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SPECIAL ISSUE: HISTORY OF HYDROLOGY

The first catchment water balance: new insights into Pierre Perrault, his perceptual model and his peculiar catchment

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ABSTRACT

Pierre Perrault's 1674 book *De l'Origine des Fontaines* is widely acknowledged in hydrology as the first formal articulation of the catchment water balance based on field data. Many summaries of his work have now been written, but few of these summaries have examined Perrault's perceptual model in detail and none that we are aware of have gone back to his study catchment to collect new data in which to frame these historic findings in a modern context. Here we report new insights (with re-calculations of some of his analyses) into Perrault's work, his perceptual model of streamflow generation and his rather peculiar 119 km^2 headwater catchment of the Seine River basin. We show the uncertainty of his flow and catchment area estimates, some errors in perception about hydrological flowpaths and new age estimates for the spring-fed site where he worked.

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Introduction

Pierre Perrault (1608–1680) is perhaps the first field hydrologist. His book *De l'Origine des Fontaines* from 1674 brought a quantitative approach to the catchment water balance, in the upper headwaters of the Seine River catchment in France. He demonstrated that annual rainfall was more than sufficient to sustain the normal river flows over a year. Many papers have chronicled these historic achievements (Delorme 1948, Tuan 1968, Dooge 1974, Nace 1974, Hubbart 2011, Deming 2014, Duffy 2017, Barontini and Settura 2020). Biswas (1970) is perhaps the definitive treatment of the Perrault work in the context of the full history of hydrology. That work appeared four years after the first complete translation of *De l'Origine des Fontaines* by Aurèle La Rocque, published in 1967.[1] Biswas (1971) included some of those translated sections and noted that other papers before that had translated smaller sections of the Perrault work, including an anonymous review of Perrault book in the *Philosophical Transactions of the Royal Society of London* in 1675 and in early 20th century reviews (e.g. Mather and Mason 1932).

Beyond the details of the findings, many have noted that *De l'Origine des Fontaines* was first published anonymously, with the authorship being assigned to a few different French scientists. Dooge (1974) presents perhaps the most thoroughgoing analysis of this, concluding that Pierre Perrault "is very likely the author" but that in the absence of any conclusive new evidence that "Perrault's authorship would appear to remain a probability than a certainty." So, while in the modern discussion this book is now universally attributed to Perrault, we must acknowledge that some uncertainty still exists in this regard and we hope that some future historian will put this issue to rest.

The Perrault book was dedicated to the Dutch scientist Christiaan Huygens (or in Perrault's spelling Huguens) (1629–1695), the celebrated physicist, mathematician, and astronomer, who was a Fellow of the Royal Society of London and member of the French Academy of Sciences and who visited Paris quite frequently. In Part 1 of *De l'Origine des Fontaines*, Perrault reviewed the opinions of a variety of authors in turn regarding how to explain the continued flow of rivers and springs, from the Greeks and Romans up to the writings of his contemporaries. Barontini and Settura (2020) do a good job at showing, in table form, how Perrault disagreed with all previous accounts, partly because of his own observations and experiments, including showing that water does not lose its salinity when it flows through columns of soil (in order to disprove the idea that springs were fed from the sea). In Part 2 of the book, Perrault explained his own perceptual model of catchment hydrology at length.

Here we conduct new field work and a new analysis of contemporary water balance data from his study area and reflect on these factors in considering Perrault's first catchment water balance, his at-times incorrect process perceptions and the nature of his peculiar catchment. We begin with a re-

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[1]Joseph Alfred Aurèle La Rocque (1909–1990) also translated *The Admirable Discourses of Bernard Palissy*, published by the University of Illinois Press, Urbana, in 1957. He was a specialist in freshwater mussels at the Department of Geology, Ohio State University. His translation of Perrault includes extensive notes and a useful introduction.

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examination of some of the basic issues with Perrault's estimates of catchment area and streamflow.

Issues with Perrault's estimates of area and flow

One thing that does not seem to have been widely commented upon by others (other than Dooge 1974) is that while Perrault's quantitative water balance assessment was acknowledged as approximate, it does seem to be problematic on a number of counts. He starts by simplifying the catchment area as a rectangle of 3 leagues in length and 2 leagues in width, an area of 31 245 144 toises. Of course, this is due to the extreme challenge of survey information availability of the day and the extremely rounded hilltops of his study area, where even today, accurate discrimination of catchment area would prove difficult. His *toise* unit, however, is not a measure of area but of length (= 1.949 m). So, Perrault has omitted here the square *toises carrées* (36 *pieds carrés* = ~3.799 m^2). Under this assumption the catchment area can be interpreted as approximately 118.7 km^2 (see Fig. 1).[2] He has 3 years of rainfall data from October 1669 to the same month in 1672 (the location is not clear, but it would seem to be in Dijon, some 45 km to the southeast), giving an average annual input of "19 inches, 2 lines one third." This is again somewhat ambiguous but can be assumed as approximately 519 mm as an average annual depth per unit area. Perrault then calculates that this combination of area and depth then suggests an input volume of 224 899 942 muids of water in a year.[3]

More problematic than the calculation of catchment area for his water balance work was his estimate of streamflow at his site. He estimated that the headwater stream at Aignay-le-Duc (Fig. 1) had a "size" of 1000 to 1200 *poulces d'eau* and was "always flowing." He compared this to the Gobelins River near Versailles where he measured 50 *poulces d'eau* but estimates the flow at Aignay-le-Duc to be 24 or 25 times as much. A *poulce d'eau* at that time was a measure of flow, equivalent to discharge as the outflow from a circular pipe one inch (*pouce* or *poulce*) in diameter, with its centre at seven lignes below the water level in the basin it drains.[4] Such an orifice would produce a flow of about 19.2 m^3 per day.

