

Reply to Reviewer's comments

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1 Reply to Reviewer #1 (Dani Or)

We thank Prof. Dani Or for the comments. We accounted for them in the revised version of the paper, as we report in the point-to-point reply. For the sake of clarity, recalls of Reviewer's suggestions are *emphasized* in the following notes. The reply includes Authors' Comment #1 previously published in the discussion, as a starting point.

1. *Generally, the treatment tends to be superficial and not as definitive as the account of Raymond Nace 1974 (Wat. Res. Bull. Am. Wat. Res. Ass.) regarding Pierre Perrault's contributions to hydrology (and, as the authors argue, to systematic experimental approaches to hydrology).*

Nace's article of 1974 (doi:10.1111/j.1752-1688.1974.tb05623.x) represented an important source for our paper, however the aim and methods of the two papers are essentially different. Nace presented both a thorough historical and biographical account of Perrault's life and a detailed summary of the content of Perrault's book. Our focus is rather on the epistemological value of Perrault's experiment and on the relationship between his work and Scientific Revolution. For example we analysed Perrault's text and found relevant correspondences between his sentences and that of thinkers such as Pascal and Descartes. Moreover we analysed Perrault's view on experiments and experimental method as expressed in the letter to Mr. Huygens, which has been quite ignored by previous works on the argument. In the present version of the paper, we better recalled Perrault's main achievements in the Introduction, on the basis of Nace's paper, as it was suggested also by Reviewer #2.

2. *The attribution of the experiments that formed the basis of his early research, namely the capillary rise observations of Magnanus (Maignan) as reported by Schott are very sketchy, and despite their importance are poorly attributed*

Maignan's experiment is reported in the third part (*Philosophia naturalis, Natural philosophy*, Chapter 14, Proposition 14) of his *Cursus philosophicus... (Philosophical course...)* published in 1653. In the present version of the paper we added the full reference to Maignan's experiment and some more details. Yet his report is as detailed as what is reported by Schott (1663), most of which was already reported in the previous version of the paper. Both Maignan and Schott complete their comment with a brief discussion on how a fluid in a sponge behaves as the water in the soil, but it is noteworthy that Maignan presents his experience in the context of a wider discussion *De gravi & levi*, i.e. *On the gravity of things*, deeply framed in Aristotelian Physics, and his experience is not directly referred to a discussion on the hydrological cycle. It was Schott who took Maignan's experience and used it to support his dissertation on the hydrological cycle. We preferred to omit the description of the rise in a sponge, because in our opinion did not added more regarding Maignan's and Schott's comprehension of water hydrology, than it was already expressed by the citation.

3. *Considering the focus on epistemology advanced by the authors, I find it remarkable that the authors have chosen to make focus on Aristotle in reference to to ancient school of thoughts when a pivotal book by Lucretius Caro (De Rerum Nature - on the nature of things) discusses much more definitively the basics and far more advanced concepts relevant to hydrology than Aristotle's work (Caro was influenced by the scientific school of Epicurus and wrote about 200 years after Aristotle published Meteorology). For example, the role of the sun in the process of evaporation was well known in Lucretius Caro's time (99-55 BC) as he writes «The same, spread out before the sun, will dry; Yet no one saw how sank the moisture in, Nor how by heat off-driven. Thus we know, That moisture is dispersed about in bits Too small for eyes to see.»*

We agree that Lucretius had a quite advanced understanding of the water cycle, but we did not focus on his work, because he is not mentioned in Perrault’s book. In fact Perrault cursory mentioned Epicurus, while a reference to Lucretius may be found in Schott. However they did not enter in detail of the comparison between their own understanding of the hydrological cycle and Epicurus’ and Lucretius’ ones, as their main term of reference is always the Aristotelian tradition, which was followed by many scholars until Perrault’s age and beyond.

4. *We all agree that the work of Perrault was very important for modern hydrology as a scientific discipline – hence, it seems a bit odd that the authors have chosen to “recycle” an old exercise by the main authors to focus on unsaturated flow parameterization towards explaining the incomplete understanding of unsaturated flow at the time (it seems similar to Philip et al (1989, WRR - <https://doi.org/10.1029/WR025i001p00016> that relished the “surprise” of Perrault for not finding water in the buried clay pot experiment. . .) In other words, both the Hydrus experiment of Barontini, and the general tendency to glorify present state of knowledge regarding the unsaturated state does not add much insight nor appreciation of the the historically significant work of Pierre Perrault. In my view, the parameterization and interpretation (through modern tools) of unsaturated flow are detrimental to the main story of this paper*

In our opinion, relevant keys to enlighten the cultural importance of Perrault’s experiments, also by an epistemological point of view, are their repeatability and their didactic implications for modern students. Moreover, far from the idea both of glorifying modern models of soil hydrology with respect to ancient understandings, and of glorifying Perrault’s experiments with modern frameworks, we think that put ancient conclusions at a test with modern theories is a constructive exercise to deeply understand ancient Authors’ comprehension of the phenomena.

This is why we presented (for the first time, the laboratory technical report being on its way to be published) some results of the laboratory repetition of the experiments. The fact that we may qualitatively and, at some extents, quantitatively repeat Perrault’s experiments, more than three centuries later, emphasizes their relevance in the context of the Scientific Revolution.

Then, we proposed a discussion on the didactic implications of teaching the soil hydrology through Perrault’s experiments, and in this context we reported some aspects of a numerical experiment we performed some years ago. Yet we did not reported the results of the reanalysis, as they have already been published in the referred work (Barontini et al., 2013, doi:10.1016/j.proenv.2013.06.067). Here our focus was to propose a discussion on the framework that was followed, with respect to its didactic usefulness.

In the revised version of the paper added a reference to the buried clay pot experiment, performed by Pierre’s brother Charles and by Philippe de la Hire (Philip et al., 1989, doi:10.1029/WR025i001p00016), in view of contextualizing Pierre’s importance in the context of his age. At the same point we referred also to Mariotte’s recognition of the importance of macropores for percolation.

5. *I am not convinced by the argument that Perrault pioneered and contributed to complexity, perhaps to experimentation – a more critical (and much earlier) thinker was Lucretius Caro that anticipated modern hydrology (and atomistic theories) – but this is my view. . .*

We agree that it would be excessive to define Perrault as an epistemologist of complexity: it is always important, while discussing such issues, to bear in mind the historical context. However, Perrault’s experience in soil hydrology led him to general reflections on the limits of experimental method. These reflections are not our subjective opinions: in the letter to Mr. Huygens Perrault clearly and openly expresses his perplexities about the blind faith in experiments that seems to dominate some of his contemporaries. As far as we know, nobody has yet focused on this aspect of Perrault thought, and we find it interesting because it partially clashes with the typical image of a pioneer in Scientific Revolution.

6. *Since this is an opinion piece with subjective interpretation of the work and Pierre Perrault to early hydrology and thus is a historical narrative – I am not in a position to ask the authors to write their piece the way I would have liked to see, but I hope the comments are useful.*

We hope that this new version of the paper contributes to clarify our perspective on Perrault’s opus.

2 Reply to Reviewer #2 (Okke Batelaan)

We thank Prof. Okke Batelaan for the appreciation and the suggestions. We accounted for them in the revised version of the paper, as we report in the point-to-point reply. For the sake of clarity, recalls of Reviewer's suggestions are *emphasized* in the following notes. The reply includes Authors' Comment #2 previously published in the discussion, as a starting point.

