji is describing a capillary phenomenon referred to as hydraulic lift or hydraulic redistribution, a mechanism rediscovered in the 1980s where certain desert plants known as phreatophytes have taproots that reach down to the groundwater water table raising capillary water and then exuding it through fine lateral roots into the shallow, dry, surface soil for later consumption (in this case by intervention). The other quotes concerning hydrostatics of unconfined
and confined or artesian aquifers are also centuries ahead of their time.

Some 500 years later, Bernard Palissy (1510–1589) a ceramicist to Louis XIV, came to similar although independent conclusions regarding the hydrologic cycle in his Discours admirables, de la nature des eaux et fontaines, tant naturelles qu’artificielles (1580). Biswas (Ref 2, p. 151) suggests that Palissy was familiar with the work of Vitruvius and that this may have contributed to his views on the origin of springs and rivers. The following Palissy quote is from his biographer, Morley (Ref 31, p. 324):

when the waters of the rains fall from the air upon the earth, they are retained on the said rocks, and the said rocks serve as vessel and receptacle for the said waters; for otherwise the water would descend into the depths or centre of the earth; but being thus retained upon the rocks, they find some joints and veins in the said rocks, and having found an oozing-place, whatever trilling, be it crack or cleft, or what it may, the said waters will take their course in the direction of the downward slope, provided they can find the smallest outlet: thence it most frequently happens that out of rocks and hilly places escape many beautiful springs.

Palissy makes another independent observation similar to al-Karaji related to the drilling of wells in the stratified sediments which at some locations produced water levels that rose in the well shaft. He goes on to give a reasonable explanation of the hydrostatic balance for groundwater levels possibly artesian wells, influenced by a source of water from above (Ref 31, p. 179):

...well-waters which might often rise above the spot at which the auger found them; and that could take place provided they came from a place higher than the bottom of the hole that you have made.

Somewhat later, an important contribution to the modern hydrologic cycle was made by the Italian Bernardo Ramazzini (1633–1714). Ramazzini’s de Fontium mutinensium amiranda scaturigine tractatus physico-hydrostaticus (1691, 1st ed., 1718, 4th ed. used here), in the chapter ‘The famous springs of Modena,’ gave an explicit description of the artesian concept using new developments in hydrostatics proposed earlier by Torricelli a student of Galileo. Ramazzini describes the pressure condition below a firm and hard geologic layer, where water ‘is lifted up to this height when a hole is made with an auger, according to the law of hydrostatics.’ In Figure 6 Ramazzini demonstrates the phenomenon of artesian fountains or flowing wells with a physical experiment due to Torricelli. The experiment (lower left Fig. 6) represents the source of water from the surrounding mountains as a large reservoir and the underlying artesian aquifer as a conduit discharging at some distance. Ramazzini’s experiment showed that the rise in a pipe (well) penetrating the tube (aquifer) was always less than the height in the reservoir. The difference in height was partly due to the resistance of flow in the pipe, and partly due to the motion of the fluid itself as stated by Torricelli (Ref 43, p. 62). Dugas (Ref 15, p. 148) points out that Torricelli posessed a height-velocity^2 relation by analogy to the motion of falling bodies studied by Galileo. The important point here is that Ramazzini uses Torricelli’s idea to explain flowing artesian wells or fountains, which would flow as long as the height of the fountain or well is less than the height in the reservoir by some amount related to the velocity of the fluid flow. Torricelli published De motu gravium projec-torum in 1643, but it would take another century before the relation height-velocity^2 was incorporated into what we call today Bernoulli’s equation or the con-servation of energy for fluids. It should also be noted that Ramazzini suggested a linear relation or h ~ v for constrict flow in a horizontal tube. Henry Darcy re-examined Torricelli’s experiment (1854) and found that for small tubes and low velocities the viscous resistance would be most important and not the falling body effect, and that the change in height under these conditions was indeed proportional to the velocity^5 or, h ~ v. Darcy of course went on to use this relation to establish Darcy’s Law for flow through porous media in 1856.