Perrault, however, does not use that definition but rather appears to treat the *poulce d'eau* as a measure of cross-sectional area rather than flux, as he goes on to choose a conversion factor to go from *poulces d'eau* to discharge as a volume per unit time. This perhaps reflects the fact that the definition of a *poulce* d'eau as a flux was not precise at that time. He cites values of 70 to 144 muids per day used by the *Fontainiers* or "Keepers of Springs" and fixes on a value of 83 muids per day. In the original text this is stated as:

> Ceux qui font profession de gouverner & conduire les eaux des Fontaines, disent qu'vn poulce d'eau donne en vingt-quatre heures cent quarante quatre muids d'eau, d'autres ne disent que soixante & dix; & je croy avoir trouvé qu'il en donne quatre-vingt trois sur le pied de quatorze-vingt pintes pour muid, sur laquelle mesure je me regleray pour le calcul que je veux faire dans la suite. Ils disent aussi qu'vn muid d'eau vaut huit pieds cubes, c'est à dire qu'vn vaisseau de deux pieds de haut & de long & de large tient un muid. (Perrault (1674, pp. 198/199, font characters updated for clarity)

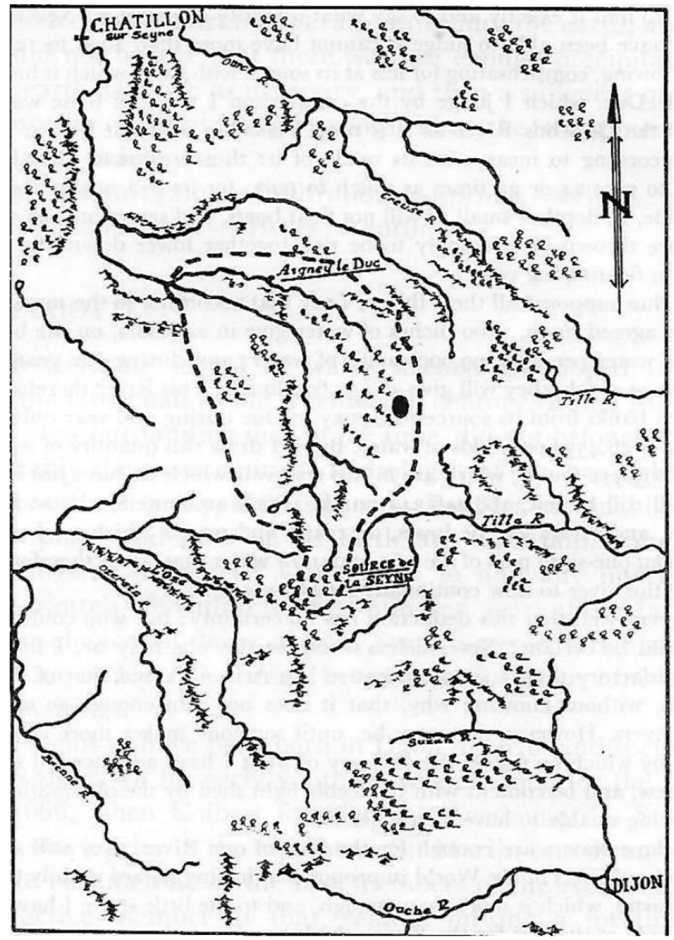

Figure 1. The upper Seine River headwaters where Perrault estimated flows between the upper Spring at Source de Seine and the town of Aignay-le-Duc (from Dooge 1959, 1974 as used in Biswas 1970). Note that the Seine River no longer flows through the town of Aignay-le-Duc. The current hamlet of Aignay-le-Duc has a small stream (called the Coquille, that flows into the Revinson, see https://fr.wikipedia.org/wiki/Aignay-le-Duc), and the Revinson then flows into the Seine in the town of Quemigny-sur-Seine (see https://fr.wikipedia.org/wiki/Quemigny-sur-Seine). We do not know for certain whether Quemigny-sur-Seine existed before 1790.

And in the La Rocque translation this passage is interpreted as:

> Those whose business it is to regulate and control Spring waters, say that one inch of water yields in twenty-four hours 144 muids of water, others say only 70; and I believe I have found that it gives 83 on the basis of 280 pints per muid, which measure I shall follow in the calculations I wish to make later. They say also that one muid of water equals eight cubic feet, that is to say that a container two feet high, long and wide holds one muid. (La Rocque translation, 1967, p. 95)

[2]See https://en.wikipedia.org/wiki/Traditional_French_units_of_measurement (last accessed 8.10.23)

[3]The *Ancien Régime* French volume unit of *muid* (a cask, translated as "hogshead" in Nace 1974) was equivalent to 8 cubic Royal feet or about 274 L. The inch (*pouce* or *poulce*) was 1/12 of a Royal foot, and could be sub-divided into 12 lines (*lignes*).

[4]see https://www.sizes.com/units/pouce_deau.htm. The *poulce d'eau* could be divided into 144 *lignes d'eau* equivalent to the outflow for a pipe of diameter one *ligne*, but this does not relate to the conversion of 1 *poulce d'eau* to muids per day as used by Perrault. The definition of a *poulce d'eau* as a flow of 19.2 m^3/day would give a conversion factor to muids per day of 70.1, lower than that chosen by Perrault. The term *pouce d'eau* was also later used as a measure of pressure head (equivalent to inches of water).

This is effectively a form of primitive rating curve, making the assumption that velocity is constant per unit area of flow (at 83 *muids* per day per *poulce d'eau*). The annual discharge for the stream can then be calculated as follows (Perrault uses 366 days per year):

$$\begin{aligned} Annual\ discharge &= 1200\ poulces\ d'eau\ x\ 83\ muids\ per\ day \\ &\quad x\ 366\ days \\ &= 99600\ muids\ per\ day\ x\ 366\ days \\ &= 36453600\ muids\ per\ year \end{aligned}$$

No experimental basis for the value of 83 muids is given, nor does it appear to take any account of depth of flow in comparing values for different sites, or of the potential for changing velocity with increasing depth. It is not therefore strictly correct to say, as Biswas (1968) does for example, that "Pierre Perrault proved by experimental investigations that rainfall is adequate to sustain river flows," though Nace (1974) more correctly allows for the approximate nature of the calculation, and recognizes the later calculations of Mariotte (1686), farther downstream on the Seine at Paris, as having a firmer basis. Nevertheless, the resulting estimate of discharge by Perrault is 99 600 muids per day, or 36 453 600 muids per year or 9 998 286 m^3/year or 84.15 mm per unit area (using his assumed area of 31 245 144 toises carrées or 118.7 km^2 for the catchment). Thus, comparing with the average rainfall estimate of 519 mm, this suggests a (baseflow) runoff coefficient of 16%. For the median annual rainfall (797 mm) of the 1852–2022 period at Châtillon/Seine, the runoff coefficient is estimated at 10.5%.