1. *The main problems can be summarized as: 1: The language and structure of the text is not good. It would strongly benefit from a detailed English editing and some rewriting of sections to make certain aspects clearer. 2: Although the paper does not focus on the main scientific achievements of Perrault, the authors cannot assume that the reader is fully aware of these. They may have been highlighted in the paper of Nace (1974), however that paper might not be directly available (I had to order it).*

We reviewed the paper according to the suggestions, please see below in the detailed comments;

2. *I suggest that the authors add the reference to English translation of Perrault's work. This makes it possible for interested readers to trace and read the work itself. La Roque, A. (1967). On the origin of springs, Pierre Perrault (translation). New York and London, Hafner Publishin.g Co.*

All the citations of Perrault's opus were taken from La Roque's 1967 translation, but in the first version of the paper we chose to cite it as Perrault (1967) and we did not note that the compiler missed the translation note in the references section. In the present version we explicitly recalled the (main) translators directly in the reference citation, so that they are acknowledgeable by the reader. The resulting citation is e.g. Perrault and LaRoque (1967);

3. *the abstract does not represent a proper summary of the main text, currently it reads more like an introduction. It needs to be completely rewritten.*

The abstract was modified according to the suggestion. Particularly we shortened the first part (first two paragraphs), relieving its introductory style and better focusing on Perrault's opus. Than we better evidenced which are the focus and the original contribution of the paper in the second part.

4. *The introduction should better explain/summarize the main achievements of Perrault as known and described by e.g. Nace (1974). Then is should explain what the issue is that is not known well about Perrault and how this paper will enlighten us in showing these aspects of Perrault's work.*

We reorganized the Introduction according to the suggestion of firstly recalling Perrault's main achievements and enlightening Nace's (1974) contribution to their comprehension, and then of better detailing our focus. We also enucleated the analysis of the cultural context at Perrault's ages in a standing-alone new Section 2, between the Introduction and the section regarding the comparison between Perrault's and Schott's opus;

5. *The English grammar and spelling needs to be improved. Now there are sentences, which are difficult to understand or where the formulation is imprecise(...)*

The style of writing is also with a lot of long sentences and paragraphs, which makes it more difficult to follow. An example is p6, line 23-27. Line 4 page 2, '...in order to become a modern science, Hydrology needed two steps...'; I do not like this style of de-personified subjects. Sciences, including hydrology is advanced by people, crediting then the science itself with steps 'needed' is, especially in a historical oriented paper, to be avoided

English grammar and spelling were thoroughly reviewed, and too long sentences were cut in order to make the paper better readable. In the previous version of the paper we capitalized the subjects (Hydrology, Physics, etc.) according to a common usage in the historical and philosophical milieu. We preferred to maintain this usage in a revised manuscript, and we paid attention avoid it when it was misleading, as in the cases raised by the Reviewer. In that cases we rephrased the sentence;

6. *E.g. the very first words of the abstract state: 'The studies conducted...', which studies do the author refer to?*

We referred to naturalistic and philosophical studies. The sentence was rephrased while reviewing the abstract;

7. *P.6, line 21: Experiences?*: The word was substituted with *experiments*, thanks for the note;
8. *not all symbols of the equations are explained. Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated?*
We checked all the symbols. Now all of them should be properly recalled.
9. *I did not find the explanations on the experiments (section 4 and 5) and the accompanying figures very clear, I suggest some strong editing of these sections as well.*
Sections 4, 5 and 6 (actual numbers) were accurately read and partially rephrased in order to avoid unclear statements. We better detailed the captions of the corresponding Figures;
10. *Add reference to La Roque*: Please refer to item 2 in this list.

Beyond Perrault's experiments: Repeatability, didactics and complexity

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Abstract. The naturalistic and philosophical studies conducted in the second half of the ~~Sixteenth-Century~~ XVII century were crucial both for the birth of ~~the~~-modern hydrological science and ~~for the~~-modern epistemology. Thanks to quantitative observations and to the new experiment-based scientific approach, the Sun was about to be fully recognized as the engine of the hydrological cycle, ~~instead of an endogenous engine within the Earth, originally conjectured by Aristotle to explain the~~
5 ~~water supply of great rivers~~. In this context of great vitality and rapid cultural changes, ~~two works were published on~~ Pierre Perrault published his classical opus *De l'origine des fontaines* (On the origin of springs-

In 1663 Gaspar Schott published the *Anatomia physico-hydrostatica fontium ac fluminum* (Physical-hydrostatic anatomy of springs and rivers)-, deeply rooted in the Aristotelian epistemology and based on the ancient humanistic and dialectical method. In this book, Schott cited some observations recently made about the capability of the water to rise within-) in 1674.

10 The opus presents a discussion on the origin of springs and contains the report of a set of experiments of water flow through a soil column. Pierre Perrault referred to these observations as a starting point to design the experiments reported in his classical opus *De l'origine des fontaines* (On the origin of springs), published in 1674. With this approach, which may be considered the first of modern hydrology.

Aiming at contributing to understand the importance of Perrault's opus, we will discuss his epistemological relevance by
15 looking at the novelty of his approach, at the repeatability of the experiments, at the intriguing didactic aspects for modern teaching of hydrology, and at his attitude to face the complexity of hydrological processes.

Perrault places himself in the perspective of a deeply renewed epistemology: ~~only a decade passed between the publication of Schott's opus and Perrault's one, but their perspective is radically different.~~

~~At the same time, the questions posed on-~~ On the basis of our analyses he seems to be aware that the processes involved in
20 the hydrological cycle and on the soil hydrology-, which in soil hydrology are hardly reproducible by means of a controlled laboratory model, severely tested-. This circumstance severely put the modern scientific approach to a test at its beginning -
~~Perrault seems to be aware of such difficulties and-, after discussing the results of the experiments, he moves the point of view from the scale of the laboratory model, to that of the catchment. This choice makes him a progenitor of the contemporary~~
and some of Perrault's epistemological and methodological reflections lead to nodal points of the modern epistemology of
25 ~~complexity, which is framed both on laboratory analysis and on cases study.~~ Thus even if Perrault's conclusions ~~went in the~~

~~direction of followed~~ the ancient opinion, his work is not only seminal for hydrology, but also it helps to enlighten some intricate features of scientific revolution.

~~Aiming at contributing to understand the importance of Perrault's opus, we will discuss his epistemological relevance through the lens of the repeatability of the experiments, of the intriguing didactic aspects which, starting from his experiments, arise for modern teaching of hydrology, and of his attitude to face the complexity of the hydrological processes.~~

1 Introduction

By the half of the XVII century, Hydrology was at a crucial passage of its evolution, because the ~~Sun was about to be fully reeognized~~ scientists were about to fully recognize the Sun as the engine of the hydrological cycle, ~~instead of an endogenous one within.~~ The debate on what the engine of the hydrological cycle was, whether it was the Sun or the Earth, originally conjectured by Aristotle to explain the water supply of great rivers. Anyway, in order to become a modern science, Hydrology needed two steps, that are the concept of scientific experiment and the assessment of the quantitative evaluation of the water cycle is ancient and it dates back to Aristotle. He in fact assumed that, whereas little rivers and small springs could be supplied by subsurface reservoirs, the amount of water flowing in big rivers was too great to be stored in any reservoir and, thus, it could not derive entirely from precipitations. Therefore he concluded that big rivers must be supplied by a continuous evaporation and condensation process, acting within the Earth as a result of an unknown underground source of heat (Aristotle and Lee, 1952, Book 1). By this assertion, Aristotle openly disagreed with previous Presocratic philosophers who had already given a substantially correct view of the hydrological cycle (Brutsaert, 2005, p.560 and following). The discussion on what the relative importance of the two engines was characterised the scientific debate until XVII century and beyond (see Biswas, 1970; Duffy, 2017, for an overview), when quantitative observations and a new experiment-based scientific approach proved that precipitations are adequate to account for all the water flowing in rivers.

Pierre Perrault (1611—1680) was one of the first, if not the first to uphold such an idea. In his ~~classieal~~ opus *De l'origine des fontaines* (On the origin of springs, Figure 1), ~~Pierre Perrault (1611—1680) took both these steps. He~~ Perrault devised methods of measurement, performed experiments and collected many observations both to assess the water balance at the basin scale and to understand the water movement in the upper soil layers (Perrault, 1674, 1678; Perrault and LaRoque, 1967; Perrault, 1986). Perrault seemed to be aware that his measurements of the water balance where quite raw and affected by some inaccuracies (see Section 7). However these errors compensated each another, so that his assessment of the water balance turned out to be quite correct (Gascuel-Odoux, 2000). A few years later, Perrault's countryman Mariotte (1686) refined and improved his method and offered the first rigorous basin scale measurement in the history of Hydrology. In fact, Perrault paved the way for the effective comprehension of the water cycle, although he himself did not understand it correctly. Indeed even if he showed with his experiments that precipitations might provide much more water than necessary to supply springs and rivers, yet he still decided to subscribe Aristotle's position.