Stephen Hales (1677–1761) was an English clergyman and natural scientist famous for his essays in hydrostatics. He was a fellow of the Royal Society London and a foreign member of the Royal Academy of Sciences, Paris and a member of the Academy of Sciences, Bologna. His first work in hydrostatics was Vegetable Staticks (1727) which dealt with carefully contrived experiments on the capillary pressure and transpiration in plants. Vegetable Staticks was the final Royal Society publication with Isaac Newton’s imprimatur as president. His second work, Haemostaticks (1733), dealt with measurements of the force of blood in mammals.

Figure 7 illustrates one of his many experiments, where a glass tube is bonded to the cut stem of a pear tree, filled with water, and inverted in a mercury bath. The device served as a manometer to measure capillary pressure (pressure head) as well as
the rate of uptake of water. One can speculate that his many experiments in plant physiology and measurements of the pressure and rates of transpiration of plants had an influence on his later work in human physiology where he is credited with inventing the concept of blood pressure.

Hales was aware of the experiments of Perrault at the Royal Academy and had a very clear idea of the modern hydrologic cycle that included the role of plants. Although to date there had been no quantitative measurements of how much water plants transpired except by difference. In *Vegetable Staticks*, he describes experiments that include not only the amount of water imbibed and ‘perspired’ by plants, but he also estimates the capillary force associated with the rise of sap in plants, anticipating the cohesion theory of capillary rise made famous by Dixon and Joly (1895) more than a century later. Hales clearly explains the phenomena of capillary rise in the pores of the soil itself and its relation to plant-water use (Ref 35, p. 54) and the role of evaporation from the soil.

In the long dry season ... we must have recourse for sufficient moisture (to keep plants alive) to the moist strata of earth, which lay next below that in which the roots are. Now moist bodies always communicate of their moisture to more dry adjoining bodies; but this flow motion of the ascent of moisture is much accelerated by the sun’s heat to considerable depths in the earth....

Here Hales sets some limits on the magnitude of the ‘ascent of water’ within adjacent layers of the soil that are influenced by the sun’s heat, which is typically from 1 to a few meters. Hales was a proponent of the modern model of the hydrologic cycle, which he supported with a detailed balance a la Perrault:

The quantity of Rain and Dew which falls in a year is at a medium 22 inches. The quantity of the earth’s evaporation in a year [less the amount circulating as dew] there remains 6.2 inches ... [which is] deducted from the quantity of Rain which falls in a year, there are at least 16 inches depth to replenish the earth with moisture for vegetation, and to supply Springs and Rivers.

Hales gives a rather clear picture of the vertical hydrologic balance and confirms the modern model (Figure 1(c)) by difference, balancing the sources of rain, dew, evaporation, transpiration with recharge to groundwater and baseflow to streams. He was aware of Galileo and Torricelli’s work that extends hydrostatics to the equilibrium of fluids in motion.
It is again interesting to note how much right thinking about the terrestrial hydrologic cycle emerges from practical concerns, and furthermore how these techniques, innovations, and adaptations led to the diffusion of ideas, knowledge, and scientific understanding.

Proportion, Change, and the Continuity Principle

We now must again return to an earlier era to address some underlying problems involving motion and change in space and time that were critical to the confirmation of sources. In the first half of the 14th century, Thomas Bradwardine at Merton College, Oxford wrote *Proportions of Velocities and Movements* (1328), a treatise that laid important groundwork for the kinematics of motion, a field of mechanics that is concerned only with the spatial and temporal changes in motion, as opposed to the causes of motion which we call dynamics. Bradwardine and his colleagues at Merton deduced what is now known as the mean speed theorem for uniformly accelerated bodies, relating distance, time and velocity in a mathematical form. That is, a uniformly changing velocity over the distance \( S \) and time \( t \), can be expressed in terms of the mean velocity. In modern terms, the Merton theorem can be written:

\[
S = \left( v_0 + \frac{v_f - v_0}{2} \right) t = \left( \frac{v_f + v_0}{2} \right) t \quad \text{or} \quad S = vt,
\]

where \( v_0 \) is initial velocity, \( v_f \) is final velocity, \( S \) is distance traveled in time interval \( t \), and \( v \) is the mean velocity. The kinematics developed at the Merton school spread to Italy and France around 1350 when Nicole Oresme at the University of Paris took up the problem using a new method based on graphical representation of velocities of any intensive property over distance and time (Ref 11, p. 331).

According to Claggett (Ref 11, p. 574), the Italian polymath Leonardo da Vinci (1452–1519) was fully aware of these earlier developments in kinematics and was able to apply this understanding to advance the principle of continuity applied to flow in rivers. At the turn of the 16th century, river engineering had been underway for centuries by the Romans and flow characteristics along a river, such as the relative proportions of river width, depth, and velocity were necessary to evaluate conditions for navigation and commerce, flood control, and civil defense. Leonardo, who was deeply involved in water engineering, used the principles of kinematics to extend the proportionality of depth, width, and velocity to a branching network. The idea is reproduced in Figure 8(a). In the following quotation (Ref 39, p. 273, V1), Leonardo explains the concept by analogy:

> All the branches of a tree at every stage of its height when put together are equal in thickness to the trunk [below them]. All the branches of a water [course], at every stage of its course, if they are of equal rapidity, are equal to the body of the main stream.

Leonardo has defined here the continuity principle for a branching network in flow of uniform depth. Today, of course, branching laws are widely used to
describe physical networks such as: river networks, arterial and bronchial networks of mammals, lightning, and so on.40,41 Elsewhere in his Notebooks, Leonardo establishes the continuity equation for the limiting case of a nonbranching flow or sequential river segments with nonuniform cross section in the following statement (Refs 42 and 43, p. 51):

\[ Q_3 = A_1 v_1 + A_2 v_2 = A_3 v_3, \]

\[ v_3 = \frac{A_1}{A_3} v_1 + \frac{A_2}{A_3} v_2. \]

For a nonbranching sequence of channels, the mean velocity of a river segment is a simple proportion with the ratio of areas (or widths for uniform depth).

\[ Q = A_1 v_1 + A_2 v_3 = A_3 v_3, \]

\[ v_3 = \frac{A_1}{A_3} v_1 + \frac{A_2}{A_3} v_2. \]

According to Biswas (Ref 2, p. 145), Leonardo attempted some of the first quantitative measurements of stream velocity in his experiments using floats along the Arno river. But it was Galileo and particularly his disciple Castelli (Ref 44, pp. 82–84) some 150 years after Leonardo who offered the first clear statement of how to use the continuity principal to measure flow in a channel:

Being upon the business of taking the measure of the Waters that move, it is necessary ... to keep account of all the three Dimensions, that is of length, breadth, and depth ... And I say, that if one would know the whole length of the water of a Fountain or River, thereby to come to know the quantity of all the Water, it would prove an impossible enterprise, nay the knowing of it would not be useful. But if one would know how much water a Fountain, or a River carrith in a determinate time of an hour, of a day, or of a month, I say, that it is very possible ... to know how much Water a Channel carrith in a time given.

Castelli is precise in his statement for the volumetric discharge in a river segment or river reach. \( S \) is the distance the float travels in time \( t \), the quantity of water the river carries is a function of all three dimensions and the kinematic equation for mean velocity (2) is:

\[ Q = \frac{\text{depth} \times \text{width} \times S}{t} = v A_x, \]

where \( Q \) is the volumetric discharge and \( A_x \) is the cross-sectional area of the stream (width \times depth).
Equation (4) is of course a local form of the conservation law or continuity principal. One can argue that kinematics, Leonardo’s ideas and Castelli’s measurements provide the basic formula to measure accurately the flow in a river network, a fundamental advance for the hydrologic model of balance.