Perrault does properly recognize where the rest of the rainfall input to the catchment might "be used":

> All of this water thus accumulated in the quantity just mentioned is what must be used to cause this river to flow for one year, from its source to the place designated, and which must serve also to supply all the losses, such as the feeding of trees, plants, grasses, evaporation, useless flows in the River which swell it for a time and while it rains, turning away of waters which can take another course other than that towards this River because of irregular and opposite slopes and other such wastes, losses, and reductions. (La Rocque translation, 1967, pp. 96–97)

We will explore further Perrault's concept of "useless flows in the river" ("*écoulemens inutiles dans la Rivière qui ne font que la grossir pour un temps & pendant qu'il pleut*" (Perrault 1674, p. 202) in the section below on his perceptual model. But first, let us now explore the Perrault catchment from a modern perspective, to contextualize the site in preparation for examining Perrault's thinking process.

A modern take on the Perrault catchment

So, what was the Perrault catchment like? Here we describe some of the basics and present some new data to help define it in modern terms related to the water balance, the runoff ratio and stream baseflow age. The geology of Perrault's 119 km^2 catchment is dominated by marls (Liassic marls, Acuminata marls) of low permeability. These marls have been noted as "prone to weathering" with more resistant overlying limestone formations (entrochal limestone, oolite) (Arbault and Rat 1974). The topography of the Perrault catchment is dominated by gentle slopes (<5°) on the marly terrain, locally disrupted by steep slopes and cliffs (30 to 45°) in areas with limestone outcrops. Figure 2 shows a photo of a section of his stream, roughly mid-way between Source de Seine and the town of Quemigny-sur-Seine. The extension of the main stream network is very limited and most secondary valleys are dry. Small springs appear in the marly limestone area, which also clearly exhibit karst features (e.g. a series of caves located in the vicinity of Aignay-le-Duc).

Figure 2. A view into the Perrault headwater catchment looking upstream. This site is upstream of and between Quemigny-sur-Seine and Source de la Seine spring (photo: McDonnell).

While there is no gauge at the exact place where Perrault estimated streamflow, there is a stage recording station at Seine à Quemigny-sur-Seine (Cosne). Given that the exact delimitation of towns and villages has changed since the late 1700s – and that the Seine does not flow in Aignay-le-Duc currently – we believe that current gauging station roughly corresponds to the catchment as drawn in Fig. 1. There is corresponding meteorological data at a Meteo-France site nearby at Chatillon/Seine (lat: 47°50′57"N, long: 4°34′52"E). Using these data, the 1991–2020 30-year normal water balance for this gauging station (with a catchment area of 188 km^2) is shown in Fig. 3. Annual precipitation is 833 mm, with a measured runoff of 471 mm; potential evapotranspiration is estimated to be 770 mm.

The 30-year normal for annual precipitation for the Eaufrance gauged catchment is 833 mm; potential

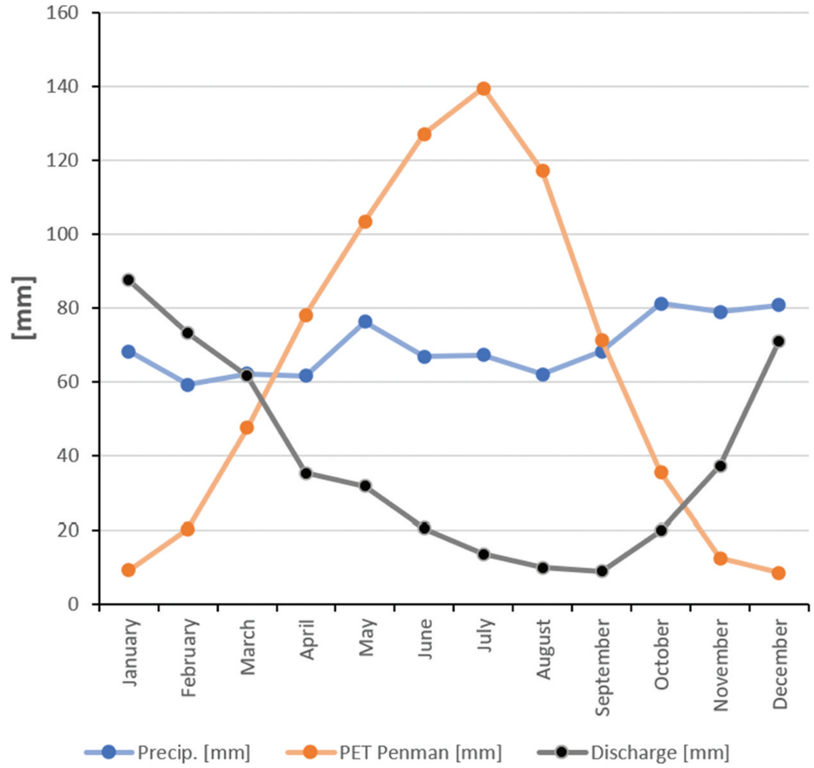

Figure 3. The Eaufrance (https://hydro.eaufrance.fr/sitehydro/H0020010/series) and Meteo-France (https://donneespubliques.meteofrance.fr) data showing the 30-year normals for the period 1991–2020. Meteorological data is from the Chatillon-sur-Seine station (Lat.: 47°50′57″N, Long.: 4°34′52″E; Alt.: 262 m.a.s.l.). The streamgauge station is located on the Seine, near Quemigny-sur-Seine (Cosne, station ID H002 0010 01), some kilometres downstream of Perrault's Aignay le Duc site. The modern gauged catchment has an area of 188 km^2.

evapotranspiration is 770 mm; runoff is 471 mm. While the annual runoff is 56% of annual precipitation, event runoff ratios are very low. Monthly runoff ratios tend to be very low in summer (<15%) and very high in winter (~100%) (Fig. 3). Direct comparison of our calculations to Perrault's are somewhat challenging. If we interpret his term "always running waters" as summer baseflow discharge, then his data and recent data are very similar. For instance, if we use a mean discharge as observed on average from June to August (i.e. 11 mm per month), then apply this value of "always flowing" discharge to all 12 months of a year, we obtain a total annual discharge of 132 mm. Against a mean annual rainfall of 833 mm this corresponds to a rainfall-runoff coefficient of 0.16 for the period 1991–2020 – a value that equals that provided by Perrault.

Of course, streamflow information is only half the story of how Perrault's or any catchment stores and releases water (McDonnell and Beven 2014). The other essential modern descriptor is streamwater age. We collected 4 years of data on four sampling trips from the Perrault spring at Source de la Seine and the Eaufrance gauging location for tritium analysis to quantify both spring and stream water ages. Only the spring tritium data could be interpreted in terms of water age because the downstream gauging location showed elevated levels of anthropogenic tritium, most likely due to point source landfill leaching of buried luminous material. While there is uncertainty in the age estimates, Fig. 4 suggests that the mean age of the Seine Source spring flow is 50 years, and during extreme drought conditions, as experienced in summer 2022, closer to 65 years (see the Appendix for details of our procedure).