Despite these limits, Perrault's contribution to Hydrology has been remarkable, as already illustrated in the seminal article by R.L. Nace, published in 1974, in occasion of the Tercentenary of Scientific Hydrology (Nace, 1974). The *Origine* contains a

number of significant insights on various hydrological matters, such as the ideas of bank and flood–plain storage and return flow (even if he had no name for these processes). He also proposed several accurate observations on soil, weather and climate, not to speak of his acute considerations about phenomena like evaporation, condensation and infiltration (for more detailed discussions of single is
5 (Nace, 1974).

The aim of this paper is to clarify the new frame of mind, which made Hydrology possible as a science. Indeed, Hydrology needed two steps in order to become a modern science: they were the concept of scientific experiment and the assessment of the quantitative evaluation of the water cycle. Perrault took both these steps. His work therefore ~~attests that~~ allows to understand ~~how~~ the birth of ~~the~~ modern hydrological science ~~is was~~ strictly linked to the Scientific Revolution of the XVII century. ~~Indeed, Perrault was able to achieve the passage~~ In fact, Perrault paved the way to scientific hydrology because he had a new, critical attitude towards tradition, ~~which was also born by~~ also shared with scientist–philosophers like Descartes and Pascal (Tixeront, 1974).

For this purpose, we will reconstruct the cultural and intellectual context in which Perrault operated, highlighting the assonances between his position and that of the major scientists and philosophers of the age (Section 2). Afterwards, we will
15 focus more specifically on Perrault’s book, adopting a comparative method of analysis, to show the novelty of his approach to hydrological matters compared to its contemporary Gaspar Schott (Section 3). Then, we will analyse Perrault’s experiments in–depth and present today’s repetition of them, on the basis of the reports contained in his book, thus stressing the importance of the notion of repeatability (Section 4 and 5). In the following section we will enhance the didactical aspects of Perrault’s experiments, that can be used to illustrate the general aspects of the scientific practice and the specific problems connected with
20 soil hydrology (Section 6). In conclusion, we will go into more detail about Perrault’s epistemological assumptions, contained in his *Letter to Mr. Huygens*, by showing interesting correspondences between Perrault’s anti–dogmatic and problematising approach, and some issues arising from the modern paradigm of complexity in Hydrology (Section 7 and Conclusion).

2 Perrault’s cultural and scientific context

Perrault’s seminal opus may be framed in the context of the *querelle des anciens et des modernes* (controversy between
25 the Ancients and the Moderns), a spirited debate that took place in France during the second half of the XVII century and had profound resonances all–over Europe (Fumaroli, 2001). Although the controversy emerged in a literary milieu, it rapidly spread in the scientific field ~~, so as to intertwine and intertwined~~ the debates of the nascent Scientific Revolution. Pierre Perrault was a cultured man of noble origin and he played a role in the controversy, as well as his brothers, who were prominent figures in various fields of politics and culture (Nace, 1974). For instance Perrault’s brother Charles, a renowned poet of the age, was ~~the~~
30 author of four volumes ~~that~~ focused on the question of whether the primacy in art and knowledge should lie with the Ancients or with the Moderns (Perrault, 1688–1697).

The epistemological meaning of this opposition was immediately evident for the intellectuals of the age: at stake ~~there~~ was the correct way of achieving the truth. Whereas the supporters of the Ancients defended the pre–eminence of the old principle

of authority, the Moderns put forward the idea that knowledge must be grounded only on reason and experience. The *querelle* can thus be seen as the way French intellectuals of the ~~age~~ âge *d'or* dealt with the deep cultural transformations of their time. ~~Indeed, the comparison between the~~ The comparison between modern knowledge and skills and those inherited from Antiquity represented for them an effort to become aware of the historical and intellectual breakup they were living in. Like his brother

5 Charles, Pierre Perrault ~~took side-sided~~ with the Moderns ~~, applying in his research field and applied~~ the new experimental method to the problems of ~~soil hydrology~~ Hydrology for the first time. Therefore, it is ~~no surprise~~ not surprising to find in his writings a strong reflection of the spirit of the Scientific Revolution and a thorough awareness of its achievements. He appears fully conscious of the difference between his own approach and that of the predecessors, and considers the experiments as the primal source of scientific knowledge:

- 10 I know all too well that it is to experiments that we owe the finest knowledge we now have concerning the things of nature which had been unknown to Antiquity; and I base myself only on such principles (Perrault and LaRoque, 1967, p.11).

In the introductory *Avertissement* (Warning) of the *Origine*, Perrault explains his method and circumscribes the field of his enquiry, ~~stating~~ He states that he will not present “great reasonings of Physics”. Rather, he will speak “with a simplicity

15 which can appeal to the most ordinary brains” (Perrault and LaRoque, 1967, p.9). In so doing, the ~~author~~ Author immediately distances himself from the Aristotelian approach, according to which Natural Science was a “logical deductive structure derived from uncontestable basic statements or premises” (Applebaum, 2000, p.341). Perrault is not interested in discussing the primal causes of natural phenomena and the principles of Physics. He focuses only on the specific issue of the hydrological cycle, providing sensate experiences to support his opinion: “my intention has been to speak only of that which is obviously perceived

20 by the senses” (Perrault and LaRoque, 1967, p.10). Such a declaration of intents is in-line with the *incipit* of René Descartes’ seminal opus, the *Discours de la méthode* (Discourse on the method), a text that aimed to divulge the correct approach in “conducting one’s reason and seeking truth in sciences”, as stated in the title (Descartes, 1637; Descartes and Maclean, 2006). Descartes plainly rejects the traditional centrality of classical studies and, therefore, the authority of past philosophers. On the contrary, he claims that “good sense is the most evenly distributed thing in the world” and that science is in principle accessible

25 to anyone, provided that one proceeds step by step, “for it is not enough to possess a good mind; the most important thing is to apply it correctly” (Descartes and Maclean, 2006, p.5). According to Descartes, the method should not start from general principles derived ~~by the~~ from philosophical heritage:

As for the ~~other~~ other disciplines, in so far as they borrow their principles from philosophy, I concluded that nothing solid could have been built on such shaky foundations (Descartes and Maclean, 2006, p.10).

- 30 On the contrary, the path of science can only consist in an analytically ordered succession of experiences, each one supported by the constant check of reason. Thus, in this new perspective, reason does not dictate abstract principles, rather it plays an ordering and regulative role. At the same time, reason and experience are not opposite, for the latter provides the indispensable “matter” to any reasoning (Descartes and Maclean, 2006, p. 20).

A similar centrality of experience can be found also in Pascal's *Préface pour un traité du vide* (Preface to the treatise on vacuum, written in 1651), which is another relevant reference to understand Perrault's position (Pascal, 1954, 1910). Here, the French philosopher and scientist states that whereas authority is essential with regard to literary and historical issues, it is useless in the domain of matters that fall under our senses, such as the investigation of nature. In a few pages Pascal establishes the basis for the separation between humanistic and scientific ~~attitude~~attitudes, which still persists nowadays, yet with important differences (Preti, 2018). In fact, Pascal's separation between the so-called "two cultures" (Snow, 1998) is an argument against those academicians who wished to submit science to the dogmatic authority of Metaphysics and Theology. According to the author, the investigation of nature is characterised by "freedom", as it is based on experience, whereas "dogmatism" is typical of literary, philosophical and theological studies. This position paved the way to the overcoming of Aristotelianism: as ~~far~~long as experience plays a crucial role, the Philosopher's word could not be ~~the final word~~authoritative in the knowledge of nature. In his *Avertissement* Perrault shares this posture towards the past authors without falling into arrogance, as he claims that:

It is not an extraordinary thing to examine the ideas of any author, it is permitted to the least disciples to ask the most renowned Philosophers, in the very school where they have most credit, the reasons for the propositions that they have ~~avaneed~~(-)advanced (Perrault and LaRoque, 1967, p. 10).