**The Drainage Basin: And the Notion of Balance**

In 1674, the French scientist Pierre Perrault, mentioned earlier, had devised a series of experiments to test the sufficiency of precipitation to explain the origin of rivers. Perrault proposed that in order to compare river discharge with precipitation another area must be considered. Using an assumed measure of the drainage basin area and the mean annual precipitation over the same area, he could construct a rough volume of the source and compare it with the annual volume of river discharge leaving the basin. By difference, he could assess the losses from the ‘feeding of trees, plants, grasses, evaporation, useless flows ... and other such losses.’ The Perrault monograph *De l’origine des fontaines* (1674), was a breakthrough offering an explicit and potentially measureable hydrologic balance (Ref 20, p. 97):

The course of this young River ... from its source to Annay le Duc is about three leagues long, by two leagues wide ... If a reservoir had been made with this length and width ... Into this reservoir, we must imagine that rain has fallen for one year to a height of 19 1/3 inches which is the height of an average year.

Perrault introduces the conceptual catchment area or drainage basin area necessary to compute the volume of rain that falls within the hypothetical basin in a year, which he then compares to the volume of river flow at the outlet. He establishes from measurement the inequality $Q < A \ast P$ that proves rain ($P$) is more than sufficient to supply the flow of rivers ($Q$) (Ref 20, p. 96):

Only about one-sixth part of the rain and snow water that falls is needed to cause this river to flow continually for one year.

Perrault leads the modern revolution in the terrestrial hydrologic cycle, by proving that rivers require catchments to form a hydrologic balance using an inequality argument, and as such unifies the hydrologic model of balance with the drainage basin and contributes a means to measure the missing elements. Perrault also provides some guidance about the uncertainty of his inequality (Ref 20, p. 97):

I know very well that this deduction has no certainty ... Nevertheless ... I believe it is more satisfactory than a simple negative like Aristotle’s ... that it does not rain enough to supply the flow of rivers.

Later in his treatise Perrault introduces an interesting point about uncertainty or variability with regard to the origin of great floods (Ref 20, p. 101), which he assumes are not part of the ‘subsistence’ flow or long-term balance. He then also describes another source of flooding without rain that of rapidly melting snow on frozen ground:

And although it seems that only great storms cause these waters to fall into the Rivers in the way I contend [torrents with flooding] which happens too seldom to furnish the subsistence of Rivers, ... it is nevertheless certain that without storms Rivers [also] flood and overflow ... the great thaws of Winter ... when the earth being frozen under the snow when it melts it cannot soak up its waters.

Perrault’s inequality $Q < P\ast A$ sets a limit on the annual flow of rivers in proportion to the area of the topography that lies above the outlet of the drainage basin and the annual depth of rain. It was only another decade before Edme Marriotte added to the confirmation of a pluvial source (*Traite de mouvement de eaux et des autres corp fluids*, 1686), using the new methods for hydraulic measurement of rivers devised by the Italian school and later improved by the French school, proving that rainfall over the estimated drainage basin was more than sufficient to explain the annual flow in the Seine. Although Perrault and Marriotte get the credit for confirming the modern hydrologic model of balance from measurement, there is still some unfinished business: How to quantify the drainage basin and define the groundwater contribution to rivers?

**THE HYDROGEOGRAPHIC LANDSCAPE**

**Closing the Balance**

Circa 1585 an unknown Italian cartographer created a beautiful and unique map showing the Tiber river network flowing through Rome, and the surrounding hills and mountains where the river network originates (Figure 9). This very rare map, which we will refer to here as the ‘Rivers of Rome’ map, is
interesting for our purposes since the river network has a certain organic quality. It is drawn with topographic area distributed in proportion to the river network, and with the drainage basin clearly defined by the extent of the map. We have seen that Leonardo dealt with the proportionality of bifurcating flow in channels; however, this map hints at a larger scale concept where proportionality of flow with drainage basin area is preserved as a spatial theme.