These data suggest that the Perrault catchment is somewhat peculiar compared to many of today's long-term experimental headwater catchments. Qualitatively, the flow rate shown for streamflow mid-catchment as in Fig. 2 is very similar to the flow rate some tens of metres downstream from the spring at Source de la Seine. This would imply similarly very old waters in stream baseflow at this section. Most headwater catchments summarized in McGuire and McDonnell (2006) show mean streamwater ages of 0.5–20 years, with the bulk of reported values <2 years. But the extensive nationwide stream age dating done across the many geological terrains – not constrained by gauged headwater catchments – in New Zealand helps to place the Perrault headwater catchment work into a context of other "peculiar" geological formations, like ignimbrite and limestone where they can form streamflow ages of 50–100 years (e.g. Morgenstern *et al.* 2010, 2015). Something else we know now that was not known in Perrualt's time is that the "catchment area" for groundwater can be quite different than the topographically defined catchment area for streamflow – very likely a factor in generating the high values for the Seine Spring that feeds the baseflow in Perrault's catchment.

The Perrault perceptual model revisited

In *De l'Origine des Fontaines*, Perrault presents an early perceptual model of the origins of springs and streamflow.

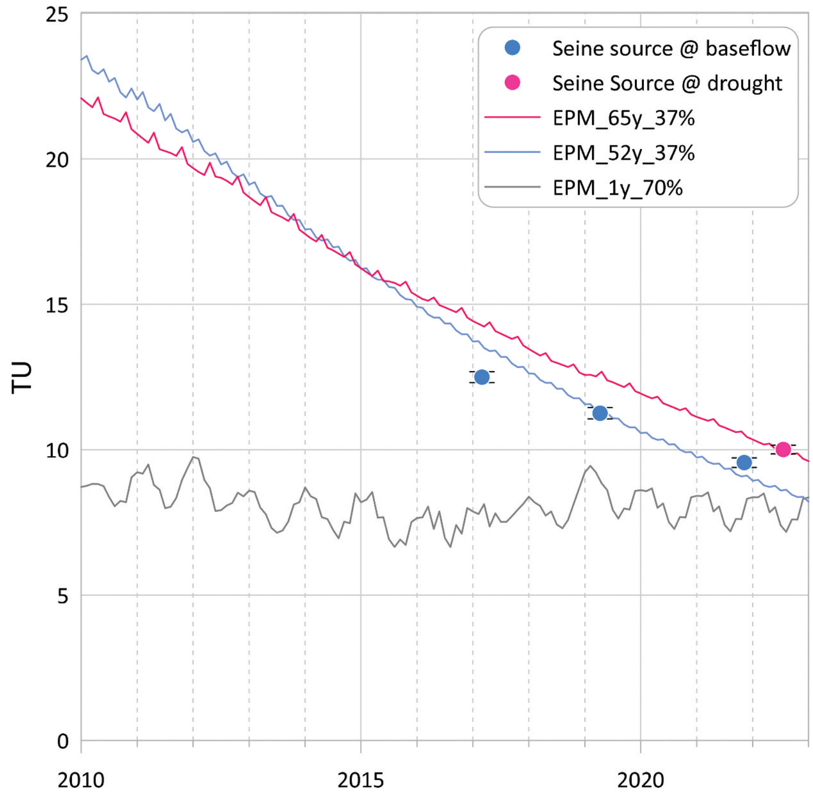

Figure 4. Tritium concentrations measured at the Source de la Seine, and model outputs for very young water (grey) and older water with model parameters matching the spring data (blue and red), using the Trier Germany tritium input record (see the Appendix for methodological details). EPM stands for exponential piston flow model, as described in the Appendix.

Reflecting on Perrault's interpretations in light of what we know now generally in hydrology, he was certainly not the first to suggest that the waters of springs could be sustained by the inputs of rain and snowmelt over a catchment area.[5] Indeed, he refers to what he calls the common opinion (*"l'Opinion commune*," Perrault 1674, pp. 175–183), what we might now call "common knowledge," citing in particular earlier scholars like Vitruvius, Gassendi, Palissy and the Jesuit priest Fr. Jean François as examples of that opinion. We note that Fr. Jean François was the author of a book called the *Science of Waters and Natural Springs Together with the Arts of the Transport of Water* that appeared two decades earlier in Paris, in 1654 (see Beven 2024 for more detail on the work of François).[6] Perrault had two objections to this common opinion, based explicitly on his observations of water in the soil.

His first perceptual inference was that rain does not infiltrate into the soil deeply enough to be the cause of springs. He cites Seneca to be of the same opinion on this point. The highlighted passage below describes this:

> As for me, by the experiments and the observations I have made at different times; I have not found that this penetration went so far; I have caused the earth to be opened on mountains, on the slopes of hills, in the low parts of plains, in cultivated gardens, after great and prolonged rains, I have never found the earth wet deeper down than a foot and a half or two feet, and immediately after I found it in such a state that it could be called dry, and so hard that it took a besoche or a pick to breach it, for a spade or a hoe could not breach it. I have had wells dug; I have looked for water on mountain slopes: I have found the same thing on opening the earth, that is to say the same moisture at first, and the same dryness deeper down, without any sign that water had flowed in it, nor that it had ever been wet; I have found that this dryness of the earth still continued, down to a depth of eighteen or twenty feet, sometimes more, sometimes less: now in earth, now in sand, at other times gravel. (La Rocque translation, 1967, p. 83)

Perrault's second perceptual inference is that there is not enough rain falling on high ground to supply springs when nearly all that water is strongly absorbed by the soil and later lost by evaporation "without any of it profiting sources and natural springs" (La Rocque translation, 1967, p. 86). His argument here is based on his studies of the capillary rise of water in columns of soil. He discussed the experiments he carried out on the capillary rise of water into soils, inspired by, and initially sceptical of, the earlier work of Maignan that had been reported in the book *Anatomia physico-hydrostatica fontium ac flumen* by Gaspard Schottus that had appeared in 1663. His experiments confirmed the phenomenon of capillary rise into dry soil columns and he also demonstrated that water

[5]Koutsoyiannis and Mamassis (2021) take this all the way back to certain classical Greek philosophers.