Beyond the consonance of the epistemological attitude, it is also noteworthy that Pascal's role in the development of scientific hydrology was not merely speculative. He knew the work of Galilei and Torricelli, which shaped modern Mechanics and Hydraulics, and he tried in many different ways to reproduce the experiment performed in 1644 by Torricelli, to measure the atmospheric pressure (Tixeront, 1974; Applebaum, 2000). His measurements and observations were important terms of comparison for the implementation of Perrault's experiments. Although Perrault criticises some of Pascal's assertions on specific issues (Perrault and LaRoque, 1967, p.150), the epistemological perspective and the method that underpins his work refers to ~~the position of~~ Pascal's *Préface*. On this basis, we can claim that Perrault is permeated with the critical attitude that should characterise a *modern* scientist. In his critique of both ancient (e.g. Aristotle) and modern scholars (e.g. Nicolas Papin) he makes use of concepts drawn from the works of Bacon and Galilei, Descartes and Pascal. Thus the driving forces in the passage ~~to~~towards quantitative hydrology are the overturning of the primacy of *auctoritas* and the centrality of experiments as a primal source of knowledge. ~~Having clarified the major cultural premises of Perrault's work, in Section 3 Perrault's opus will be compared with that of his contemporary Gaspar Schott, to point out the shift of paradigm he brought in soil hydrology. In the followings, Perrault's experiments will be investigated through the lens of their repeatability (Sections 4 and 5), presenting also their possible didactic implications (Section 6). Finally Perrault's seminal contribution to the perception of complexity in the hydrological science will be enlightened (Section 7).~~

3 Comparison between Schott's and Perrault's opus

How deep ~~was~~ the paradigmatic renewal fostered by Perrault with his opus was, may be realized by comparing the *Origine* with another opus, the *Anatomia physico-hydrostatica fontium ac fluminum* (Physical-hydrostatic anatomy of springs and rivers,

Figure 2), published only ten years before by the Jesuit Gaspar Schott (Schott, 1663). The Origine was written in French, so to be accessible to a broader audience, whereas the Anatomia was written in Latin. In his opus, Schott carefully reviews and discusses the opinions of ancient and modern authors about the origin of springs and rivers (see Table 1), ~~finally stating-~~ Finally he states his own conjecture, according to which (a) the sea is the origin of most of the springs, and (b) the water rises from the sea mostly due to the greater altitude of the sea, with respect to the mountains. ~~The Anatomia, which was written in Latin—whereas the Origine was written in French, thus being intended to be open to a broader audience—, is an opinionones (opinions) book, deeply rooted in the ancient humanistic and dialectical approach and far from the modern scientific method.~~ A comparison between the form and structure of the two texts reveals further important differences, despite the short lapse of time which separates them.

~~As a start, it~~ The Anatomia appears to be an opinionones (opinions) book, deeply rooted in the ancient humanistic and dialectical approach and far from the modern scientific method. It is noteworthy how Schott felt it necessary to focus on histories of ancient springs, drawn by classic literary sources, in which mythological and imaginary witnesses are mixed together with historical and geographical accounts (Schott, 1663, pp.12–63). In Schott’s ~~view~~ frame of mind, the purpose of scientific description does not conflict with the recreational intent of literature and the stories handed down by the Ancients still represent for him the point of departure for intellectual investigation. Therefore it seems that he does not take into account the distinction between humanistic and scientific discourse proposed by Pascal. In contrast, Perrault does not take ~~in any consideration any~~ consideration in the mythological and literary tradition about springs, showing a deep awareness of the above-mentioned separation between the “two cultures”. However, both the authors provide an extensive and detailed discussion of past scholars’ opinions about the origin and nature of springs and rivers. Here the difference between Schott and Perrault lies ~~both~~ (a) in the way ~~the discussion is conducted and in the~~ of discussing texts and (b) in the choice of the authors which are cited (or not) by them (see again Table 1). It can be assessed in general terms that Schott’s text does not present a clear demarcation between the exposition and the critique. In addition, his critiques appear often to be grounded on philosophical considerations and also on the appeal to authority arguments. In particular, he dedicates a detailed examination ~~to of~~ the Holy Scriptures, which are regarded to be reliable also as a scientific treatise (Schott, 1663, pp.88–102).

By contrast, Perrault’s opus provides, for each author discussed, a clear separation between exposition and critique and, most important, he motivates his objections on the basis of the experimental results which are presented in the Second Part of the work. He does not consider the Holy Scriptures as a pertinent source in the context of his work. This choice represents another indication of his critical attitude towards the principle of authority. Furthermore, Perrault discusses a set of authors that he defines as supporters of the *Opinion commune* (Common opinion) (Perrault, 1674, p.150 ff.). These authors are Vitruvius, Bernard Palissy, Paul Gassendi and père Jean-François. It is noteworthy that Vitruvius’ capital opus *De Architectura* (On architecture) was translated into French by Perrault’s brother Claude, one of the major architects of the time, in 1673 (Vitruvius and Perrault, 1673). All these authors share an interest in the practical application of hydrological knowledge, and all of them are absent from Schott’s treatise. This discrepancy reveals the different epistemological positions held by the two authors: ~~whereas-~~ Schott still considers his work as an essentially intellectual activity and as definitely distant from the practical

problems of technical application. On the other hand, Perrault regards ~~hydrology~~ Hydrology as strictly connected with the sphere of technique and engineering.

It is in our opinion no coincidence that Schott did not refer to Palissy's work. Indeed Bernard Palissy was not a scholar, but ~~an artist-ceramist~~ a ceramist artist. His strong attitude for ~~the~~ technical investigation is reflected also in the *Discours admirable* (The admirable discourses, 1580), where he imagines a polemical dialogue between the personifications of Theory and Practice (Palissy, 1580; Palissy and LaRoque, 1957). The triumph of the latter signifies the superiority of the "vulgar methods" over the scholastic and speculative approach of the traditional philosophy of nature. Although Perrault argues against Palissy and the Common opinion, he agrees with him that practice could teach more than books about nature. However, Palissy's approach still reflects a Renaissance idea of experience, related to ~~the~~ craft work, in which ~~the~~ an artist craftsman subjectively learns from his experience and on the basis of his own sensibility. By contrast, the Scientific Revolution broke the tie between art and knowledge of nature, the latter deriving from a series of ordered experiences whose objectivity is guaranteed by the repeatability of measures. Perrault does not only affirm the superiority of experience over authority, but he also *performs* an experiment and, most importantly, provides an experimental report whose accuracy fits the standards of ~~the~~ modern scientific practice. Differently from Palissy, Perrault felt the necessity of submitting concrete and checkable results in order to support his thesis.

~~Getting back to the comparison between Perrault and Schott, the crucial difference still lies~~ The crucial difference with Schott's opus lies, indeed, in the fact that ~~the former~~ Perrault supports his theses with the report of an experimental activity. In fact, ~~after the reference to experience is not absent in the Anatomia but Schott did not perform the experiment first hand, and his exposition does not match the feature of an experimental report. In his book, he mentions some observations recently made~~ by Maignan (1653) about the capability of water to rise within a soil column:

Fill, with dry sand, a glass pipe opened on both sides, then cover the lower mouth with a cloth so that the sand cannot pour out; and dip the covered mouth into water only for the altitude of a transverse finger: you will observe that water rises a little and all the sand is wetted, up to the height of three palms above the surface of the water [which is] in a vessel (Schott, 1663, p.254, our translation).