Although the ‘rivers of Rome’ map is perhaps the first map to express a proportional relation between the river network and the drainage basin, and to define the drainage basin itself, in 1585 the idea of proportionality of river networks with surrounding terrain is not a new idea. In fact, the concept was well described by Leonardo circa 1502.47

The rivers in great valleys make greater changes in their beds in proportion as they are farther away from the roots of the mountains ... the largest rivers flow through the largest valleys....

Now recall Leonardo’s idea of the hydrologic cycle as an analogy with the human circulatory system, using the microcosm–macrocosm notion described earlier. The following quote from Leonardo’s Notebooks relates this idea to the river network and the drainage basin (Ref 47, p. 199):

And as the water is driven up from the lower part of the vine towards its severed stems and afterwards falls back to its roots, penetrates these and rises again anew, so from the lowest depth of the sea the water rises to the tops of mountains, and falls down through their burst veins and returns to the sea and rises again anew.

In this scheme, Leonardo is describing a fully connected surface and subsurface hydrologic cycle, albeit a reverse one, where springs burst forth on the top of mountains and hills like circulating blood from the ‘cut veins’ of the earth that flows through the valleys and river network to the sea. Leonardo defines the network below the surface as a unified reflection of the topographic and riverine landscape above the surface. The balance is complete. It is clear that Leonardo’s model of balance, and the proportion of surface and subsurface sources, was necessary for his story of the hydrologic cycle. One can only speculate that his idea was the inspiration for the ‘Rivers of Rome’ map a few decades later. The map does something important. It introduces space and

![FIGURE 9](Tiber river flowing through Rome.png)
The Drainage Basin and Groundwater

It may be that once a relation for drainage basin area and the river network was introduced, the problem of subsurface waters may have been much easier to consider. Although Mariotte claimed that water penetrates into the earth to a depth where a layer of clay or a continuous bed of rock is encountered (Ref 2, p. 216), there is no indication that he attempted to quantify the depth and extent of the zone of saturation. Meinzer in his review *The History and Development of Groundwater Hydrology* (1934) states that the concept of a zone of saturation and the groundwater table developed considerably later than the artesian concept. However, there were some important and little appreciated exceptions. According to Guillerme, in his treatise *The Age of Water* (1988) a history of urban waterworks in northern Europe, it was Silberschlag (1721–1791) a German Jesuit scholar that made clear the relationship of the water table to the river network in *Theorie de Flueve* (1743):

\[\text{...each river is a great lake stretching far underground, and whose exposed part, the part that we call river, is merely the channel enabling it to run off.}\]

It was a contemporary of Silberschlag, Phillippe Buache (1700–1773), a pioneer in cartography and the first geographer to sit in the French Academy of Sciences, who made an explicit and quantitative representation of the river network and drainage basin topography as a thematic map.

His map showing the rivers of Europe was published in 1753 in the paper *Essai de Geographie* Buache, 1753, Memoires de l’Academie Royale des Sciences. The map shows an explicit connection between the river network and the contributing area or drainage basin, then applies his idea to all the rivers of Europe. Although Buache was criticized for this proposal of mapping the globe as drainage basins during and after his lifetime, his work serves today as a foundation for thematic surveys, and the quantification of hydrographic basins as a theme.

Figure 10 is a portion of Buache’s map from his 1753 essay, which explicitly outlines the drainage basin enclosing the river network for the major rivers

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![Figure 10](image-url) | The rivers of Europe map by Phillipe Buache (1753) presented to the Royal Academy, Paris showing the river network and a quantitative outline of the drainage basin. Also note that the location of the river source and the depth of groundwater below the basin are indicated.
of Europe. Note that Buache indicates the source or highest elevation in each basin. Buache then introduces another scale along the right edge of each basin that indicates the extent of the subsurface body of water belonging to that basin\(^{50,51}\) (p. 132). This establishes it seems for the first time a spatial representation of the geometry and geographic domain of the modern hydrologic balance, and further indicates the extent of the groundwater reservoir within each river basin as proposed by Silberschlag. Buache has

**FIGURE 11** | John Dalton’s 1799 Water Management Districts of England and Wales based on the drainage basins.\(^59\)
now made the hypothetical reservoir of Edme Perrault a physical reality.