[6]*La Science des Eaux* of Fr. Jean François consisted of 10 parts, including the formation, transport and movements of water (including the effects of tides), the mixing of waters (including salt waters and mineral springs), the design and maintenance of fountains and canals, the art of surveying slopes, the art of raising waters by different methods, the construction of plans, and a final chapter on integer and real number arithmetic; see Beven (2024) for more detail.

rising into soil in this way could not be induced to seep out of a hole in the side of his column (he notes that if the water could be returned to the reservoir at the base of the column in this way it would provide a form of perpetual motion).

Perrault suggested that rainwater infiltrating into the soil would be strongly bound to the soil by the same attractive forces that produce capillary rise. Further rainfall could not fill the same space, but would also be firmly held, even if it penetrated a little deeper. Evaporation at the surface would empty some of that storage, but that storage would then need to be filled before any further penetration could occur:

> . . . and this is a total loss: for this water will never leave them save by evaporation, because of its clinging quality which causes it to stick to everything it touches, and to remain attached to it without dropping downward where its weight should attract it, as seen through our experimentation. (La Rocque translation, 1967, p. 87)

Perrault had also added water to his columns, to test under what conditions there would be drainage from the bottom. His conclusion was that this would only occur when the soil was more or less saturated: " . . . the Earth is not penetrated by water to let all of it through unless it is entirely wet, and unless it is soft as mortar" (La Rocque translation, 1967, p. 81). His two objections were therefore strengthened by the argument that to saturate a complete profile of soil down to 18 or 20 feet – where he had observed dry soil – would exceed the annual total of rainfall and snowmelt.

Of course, now we would likely offer up the notion of preferential flow as a means to indeed bypass water to depth under wet conditions. Interestingly, Perrault does add a proviso concerning a recognition of preferential flow, based on observations of watering plants in plots:

> I am not speaking of the water that sometimes passes between the earth and the sides of the boxes where they have not been watered for a long time and the earth has shrunk because of drought, that cannot be called penetration. (La Rocque translation,1967, p. 81)[7]

Perrault needed an alternative explanation for the origin of natural springs and rivers consistent with his experiments. In his book, he invokes several alternative concepts. Perraut's first and most important suggestion is that when a river is in flood, there is enough water to saturate the flooded area which can then penetrate to depth. His earlier "useless flows" might in this way be stored, later to reappear from the earth between events. He therefore had a concept of overbank flows and flood plain storage, but in developing this concept, Perrault also makes use of another common opinion of the time, that at some depth under the earth there was a compact layer of clay or stones that would restrict the penetration of water to depth and serve to create a zone of saturation and which extended from the bottom of valleys under the mountains.[8]

The existence of such an impeding layer had also been confirmed by Perrault's own observations:

> Finally after digging down to eighteen or twenty feet, I have found somewhat damp sand, or marl, white chalk, or white clay, likewise damp, and which continued to be so more and more for about a foot and a half: and afterwards I saw water appear in the soil, between pebbles on a bed of clay, bubbling up more or less according to how fruitful the vein was. (La Rocque translation, 1967, p. 83)

Earlier he also made use of this layer to argue against the possibility of water rising from great depths as vapours to be the source of springs, arguing that if this layer does not allow water to seep downwards, how would it allow vapours to seep upwards? This layer was thought to be the reason why the water in rivers does not seep away if their beds are at that level, but Perrault argued that the impervious layer might be variable in depth so that any water reaching that level would flow with the slope of this impermeable surface, filling any hollows in doing so. This water could then act as a source for springs and downstream river flows, either in the same river or in neighbouring rivers:

> These waters thus getting into and rising within this sand and these rocks, rise up on these beds of clay that they meet there, enter into basins and gutters, cross over those that are raised up into bumps and slopes, and rush down the other side according to the arrangement they find there: And depending on how long these overflows last these waters have more or less chance to spread into the sand until as they go away from the river whence they started they meet other waters coming toward them, either from a neighboring river or from the same river winding as it goes as most of them do, and thus these waters joining together and taking the same level one with the other, the entire underside of the plains and mountains becomes filled with water to a great depth depending on whether the clay bed is deeply buried, the sand thicker, the channels and caverns more roomy; and finally according to the capacity of all these spaces, whence the air that filled them has escaped upward, through the pores of the earth as the water entered into them. (La Rocque translation, p. 105)

Perrault cites his observations of water collecting in the cellars of the Royal Observatory at high flows in January 1671 a half a league away from the Seine, and in 1658 from well at a similar distance that was full to overflowing during part of the summer even though the river had gone back to normal levels. The house foundations in Paris were also affected by the high flows of 1658. Perrault also cites the appearance of water in deserts as further evidence of the potential for such flows over long distances. But this explanation does not explain everything, as he recognizes:

> . . . [It] remains for me only to show how there can be springs at the top of mountains and how waters, which I assume to be below and so to speak in the foundations of these high structures can climb by themselves to their summit. (La Rocque translation, 1967, p. 108)

He has two explanations for springs on higher ground. The first, for cases where it is clear that the flow rises and falls after rain, will occur where there are shallow layers of permeable soil, sloping down towards a spring:

> . . . We must consider still another arrangement of the earth with regard to the slope of hills and mountains which is, that the earth on the slopes of hills and mountains, is arranged in such a way that

[7]The earlier book of Fr. Jean François also discusses a concept of preferential flows as subsurface threads and streams; see Beven (2024).

[8]This should perhaps not be criticized too strongly as many catchment hydrologists still make the assumption that there is an impermeable layer underlying the soil profile in assessing the catchment water balance, even if this will often not be the case (see e.g. Tromp-van Meerveld *et al.* 2007).