Schott's description is a faithful and complete report of Maignan's one. Perrault took a cue from this description to design his own experiments, but there are important differences between the approach of the authors. First, it is worth noting that Maignan does not refer to the experiment in chapter 17, which is devoted to water related issues (*De aqua*), but rather in chapter 14, which is devoted to a classical Aristotelian topic, that is heaviness and lightness of natural bodies (*De corpore naturali gravi et levi*). Second, although Schott and Maignan provide these few approximative measures, their perspective is focused on the qualitative behaviour of the water within the sand. Third, the form of their argumentation is still shaped on the model of the scholastic dialectical disputation between conflicting opinions. Even when elements derived from experience are introduced, their remarks are casual and not crucial in order to address the controversies. On the other hand, Perrault designs experiments precisely in order to support his hypotheses and he places the report of the experiments at a turning point of the book, after which the conclusions are thoroughly and quantitatively discussed. With this approach he places himself in the

perspective of a novel epistemology which reflects the major aspects of the Scientific Revolution. The expunction from the discourse of mythical, literary and religious elements, and the attention to practical and technical applications are combined with a quantitative evaluation of the phenomena. All this makes the design of crucial experiments possible, i.e. of experiences which are diriment and which can be repeated.

5 4 Perrault's experiments

After discussing previous authors' opinions (Perrault, 1674, pp.8–146), Perrault enunciates his idea (Perrault, 1674, pp.148–150, Figure 3); ~~according to which~~. According to him water cannot easily infiltrate, flow through the soil, and reach great depths, but it is retained in the superficial layers, and directly contributes to ~~the~~ evaporation and marginally to refill the surface springs. He submits his theses in contrast with the aforementioned Common opinion (Perrault, 1674, pp.150–152), according to which water could penetrate the soil until it reaches a layer of *terre grasse* (translated as “fatty earth” in Perrault and LaRoque, 1967, p.75) or rocks; ~~that~~. This impervious layer would laterally deflect its pathway until it reaches the surface, so as to form a spring. Perrault disputes this view on the basis of two major objections. First, he calls into question the fact that water could ~~really-actually~~ penetrate the soil to depth; ~~second~~. Second, he doubts that it could spontaneously outcrop (Perrault, 1678, pp.153–154). These issues were discussed few years later also by Mariotte, who recognised the importance of the macropores in water percolation, and by Perrault's brother, Charles. In fact in 1690 Charles performed an experience, together with Philippe de la Hire, during which they buried a clay vessel at a certain depth and connected it with a lead pipe to a cellar, in order to verify the water capability to percolate through the soil (Philip et al., 1989). To prove the validity of his objections, Pierre Perrault designed and implemented an experimental activity, the report of which can be found in the subsequent pages (~~Perrault, 1674, pp.154–160, see Section 4~~)(Perrault, 1674, pp.154–160). He concluded that the water alone has no tendency to deeply penetrate the soil nor to spontaneously outcrop to form springs, thus corroborating his theses (Perrault, 1674, p.160 ff.). The remaining part of the *Origine* contains a general discussion of the hydrological cycle, in which Perrault shows some evidence for the fact that about one–sixth of ~~the~~ precipitation is sufficient to provide ~~the water flowing in the rivers~~ rivers with flowing water (Perrault, 1674, p.204 ff.). Finally he admits that small springs could be affected by precipitations and snow melting, but he points out that the general circulation of water in soil is necessarily supported by a process of evaporation and condensation within the Earth; ~~-. This model is~~ in line with ~~the model that~~ described by Descartes ~~. It is worth noting that the external circulation of the hydrological cycle was originally recognized by some Presocratics (Brutsaert, 2005, p.562), but it was soon coupled by Aristotle with the idea of the presence of an internal evaporation and condensation process, taking place in the Earth's depth (Aristotle and Lee, 1952, Book 1). This dualism of the hydrological circulation underlay all the hydrological culture since Aristotle to Perrault and beyond (see Biswas, 1970; Duffy, 2017, for an overview).~~

30 Finally in his book, Schott reports about some observations recently made by Maignan about the capability of the water to rise within a soil column, to which Perrault will refer as a starting point to design his experiments: Fill, with dry sand, a glass pipe opened on both sides, then cover the lower mouth with a cloth so that the sand cannot pour out; and dip the covered mouth into water only for the altitude of a transverse finger: you will observe that water rises a little and all the sand is wetted, up

to the height of three palms above the surface of the water which is in a vessel (Schott, 1663, p.254, our translation). Despite Schott and Maignan provide these few approximative measures, their perspective is focused on the qualitative behaviour of the water within the sand. The form of Schott's argumentation is still shaped on the model of the scholastic dialectical disputation between conflicting opinions. Even when he introduces elements derived from experience, they seem casual remarks, which are not crucial in order to address the controversies. On the opposite, Perrault designs experiences in order to support his hypotheses and he places the report of his experiments at a turning point of the book, after which the conclusions are thoroughly and quantitatively discussed. With this approach he places himself in the perspective of a novel epistemology which reflects the major aspects of Scientific Revolution: the expunction from the discourse of the elements derived from mythical, literary and religious tradition, and the attention paid to practical and technical applications are combined with the passage to the quantitative evaluation of the phenomena, which makes possible the design of crucial experiments, i.e. of experiences which are diriment and which can be repeated and substantially goes back to the Aristotelian solution (see the Introduction for details). Before presenting the repetitions of his experiments, in the following we will briefly summarize what is reported by Perrault. The measurements given by Perrault are converted into the International System according to the *Toise de Châtelet* system, which entered into force in 1668 (Blamont, 2001, see Table 2).

5 Perrault's experiments

At On p.154 of his opus *the Origine*, Perrault (1674) introduces his experimental activity the experimental activity he performed to clarify the two doubts previously mentioned. We reproduce here his note in the English translation:

Before beginning the discussion of these two difficulties, I wish to describe here an experiment I have made, which may shed a little light on what we have to say (Perrault and LaRoque, 1967, p.78).

His experience is effectually grouped into four experiments that he performed with a leaden pipe, lead pipe, which was filled with various soils and in various imbibition conditions. Before presenting the repetitions of his experiments, in the following we will briefly summarize what is reported by Perrault. The measurements given by Perrault are converted into the International System according to the *Toise de Châtelet* system, which entered into force in 1668 (Blamont, 2001, see Table 2).

During the first experiment Perrault took a leaden-lead pipe, 65 cm long and with a diameter of 4.5 cm. He closed it at-on one side with a cloth and filled it with river sand, sieved with a coarse sieve. He put-held the pipe vertically and dipped it into a wide water-filled vessel, leaving it in this position for one day. After 24 hours, as he reported, he found that the water rose within the soil for-up to 48.7 cm. In-At this point it is not clear how he performed this observation, as elsewhere (at the end of the description of the first experiment) he reports that in order to appreciate how the soil was wetted, he needed to shake the pipe to let the soil slide out-from the pipe. Maybe he reports here a measurement that he performed at the end of the experiment, or he extracted the sand, he-made the measurement and than filled the pipe again to proceed with new measurements. As a first conclusion he reports that he was surprised at such a rise of the water within the column. Then he wanted to check whether a spring could spontaneously outcrop above the water surface. He therefore made a hole about 5.4 cm above the water surface, with a diameter between 1.6 and 1.8 cm, and-in. He added a 5.4 cm long spout that sloped toward the vessel, without touching

the water surface. In order to restore the medium continuity between ~~inside and outside the~~ inside and the outside of the pipe, he added a 5.4 cm long spout, sloping toward the vessel, without reaching the water surface. The ~~the~~ spout was covered by ~~with~~ a grey paper, to ~~evidenece the~~ show any possible wetting, and ~~by a thin sand layer with a thin layer of sand~~. He commented that in ~~the~~ case a spring had onset, then perpetual motion would have ~~established, but been~~ established. On the contrary he only observed that the sand and the paper were wetted, without producing any drop of water. It is worth noting that this case was already recognized by Schott (1663) in his Figure XI (see Figure 4 in this paper), ~~aeccording to which~~. According to it a spring might onset only if the extreme ~~end~~ of the spout (a cloth, in Schott's example) was below the water surface in the vessel. Afterwards Perrault suspended the pipe over an empty vessel in order to check whether the soil allowed some water to drain, but also in this case no water was collected ~~within in~~ half a day's time. Then he ~~twice~~ added a certain amount of water ~~(which twice (the amount of water~~ is not specified) ~~the~~. The day after the first imbibition he collected $\frac{3}{4}$ of the added water, and the day after the second one he collected all the added water. Finally he wanted to ~~check-evaluate~~ the water content of the soil and shook the pipe in order to let the soil slide out, ~~thus recognizing~~. He thus recognized that the lower part of the soil was thoroughly wetted as "very wet mortar" (Perrault and LaRoque, 1967, p.79). The second experiment was the repetition of the first one with three different soils (details are reported in Table 3). Perrault reports that he made the same observations ~~with~~ different, yet with different heights of rise (10 pouces \simeq 27.1 cm for the sand with gravel and for the sieved sandstone, and 18 pouces \simeq 48.7 cm for the crumbled loam). Perrault's measurements are reported in Table 4 together with those collected during our repetitions.