CONCLUSION: NEW THEMES, NEW LANDSCAPES, AND NEW SCIENCE

At the close of the 18th and early in the 19th century, the search for conservation laws in mechanics was the center of scientific attention. However, as noted earlier, Ernst Mach referred to an ancient foundation for the laws of mechanics that accepted the impossibility of motion without a cause, which has guided the search for causal explanations from ancient to modern times. Joel Kaye in his History of Balance proposes that the notion of balance emerged in the medieval period by scholars of mathematics, medicine, law, and natural history as an intellectual process enabling them to sort through the complexities they encountered to arrive at a practical

FIGURE 12 | Humboldt’s concept of the biogeography of the Andes, from: The Physical Atlas: A Series of Maps & Illustrations of the Geographical Distribution of Natural Phenomena (1848). Andes map extracted from p. 42: The Distribution of Plants in a perpendicular direction in the torrid temperate and frigid zones with indications of the mean temperature of the year and the coldest and warmest months (Geographiae plantarum Lineamenta, auct. A de Humboldt). Library of Congress.53
kind of equilibrium. This study has explored the history of the hydrologic cycle as a similar search of balancing evidence for sources, speculating on the diffusion of ideas and methods, testing the emergence of new physical insights, from mathematical innovations, all of which set the stage for important human societal and scientific themes to follow. We close with two examples that point to the future.

In 1799, John Dalton, in a paper to the Manchester Philosophical Society, Experiments and observations to determine whether the quantity of rain and dew is equal to the quantity of water carried off by the Rivers and raised by evaporation with an inquiry into the origin of springs, summarizes the contemporary experimental evidence for the new model of hydrologic balance and ends his paper with an image for the drainage basins of England and Whales presented in terms of the theme: ‘Water Districts’ of England and Wales.’ Dalton’s theme extolls the hydrologic balance as a means for scientifically grounded public institutions for the management of water (Figure 11) an important step and framework that is used to this day.

Carl Linnaeus (1707–1778) and his student Bilberg in ‘The Oeconomy of Nature’ (Ref 52, p. 14), offered a description of the hydrologic cycle as a metaphor for the cycle of all living things, and closes the balance as a ‘mechanical system designed by an all-wise engineer.’ Linnaeus’ sense of balance is a conceptual theme that for him applies to all of nature. Alexander von Humboldt’s vision of Nature required spatially referenced observations to arrive at his revolutionary thematic landscapes representing equilibrium patterns for biogeography, climatology, hydrology, and geophysics. Figure 12 presents Humboldt’s vertical biogeography for the Andes mountains, mapping from observations the distribution of plants, temperature, the rain-snow line, and so on. Humboldt’s sense of balance offers ‘a synthesis of atmospheric, oceanic, geological, ecological and cultural “themes”’ which he proposed to apply to the entire globe’. Like Linnaeus, Humboldt’s intuition was that all elements of the system were linked in an integrated whole, but Humboldt required spatially referenced observations to resolve the patterns.

Through images and original text, this study has attempted to provide a possible story for how scholars and practitioners viewed the hydrologic cycle from ancient times through the end of the 18th century, about the time when the modern version became generally accepted. The use of images along with contemporary text I feel helps to make the evolving story real, at least for me. The following quote from Ken Taylor55 says it well:

We see and make landscapes as a result of our system of beliefs and ideologies. A landscape is a cultural construction, a mirror of our memories and myths encoded with meaning which can be read and interpreted.

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