> the veins and threads (if they can be so called) that it may have inclined downward and outward from the hill: …. So it may be said that the earth on the slope of a hill is arranged like the tiles of a house, which are laid one on top of the other sloping outward, always throw water outward, without allowing it inside the building until it has reached the gutter or some other place below, where it is to be seen in quantity. (La Rocque translation, 1967, p. 102)

This explanation is something analogous to the thatched roof effect on sloping layered hillslopes discussed by Zavlasky and Sinai (1981). Perrault goes on to say:

> … In certain parts of Burgundy and Champagne and other hilly regions, it is seen that in the low places where these hills are joined and assembled there are always brooks flowing more or less strongly according to whether it has rained hard or moderately and which always grow stronger as they flow. Whence these waters come to them cannot be told exactly, since they are not seen to flow visibly from top to bottom of these hills: also they would be but torrents of little duration: but these waters having entered the earth from the top of the hill, and being unable to get into it straight down, as Father François would have it, for the reasons we have just noted, they flow between two layers of earth pushing or pulling each other to the bottom, where they find some mud or fatty earth, and are stopped and made visible, forming brooks which I say flow a long time, because these waters thus mixed in with the earth take a long time to leave them and to descend: and finally these brooks find a way to get away from the foot of the hills, and joined to others they form some little river which flows into a larger one whose flow it increases. (La Rocque translation, 1967, p. 103)

Perrault allows that the collection of such "fatty earth" and clay might be the result of the transport of particles in the soil, and specifically mentions the potential for collection at a plow layer:

> That is ever since it has been raining on the earth, and mainly on that which is usually plowed and cultivated, rain water has carried with it what was fatty and loose in this earth, and has caused it to sink down to where the plow has broken into it, where it has formed a sort of tamping which can resist penetration … where we have found a sort of compacting. (La Rocque translation, 1967, pp. 82/84)

Perrault does not, however, think that this is a sufficient explanation for all headwater springs, especially those that flow continuously during dry periods. He argues that this must be due to the condensation of vapours: "… Evaporated water is still water and its evaporation being merely a separation of its parts, it will not fail to become water again as soon as this separation will cease and its parts are able to join again" (La Rocque translation, 1967, p. 112). He argues that he has observed such condensation on the ceilings and passageways in cellars where "the vapor can almost be felt" (La Rocque translation, 1967, p. 113).

This, of course, demands a source for the vapours. He considers that this could either be due to heat stored in the earth from the warming of the sun, or from cold – because he had carried out experiments that had demonstrated the sublimation of snow and ice – or simply from the movement of air:

> My reason for insisting on this idea is that I see that evaporation constantly goes on without the help of either heat or cold. Water left in a container in some secluded spot where it is neither warm or cold … will evaporate. (La Rocque translation, 1967, p. 111)

Perrault suggests that whatever the cause of the vapours within the earth, they will rise through veins and channels until they reach the tops of mountains and condense. As he notes, this is different to the old thinking that:

> because it can go no further, either because the channels and openings end when they approach the surface of the earth where it is looser and where its pores are finer, or because of the coldness of the surface caused by the actual cold of Winter which draws it together and produces a crust all over the top of it, or by the coldness of the nights in places where it does not freeze … or by the cold that rain waters can give it or by some other cause unknown to us, this vapor, I say, no longer agitated by the narrowing of the pores, and because of the numbing induced by the cold it encounters, is reduced to little drops of water, which join with each other and thus become larger, descend finally towards a lower place where they find others with which they join again, and flow until they meet some bed of clay that stops them, and leads them to become ever stronger by meeting with new waters, until they make some opening for themselves on the slope of a Mountain; and that is what we call a source or spring …. (La Rocque translation, 1967, pp. 114–115)

He continues this reasoning with respect to the reduced spring flows often seen in summer, and notes:

> … and the reason why all these kinds of springs always suffer decreases during the Summer, is that the heat opening up the pores of the top of the Earth, and giving them by this means passage to these vapors, allows them to rise in the air where from time to time they cause great storms, which cause to fall upon the earth waters which otherwise would have joined with others that are in the earth and would have prevented the decrease suffered by the springs. (La Rocque translation, 1967, p. 115)

However, he also recognises that some springs might disappear almost immediately,

> since enough fountains of some size can be seen flowing on the Earth, which vanish in very little distance; and as they are too strong to make us believe that the Sun of the air could make them evaporate, of necessity the earth must soak them up; and yet it would be impossible to say exactly nor to show the place where they go into the earth. (La Rocque translation, 1967, p. 84)

He argues, however that this cannot be a good explanation for the occurrence of springs elsewhere, as it is a "very weak answer to say that this water has gone down … through distant and unknown places" (La Rocque translation, 1967, p. 85).

Finally, Perrault, a couple of pages on, concludes his perceptual reasoning with the following:

> That is my opinion on the Origin of Springs …. There is nothing hard to understand, nothing new to imagine, nothing to be assumed gratuitously or by miracle; everything is known and accepted by everybody; and perhaps for this reason I may be told that I have made great efforts to find something which was not at all difficult …. (La Rocque translation, 1967, p. 117)

Concluding remarks

The totality of Perrault's work and contribution is immense for his day, even despite the issues with his estimates of catchment area and flow. There is certainly a logic to each component of Perrault's perceptual model, in part because of the links he makes with his personal observations and experiments. But of course, in many respects his perceptual model was incorrect in hindsight, and in many ways wrongly reported in the historical summaries. What keeps streams flowing when the rain is not falling is a question as old as time, it seems. Fast-forward ~300 years from Perrault's work to Hewlett and Hibbert (1963), and incorrect assumptions about the source of stream baseflow were still being made – and, ironically, linked to how deep rainfall percolates and what barriers might exist to shift flow laterally at depth.

Of course, our 30-year averages that we report for the Perrault catchment for today are likely somewhat different for his period, especially considering the Little Ice Age that impacted his and other regions in the mid-1600s (e.g. Wang *et al*. 2023). But if Perrault had had the means to know that the baseflows he measured were on the order of 50 years old, then he could have calculated how much storage would be required to support such an age. Indeed, Perrault does mention treating the catchment as a storage in his balance calculations (Perrault uses the word *reservoir* in the original manuscript). Assuming a mean discharge of 36 354 000 muids/year (see above) then it is a simple calculation to estimate that a storage of 1 817 700 000 muids would be required. This would be equivalent to 4.196 m as an average depth of water over his assumed catchment area, or, assuming an average porosity of 0.25, an average depth beneath the water table of 16.8 m of "active storage."

It is, then, interesting to speculate how this modern knowledge might have influenced his perceptual model. In one sense it might have reinforced his perception that infiltration during events was not sufficient to replenish the water table, and therefore the (50 year old) water would have to have come from elsewhere. Thus, assuming such long turnover times for either the overbank recharge or for the sources of condensed vapours high in the mountains would not be inconsistent with his perceptual model. Perrault was also somewhat enigmatic about the sources of the flood waters that might cause those overbank flows. Perhaps this is actually our problem, with our modern viewpoint of research exploring runoff generation. In the 17th century, it was just common sense that floods occur after there has been a lot of rain. No more needed be said. But the real problem was the origins of springs that continued to flow long after rains have stopped. To have water ages greater than 50 years reinforces the concept that a large *reservoir* must be involved. However, it follows that such knowledge of the mean transit times of baseflows would not necessarily have avoided some of the 20th century misconceptions about runoff generation in the "era of infiltration" from the 1930s to the 1960s (see Beven, 2021) and that still haunt the field today, with countless papers still treating runoff as overland flow in areas with high infiltrability.