Perrault performed a third experiment to check whether the ~~soil could let the water during the precipitation rainfall water~~ could reach a layer of impervious soil or rock, where it could stop and rise to form a spring. In order to do so, he took the pipe and filled it with dry and sieved loam, compacting it with a rod. He suspended the pipe over an empty vessel and poured many times the amount of water contained in a glass vial, which was filled up to the spout, and ~~with which had~~ the same volume of as a medium ball of the *jeu de paulme* (today *jeu de paume*, palm-game; Perrault and LaRoque, 1967, p.80). The practice of measuring liquid volumes with reference to the balls of the *jeu de paulme* was quite common in XVII and XVIII century France. Yet it was not possible to find a reference for the actual dimension of a medium ball of the *jeu de paulme* ~~at in~~ Perrault's age, therefore era. Therefore in order to repeat the experiment its volume was deduced from the notes reported by Perrault in the description of the third experiment. In fact he slowly poured the water on the soil three times without recovering any water at the bottom. Afterwards he added a fourth vial and recovered $\frac{1}{3}$ of its volume ~~and~~. Then the flux stopped for at least 18 hours. He added two more vials, ~~collecting and collected~~ all their volume. He waited three days and added a seventh vial, ~~collecting and collected~~ $\frac{3}{4}$ of the volume (he observed that the surface of the soil was drier than before, because some water evaporated); ~~and~~. Afterwards he added an eighth one, ~~collecting all the and collected all the added~~ volume. Then he extracted the soil from the pipe and observed that only the lowest 48.7 cm were very wet, so ~~that he concluded he concluded (a)~~ that the soil may leak the water only if it is thoroughly wetted before, and ~~(b) that~~ in order to do so they are required $3 + \frac{1}{2}$ vials which are required. Their volume correspond to the third part of the volume of the wet soil. Even if there is a little incongruence between the data (after the first imbibition $3 + \frac{2}{3}$ vials were stored in the soil), this information is valuable because it let us to conjecture that the volume of Perrault's vial was about 74 cm^3 (Barontini et al., 2013).

In the fourth reported experiment, Perrault aimed at testing whether salty water, rising by capillarity within the soil, ~~would have~~ maintained its salt content or ~~it would have~~ if it left it in the sand. As in fact ~~the~~ spring water is commonly fresh, this was considered a key aspect ~~to understand~~ in understanding the circulation of water within the Earth. Perrault's report is not detailed in this case, but he only notes that, after the water rose in the sand column ~~for up to~~ 48.7 cm, the sand was salty both
5 at the top and at the bottom, ~~and he guessed that~~. He guessed that, if the sand at the top was less ~~salted then~~ salty than that at the bottom, it ~~should be a consequence of the fact~~ probably meant that the soil was less wet at the top than at the bottom.

About two pages (Perrault, 1674, p.160–162) are devoted to summarize the conclusions that Perrault made after the experiments. It is worth noting that the first conclusion starts from the experiment, to give a general epistemological comment on the ~~attitude~~ tendency of the authors ~~at deriving to obtain~~ general conclusions from limited observations:

10 First I know that Magnanus' opinion [Maignan's opinion] is not acceptable, and that it is based on a fact which is only half true: upon which I note in passing that what I have said elsewhere is really correct that most of those who make experiments on discoveries of which they wish to pass as the Authors, will look at them only in the aspect that serves their ends, as did Magnanus who only wanted to prove the absorption of water by the Earth (Perrault and LaRoque, 1967, p.80).

15 The other conclusions directly ~~refers~~ refer to the experiment. They may be summarized by saying that once a soil is wet, it tends to retain water and not to give it back, and this is true also when the soil is so wetted ~~to become~~ that it becomes permeable to water. In that case in fact, as soon as the water addition stops, the percolation rapidly diminishes and ~~at~~ in the end the soil still retains the amount it needed to become permeable. Perrault then comes back to the discussion of the two difficulties he found regarding the Common opinion (Perrault, 1674, pp.162–183) and concludes that:

20 After what I have just observed concerning the two difficulties which I have found in the Common opinion, I think it must be agreed that the penetration of the Earth by rain water cannot be achieved according to this opinion; and the rains to which it attributes the origin of springs not being enough to produce them, and still less to cause them to flow continually, it is proper to reject this view (Perrault and LaRoque, 1967, p.89).

5 Repetition of Perrault's experiments

25 The great detail of Perrault's experimental report ~~posed us~~ left us with two questions: (a) Are Perrault's experiments really qualitatively and quantitatively repeatable in the laboratory? (b) Is it possible, on the basis of Perrault's data, to conjecture ~~which could be~~ what the hydrological properties of his soils could be? The questions were addressed both in the laboratory (Berta and Barontini, in preparation) and with numerical simulations (Barontini et al., 2013). Some aspects of the numerical simulations will be ~~recalled~~ mentioned in the next ~~sections, here~~ section. Here the main laboratory procedures and results will
30 be summarized. The experimental details and data are fully reported by Berta and Barontini (in preparation).

A polycarbonate pipe of 4.5 cm ~~of~~ in diameter, cut at ~~the a~~ length of 65 cm, mimicked Perrault's ~~leaden~~ lead pipe. A punched metal plate and a cloth of nonwoven fabric were used to hold the soil and ~~drain to drain the~~ water when the column was held in

a vertical position (Figure 5). Three quarry sands, commonly used in building works, were chosen to repeat the experiments. In the ~~following~~ following the soils will be referred to as A, B and C, according to the order in which they were used for the repetitions. The grain size distribution curves were determined by dry sieving, ~~as~~ since the fine soil component was negligible. The soils were classified as coarse-to-medium sand (A, C) and medium-to-fine sand (B). The soils were poorly graded, with a

5 uniformity coefficient $U = d_{60}/d_{10}$ about 2.1 for A and B, and about 2.2 for C (~~d_{60} and d_{10} are the equivalent diameters which retain 40% and 90% of the soil weight, respectively~~). The hydraulic conductivity at soil saturation K_s was hardly estimable by means of the laboratory falling-head permeameter, because expected values were greater than 10^{-5} m/s, ~~therefore it was~~. It was therefore estimated by means of Kozeny and Carman's equation (see Eq. A1 in the Appendix). The soil-water retention relationships were measured by means of Richards' pressure plates for pressure values $\Psi \leq -10$ kPa (Richards and Fireman,

10 1943), and by means of ~~an~~ a hydrostatic method for ~~$-3 \text{ kPa} \leq \Psi \leq -1 \text{ kPa}$~~ $-3 \text{ kPa} < \Psi < -1 \text{ kPa}$. The couples (w, Ψ) , being w the gravimetric water content, were interpolated by means of Brooks & Corey's retention curve (A5) and van Genuchten's retention curve (A6), both with or without the usual constrain (A7) on m and n . An example of the obtained soil-water retention relationships is represented in Figure 6 for the medium-to-fine sand (soil B). Values at ~~-3 kPa~~ $\Psi = -3 \text{ kPa}$ were too sparse and were not used for the regressions.