Finally, despite these modern criticisms and updates, Perrault's place in hydrological history is secure. He *was* the first to bring quantitative analysis to fundamental questions of the terrestrial water cycle. Ironically, even for someone we might call the first field hydrologist, Perrault – in similar ways to those who had come before him – also had to resort to speculation to explain springs in the mountains. He did not really explain how the flood waters in rivers are generated – something that he considers to be the major source of groundwaters that can cause springs and the augmentation of river flows at a distance. So, while Perrault marked a turning point in hydrological history by demonstrating, with observations, that rainfall was sufficient to explain the origin of springs, the processes and mechanisms of streamflow generation, and the age distribution of flows leaving the catchment by streamflow and evapotranspiration continue to be an active area of research in the present day.

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References

Arbault, J. and Rat, P., 1974. *Carte géologique de la France (échelle 1/50000), Aignay-le-Duc, carte et notice*. Orléans et Paris: BRGM.

Barontini, S. and Settura, M., 2020. Beyond Perrault's experiments: repeatability, didactics and complexity. *Hydrology and Earth System Sciences*, 24 (4), 1907–1926. doi:10.5194/hess-24-1907-2020.

Beven, K.J., 2021. The era of infiltration. *Hydrology and Earth System Sciences*, 25 (2), 851–866. doi:10.5194/hess-2020-308.

Beven, K.J., 2024. On "The Science of Waters" by Père Jean François from 1653. *Hydrological Sciences Journal*. [Submitted]. 1–10. doi:10.1080/02626667.2024.2377352.

Beven, K.J. and Chappell, N.A., 2021. Perceptual perplexity and parameter parsimony. *WIREs Water*, 8 (4), e1530. doi:10.1002/wat2.1530.

Biswas, A.K., 1968. Beginning of quantitative hydrology. *Journal of the Hydraulics Division*, 94 (5), 1299–1316. doi:10.1061/JYCEAJ.0001875.

Biswas, A.K., 1970. *History of Hydrology*. Amsterdam: North Holland Publishing Co, 336.

Delorme, S., 1948. Pierre Perrault, auteur d'une traite de l'origine des fontaines et d'une théorie de l'expérimentation. *Archives Internationales d'Histoire Des Sciences*, 27 (23), 388–394.

Deming, D., 2014. Pierre Perrault, the hydrologic cycle and the scientific revolution. *Ground Water*, 52 (1), 156–162. doi:10.1111/gwat.12138.

Dooge, J.C.I., 1959. Quantitative hydrology in the 17th century. *La Houille Blanche*, 6, 799–807. (in both French and English). doi:10.1051/lhb/1959063.

Dooge, J.C.I., 1974. The development of hydrological concepts in Britain and Ireland between 1674 and 1874. *Hydrological Sciences Bulletin*, 19 (3), 279–302. doi:10.1080/02626667409493917.

Duffy, C.J., 2017. The terrestrial hydrologic cycle: an historical sense of balance. *Wiley Interdisciplinary Reviews: Water*, 4 (4), e1216. doi:10.1002/wat2.1216.

Hewlett, J.D. and Hibbert, A.R., 1963. Moisture and energy conditions within a sloping soil mass during drainage. *Journal of Geophysical Research*, 68 (4), 1081–1087.

Hubbart, J.A., 2011. Origins of quantitative hydrology: pierre Perrault, Edme Mariotte, and Edmond Halley. *Water Resources IMPACT*, 13 (6), 15–17.
IAEA & WMO. (2021). Global Network of Isotopes in Precipitation. The GNIP Database. Available from: https://nucleus.iaea.org/wiser [Accessed 2 Nov 2021].
Jurgens, B.C., Böhlke, J.K., and Eberts, S.M. (2012). TracerLPM (Version 1): an Excel workbook® for interpreting groundwater age distributions from environmental tracer data. Reston, VA: U.S. Geological Survey. [Techniques and Methods Report 4-F3.]
Koutsoyiannis, D. and Mamassis, N., 2021. From mythology to science: the development of scientific hydrological concepts in Greek antiquity and its relevance to modern hydrology. *Hydrology and Earth System Sciences*, 25 (5), 2419–2444. doi:10.5194/hess-25-2419-2021.
La Rocque, A., 1967. *On the Origin of Springs by Pierre Perrault*. New York: Hafner Publishing Company.
Małoszewski, P. and Zuber, A., 1982. Determining the turnover time of groundwater systems with the aid of environmental tracers: 1. Models and their applicability. *Journal of Hydrology*, 57 (3–4), 207–231. doi:10.1016/0022-1694(82)90147-0.
Mariotte, É. (1686). *Traité du Mouvement des Eaux et des Autres Corps Fluides*. (Translated into English by John Theophilus Desaguliers in 1718).
Mather, M.F. and Mason, 1932. *A source book in geology*. New York: McGraw Hill Book Co.
McDonnell, J.J. and Beven, K.J., 2014. Debates—The future of hydrological sciences: a (common) path forward? A call to action aimed at understanding velocities, celerities, and residence time distributions of the headwater hydrograph. *Water Resources Research*, 50 (6), 5342–5350. doi:10.1002/2013WR015141.
McGuire, K.J. and McDonnell, J.J., 2006. A review and evaluation of catchment transit time modeling. *Journal of Hydrology*, 330 (3–4), 543–563. doi:10.1016/j.jhydrol.2006.04.020.
Morgenstern, U., *et al*. 2015. Using groundwater age and hydrochemistry to understand sources and dynamics of nutrient contamination through the catchment into Lake Rotorua, New Zealand. *Hydrology and Earth System Sciences*, 19 (2), 803–822. doi:10.5194/hess-19-803-2015.
Morgenstern, U., Stewart, M.K., and Stenger, R., 2010. Dating of streamwater using tritium in a post nuclear bomb pulse world: continuous variation of mean transit time with streamflow. *Hydrology and Earth System Sciences*, 14, 2289–2301. doi:10.5194/hess-14-2289-2010
Morgenstern, U. and Taylor, C.B., 2009. Ultra low-level tritium measurement using electrolytic enrichment and LSC. *Isotopes in Environmental and Health Studies*, 45 (2), 96–117. doi:10.1080/10256010902931194.
Nace, R.L., 1974. Pierre Perrault: the man and his contribution to modern hydrology. *Journal of the American Water Resources Association*, 10 (4), 633–647. doi:10.1111/j.1752-1688.1974.tb05623.x.
Perrault, P. (1674). *De L'Origine des Fontaines*. Paris: chez Pierre le Petit, Printer and Bookseller in ordinary to the King, Rue Saint Jacques à la Croix d'or.
Rozanski, K., Gonfiantini, R., and Araguas-Araguas, L., 1991. Tritium in the global atmosphere: distribution patterns and recent trends. *Journal of Physics G: Nuclear and Particle Physics*, 17, S523–S536. doi:10.1088/0954-3899/17/S/053
Schmidt, A., *et al*., 2020. Overview of tritium records from precipitation and surface waters in Germany. *Hydrological Processes*, 34 (6), 1489–1493. doi:10.1002/hyp.13691.
Stewart, M.K., Morgenstern, U., and Cartwright, I., (2021). Comment on "A comparison of catchment travel times and storage deduced from deuterium and tritium tracers using StorAge Selection functions" by Rodriguezet al. (2021). *Hydrology and Earth System Sciences*, 25 (12), 6333–6338. doi:10.5194/hess-25-6333-2021.
Tromp van Meerveld, I. *et al*., 2007. Effect of bedrock permeability on subsurface stormflow and the water balance of a trenched hillslope at the Panola Mountain Research Watershed, Georgia, USA. *Hydrological Processes: An International Journal*, 21 (6), 750–769. doi:10.1002/hyp.6265.
Tuan, Y.F., 1968. *The Hydrologic Cycle and the Wisdom of God*. Toronto: University of Toronto Press.
Wang, H. *et al*., 2023. A 1000-yr record of temperature from isotopic analysis of the deep critical zone in central China. *Geophysical Research Letters*, 50 (5). doi:10.1029/2022GL101054.
WISER Database. (2021). Available from: https://nucleus.iaea.org/wiser [Accessed 2 Nov 2021].
Zaslavsky, D. and Sinai, G., 1981. Surface hydrology: IV flow in sloping, layered soil. *Journal of the Hydraulics Division*, 107 (1), 53–64. doi:10.1061/JYCEAJ.0005606.

Appendix

Tritium was measured at the GNS Water Dating Laboratory using electrolytic enrichment by a factor of ~90 (reproducibility better than 1%) prior to liquid scintillation counting using Quantulus™ low-level counters (Morgenstern and Taylor 2009). The detection limit of this method is 0.02 tritium units (TU; 1 TU is equivalent to $^3H/^1H = 10^{-18}$). Groundwater dating uses convolution of the time-dependent tritium input concentrations via the rain into and through the groundwater system, with a suitable system response function, and matching of the model output to the tracer concentrations measured in the spring water (Maloszewski and Zuber 1982). The model parameters are the mean transit time (MTT) of the water, and the fraction of exponential flow volume within the total flow volume (%). The exponential piston flow model (EPM) was chosen to account for mixing of groundwaters with different flowpath lengths, and therefore different ages. Models have been fitted to the data using Microsoft Excel-based Tracer LPM software from the United States Geological Survey (Jurgens *et al*. 2012).

With the Trier tritium record being closest to the source catchment of the Seine River, this record (Schmidt *et al*. 2020, Stewart *et al*. 2021) was used as input, with earlier data covered by the Vienna record (WISER database (2021) of the International Atomic Energy Agency, IAEA and WMO 2021).[9]

Tritium is produced naturally in small quantities in the Earth's upper atmosphere by the interaction of cosmic rays with N nuclei. However, large amounts of anthropogenic tritium were injected into the atmosphere during the Northern Hemispheric atmospheric thermonuclear weapons tests, mainly in the early 1960s (Rozanski *et al*. 1991) causing a large degree of ambiguity in age interpretations of groundwater and surface water during the following decades.

While due to the much smaller amount of bomb-tritium in the Southern Hemisphere tritium concentrations in rain had dropped to pre-bomb levels already by the mid-2000s (Morgenstern and Taylor 2009), enabling water transit time estimates from single tritium data and therefore identification of changing MTT (Morgenstern *et al*. 2010), groundwater in the Northern Hemisphere recharged during the time of the tritium bomb-spike can still contain elevated (above cosmogenic) tritium concentrations.

Figure 4 shows tritium concentrations of water samples collected from the source of the Seine River between 2017 and 2022, together with the model output of very young water using the Trier tritium record (grey curve). The elevated tritium concentrations of the Seine source water, compared to that of very young water, clearly indicate that this spring contains large fractions of old water recharged in the time following the bomb-spike. The tritium concentrations measured in the spring declined over time, according to the radioactive decay of tritium, and mixing with older low-tritium groundwater.

The tritium data between 2017 and 2021 (blue symbols in Fig. 4) cannot be matched with a young MTT. The grey curve shows the tritium output for very young water with MTT of 1 year, and a typical fraction of 70% of exponential age distribution within an EPM. Even with extreme mixing parameters it is not possible to match the data with any MTT younger than 40 years. The time series

[9]WISER is "Water Isotope System for Data Analysis, Visualization and Electronic Retrieval", a self-service platform for data of the Global Networks of Isotopes in Precipitation (GNIP) hosted within the IAEA's repository for technical resources. WMO is the World Meteorological Organization.

data can be matched well with MTT of 52 years, and 37% exponential age distribution within an EPM (blue curve). This mixing parameter is realistic for a spring which likely involves fracture flow in limestone formations.

The tritium concentration of the sample collected from the source of the Seine River in 2022, during extreme drought conditions (red symbol), is slightly elevated compared to the declining trend of the previous data (blue curve). This indicates even older water in the spring discharge during this time, with higher bomb-tritium contribution. Using the same model parameter of the EPM obtained from matching the time series data (blue symbols), the tritium concentration during the 2022 drought condition can be matched with MTT of 65 years (red curve).

Even when considering a relatively high uncertainty of the tritium input of 10%, the conclusion is robust that the spring of the Seine River discharges relatively old water with MTT of c. 50 years during normal baseflow conditions, and that the water is c. 15 years older, with MTT of c. 65 years, during extreme drought conditions.