15 In Figure 7 and in Table 4 and 5 the results of the repetitions of the first experiment are reported. The unitary amount of water poured on the soils was in this case 74 cm^3 for all the soils, as determined by Barontini et al. (2013). All the soils ~~show~~ showed a qualitative and (at some extent) a quantitative agreement, both during the spontaneous imbibition from the bottom, and during the forced imbibition from the top. In Table 4 the ~~measured~~ capillary rises, ~~both those~~ measured after one day ~~and the limiting values~~, and the upper limit values of the capillary rises, are compared ~~both~~ with data reported by Perrault and with

20 the capillary rise h_{cr} (cm) determined by Polubarinova-Kochina's relationship (Polubarinova-Kochina, 1962):

$$h_{cr} = \frac{0.45}{d_{10}} \frac{1 - \phi}{\phi} \quad (1)$$

~~where~~ In Eq. (1), d_{10} (cm) is the equivalent diameter which retains 90% of the soil weight, and ϕ is the soil porosity. The good agreement between the measured capillary rise and h_{cr} allows us to conjecture that Perrault's soils almost reached their asymptotic ~~capillary~~ rise. Thus, accounting for a porosity $\phi = \frac{1}{3}$ (because Perrault estimated the amount of water in the soil

25 as $\frac{1}{3}$ of the wetted soil volume) ~~is it~~ it is possible to estimate the competent characteristic diameter d_{10} (values are reported in Table 4).

~~To characterize~~ Characterizing the hydraulic conductivity at soil saturation is less immediate because the information given by Perrault about the percolation times are incomplete. If we consider that ~~at least some of the soils used by Perrault were sieved~~ (at least) some of Perrault's soils were sieved, in order to remove the coarse fraction, we hypothesize that the char-

30 acteristic diameter d_{10} ~~determined by means of~~, determined by Polubarinova-Kochina's equation (1), is an approximation of the ~~characteristic equivalent~~ diameter \tilde{d} (Eq. A3) ~~needed~~ to determine K_s by ~~means of~~ Kozeny and Carman's equation (A1). Comparing d_{10} and \tilde{d} as determined for soils A, B, C (~~see~~ Table 4) this conjecture may be considered realistic.

Another interesting comparison between Perrault's experiments and their repetition ~~is~~ was done with regard to the amount of water that was added and that percolated. ~~In Table 5 the~~ The imbibition and percolation volumes are represented ~~in Table~~

5. Values are expressed as the number of vials and in this case the volume of a vial was assumed equal to 74cm^3 . Data are qualitatively in agreement, and although they ~~numerically differ~~ differ numerically, it emerges that Perrault's data are complete and quantitatively comparable. The same data are presented in Figures 8 and 9 and in Table 6 for the third experiment. It is worth recalling that in this case the volume of 1 vial was chosen with reference to the capability of the soil ~~of retaining~~ to retain water. In fact in his conclusions regarding the experimental activity, Perrault stressed his point of view about the proneness of a soil to allow water to drain, ~~and~~ Here he considered that ~~this drainage~~ may happen when the soil is wetted with an amount of water which ~~correspond~~ corresponds to $\frac{1}{3}$ of the wetted volume of soil at equilibrium. In the conclusions in fact he states:
- ... that in order to wet earth and make it ready for penetration as much water as one third the height and thickness of the earth is necessary (Perrault and LaRoque, 1967, p.81).
- 10 As he stated that this amount of water corresponded, in the investigated case, to $3 + \frac{1}{2}$ vials, we obtained the unitary volume V_i of a reference vial, for each soil, by dividing the volume of water stored at equilibrium V_w by $3 + \frac{1}{2}$. The determined unitary volumes are $V_i = 31.3, 50.5, 41.0\text{cm}^3$ for the soil A, B and C, respectively. Also in this case we observe a good qualitative correspondence between Perrault's experiments and the repetitions, but what is important to stress is the fact that data provided by Perrault allow us to make a robust quantitative comparison.
- 15 With regard to the repeatability of Perrault's experiments we may therefore conclude that they are almost completely repeatable, in a qualitative sense. If we assume that a quantitative repetition should not be intended ~~at obtaining~~ to obtain the same results obtained by Perrault, but ~~at defining~~ to define results which may be compared with Perrault's ~~one results~~ on a quantitative basis, we may ~~also~~ say that Perrault's experiments are also quantitatively repeatable. The detail in fact with which Perrault describes his experimental activity allows us (aa) to clearly identify most of the quantities that he measured, (bb) to
- 20 make realistic conjectures for the quantities about which the *Origine* is not precise (i.e. the unitary amount of water added with one vial) and (cc) to recognize the lack of information (i.e. the time ~~running~~ between the beginning of ~~the~~ imbibition, the beginning of drainage and the end of drainage). In the next section some conclusions will be made also with regard to the second question posed at the beginning of this section.

6 Didactics of Perrault's experiments

- 25 Perrault's opus and experiments can be used in several didactic ways, meeting the objectives of at least the first three elements of the Dublin descriptors, i.e. knowledge and understanding, applying knowledge and understanding, making judgements (Bologna Working Group on Qualifications Frameworks, 2005). As a general preliminary aspect, facing the *Origine* and the reported ~~descriptions~~ conceptual models of the hydrological cycle induces the students to reflect on the long scientific path, which was ~~needed~~ taken to move from initial observations and conjectures to the modern description ~~of the phenomena~~. ~~It stimulates also an exercise of displacement~~. It also stimulates a displacement exercise from consolidated understandings (which may be ~~considered~~ regarded to as our *Opinion Commune*) and the exploration of alternative descriptions.
- 30

Focusing with more detail on soil hydrology, Perrault's experiments offer a wide range of didactic cases, useful to teach and exemplify many aspects of the subject, ~~so that it~~. As an application of this idea, the experiment was used as an underlying cross

theme of a recently published didactic book (Barontini, 2017). ~~The~~ In fact the description given by Perrault of the first and second ~~experiments in fact~~ experiment offers the opportunity ~~of teaching to teach~~ the hydrostatics of ~~the~~ soil–water, ~~both~~ above a groundwater table and ~~above~~ a capillary barrier, and ~~of presenting the~~ to present capillary fringe and ~~the~~ soil–water retention curves. The soil ~~resistance~~ reluctance to be crossed by the water, as reported in the third experiment, is related to the action of the capillary barrier exerted by the cloth at the bottom of the soil column. It stresses the importance of locally reaching the soil saturation at the soil bottom, before percolation starts, so as to have the continuity of the generalised piezometric potential $\Phi = \Psi + z$ ~~at the soil bottom (z being the elevation), before pereolation will start~~ (Ψ being the pressure potential and z the elevation). This issue is directly related to Perrault’s observation regarding the ~~soil capability of retaining water and about capability of soil to retain water and~~ the difficulties of infiltrated precipitations to percolate. ~~It therefore leads the students to understand the importance of soil layering on field capacity. The soil column in fact~~ During the experiment, the soil column was suspended and the soil had greater field capacity than if it ~~was~~ were in the field, so ~~that~~ Perrault was induced to think that precipitations ~~have great difficulties to pereolate~~ face great difficulties in percolating toward deep soil layers. During the discussions with students, it might be didactically effective to have them reflect on what would have happened in case the length of the soil column was different, in order to allow to understand the importance of soil depth and layering on field capacity. The fourth experiment, even if minimally described, also allows to introduce the hydrostatics of an unsaturated soil with solutes ~~to be introduced~~.

The experiments ~~allow~~ show a great variety of boundary conditions ~~to be explored, including~~. They include: the condition of known pressure potential (bottom boundary of the first experiment), of null flux (top boundary of the first experiment) and of seepage (bottom boundary of the third experiment), ~~but not the~~. The condition of known flux at the top boundary ~~does not clearly emerge from the report~~, because Perrault ~~does not report unfortunately~~ does not say how long the imbibition lasted during the third experiment. This, together with the other incomplete or omitted data, ~~trains the students with the problem of recognizing the goodness of the information they may find~~ gives the students an opportunity to recognize the goodness or lack of information. Moreover trying to interpret and understand ancient observations with modern conceptual frameworks ~~is an interesting exercise~~ makes it challenging to test and apply ~~the gained knowledge~~ their new knowledge.

Finally students may face the second question previously introduced, regarding ~~our~~ the capability of inferring the hydrological properties of Perrault’s soils, on the basis of the data reported. In the previous section the problem of the conductivity at soil saturation was introduced. Now we will focus on the soil–water retention relationships.

If Perrault’s soils are regarded to as Δ –soils, the height of capillary rise h_{cr} ~~defines also their~~ also defines the soil–water retention relationship as:

$$30 \quad \begin{cases} s = 1 & -h_{cr} \leq \Psi \leq 0 \\ s = 0 & \Psi < -h_{cr} \end{cases} . \quad (2)$$

In Eq. (2) s is the effective soil saturation as introduced by Eq. (A4). A Δ –shaped soil–water retention ~~relationships~~ relationship may be considered a first approximation of the hydrological characteristics of Perrault’s soils, but other soil–water retention curves are compatible with the information ~~given~~ provided by Perrault. As an example which is effective for the soil of the

first experiment, the hypothesis is introduced that the height of capillary rise of 48.7 cm, observed by Perrault, is between the scale factor Ψ_1 and the inflexion point Ψ_f of van Genuchten's soil–water retention relationship (~~Barontini et al., 2013~~) (see equations A6 and A8 for the explanation of the symbols; Barontini et al., 2013). Therefore, one can fix either $\phi < \frac{1}{3}$ and $\Psi_1 = 48.7$ cm, or $\phi < \frac{1}{3}$ and $\Psi_f = 48.7$ cm, ~~such that the~~. The remaining parameters of the soil–water retention relationships

5 ~~may be are~~ determined, provided that at equilibrium the volume of water stored in the soil V_w is:

$$V_w = A \int_0^{65\text{cm}} \theta(x) dx \equiv 3.5 \cdot 74 \text{ cm}^3. \quad (3)$$

In Eq. (3) θ is the volumetric soil–water content. An analogous hypothesis may be introduced with respect to Brooks and Corey's bubbling pressure Ψ_b (Barontini, 2017), and in both cases the soil will approximate a Δ –soil at increasing n or λ , and consequently at increasing the porosity ϕ . The Δ –soil will therefore be the limit case for $\phi = \frac{1}{3}$.

10 Anyway both these hypotheses, according to Perrault's epistemological approach, ~~may be now~~ should now be tested with the soils used for the repetitions of Perrault's experiments. The results are reported in Figure 10 in which the observed capillary rises are plotted together with Polubarinova–Kochina h_{cr} and with the estimated values of Ψ_b , Ψ_1 and Ψ_f . The hypotheses are not rigorously satisfied, but the capillary rises are comparable with Ψ_b , Ψ_1 and Ψ_f and this indicates that to some ~~extents~~ extent the hypotheses may lead to a realistic approximation of Perrault's soil constitutive laws. The results might be better,

15 if the experimental soil–water retention curves were measured with more detail near ~~to saturation, but~~ saturation. Yet what is important for teaching purposes at this point is that the comparison between the hypotheses and the experimental evidence induces the students to critically analyse their *modus operandi*, and to understand ~~which are what~~ the strong constraints of the epistemological approach based on the experimental practice are.

With regard to the second question posed at the beginning of Section 5, we may therefore conclude that (a) it is not possible

20 to define a set of hydrological properties which completely describes one of Perrault's soils; ~~yet, but~~ (b) it is possible to make a set of reasonable hypotheses, which allow to define a range of ~~values to be defined that are realistic~~ realistic values for the hydrological properties of the described soils.

7 Perrault and the complexity

Perrault's discussion to confute the *Opinion commune* (Perrault, 1674, pp.162–183) is conducted, at the same time, by using

25 philosophical conjecture, and by claiming the importance of his experimental activity:

What the earth drinks, this Philosopher [Seneca] says, is little (...); but I add to this reasoning experiments made daily on this penetration of the earth (Perrault and LaRoque, 1967, p.81),

and above all by showing a great attention to field phenomena:

30 To understand this [the second difficulty with the Common opinion] completely, one must picture and discuss in detail, how the penetration of the Earth according to the Common opinion can be accomplished. The water that

falls on the Earth, begins by wetting the parts of the earth or sand nearest to it; then it wets other, more distant parts, then others, always going downward² and wetting the Earth in all its parts one after the other (Perrault and LaRoque, 1967, p.86).

This attention permeates all the following pages and makes him move ~~the~~his focus from the laboratory to ~~the~~ nature.

- 5 Here Perrault, according with his refusal of the principle of authority, challenges his perspective with ~~the famous~~ Aristotle's famous assertion, according to which the total mass ~~flowed by~~flowing from springs or in rivers during one year would be greater than the ~~whole Earth~~entire Earth's mass:

The name of its Author, the number of rivers on the Earth and the length of a year, are things that strike the imagination so strongly that it is hard not to be won over to such a likely idea, and such a hard one to argue about.

- 10 But without being amazed, let us try to consider this objection, and without distrusting our strength overmuch, let us try to find a solution for it (Perrault and LaRoque, 1967, p.90).

Discussing Aristotle's statement, Perrault concludes that the total amount of water flowing in the rivers is great, but much less than Aristotle says. In order to reinforce his conjectures, Perrault recognizes the necessity ~~of collecting~~to collect measurements against those who do not agree on the fact that the precipitation volume is greater than the runoff volume:

- 15 (...) but as these reasons bear only on the destruction of the opposing opinion, some attempt must be made to give other reasons that might support the one that I maintain and show that rain waters are enough to cause the flow of springs and rivers for a whole year. (...) I shall try nevertheless by making rough estimates of the volume of rains and of that of the flow of rivers, to give some basis for judgement on the opinion that I uphold, and to arrive at such judgement (Perrault and LaRoque, 1967, p.95).

- 20 As a first step he clearly establishes the methods of measurement he will employ in his observations:

It is necessary above all to reach an agreement on ways of measuring these two kinds of water (Perrault and LaRoque, 1967, p.95).

Then he reports the results of his measurements of the precipitation and runoff made between 1668 and 1671 in the Seine catchment, thus concluding that:

- 25 only about one-sixth part of the rain and snow water that falls, is therefore needed to cause this river to flow continually for one year (Perrault and LaRoque, 1967, p.97).

~~Which~~What is the value given by Perrault to this conclusion? He seems to be aware that the measurements are imprecise and not complete, but in this context, rather than ~~at~~ providing exact results, he aims at showing a research path that will lead to the birth of ~~the modern hydrology~~modern Hydrology:

- 30 I know very well that this deduction has no certainty: but who could give one that would be certain? Nevertheless whatever this one may be, I believe it is more satisfactory than a simple negative like Aristotle's and that of those

who maintain, without knowing why, that it does not rain enough to supply the flow of rivers. However that may be, until someone makes more exact observations, by which he proves the contrary of what I have advanced, I shall hold to my view, and be content with the feeble light shed by the observations I have made, being unable to have a stronger one (Perrault and LaRoque, 1967, p.97).

- 5 The estimation of the water balance led Perrault to recognize that ~~the~~-precipitation provides enough water to guarantee the flow in ~~the~~-rivers, so ~~that~~ he should have admitted that both rivers and springs are caused by rain and snow fall. Yet Perrault takes his experiment as a milestone, and he rejects the possibility that ~~the~~-precipitation may percolate so deeply ~~to reach~~ that it reaches the impermeable layer and ~~to origin~~ originates both the groundwater table and the springs. Therefore, in order to explain the origin of springs, with particular reference to the mountain springs, Perrault surprisingly comes back to the undemonstrated
- 10 theses traditionally rooted within Aristotle's conjectures:

Since I have found the material of springs of the best quality possible, I mean fresh water in plenty, passed through and purified by pure and clean sands and that it remains for me only to raise it to the mouths of springs, I no longer have any difficulty, all Philosophy, ancient and modern, is with me, and is in agreement that that can be done easily and naturally (Perrault and LaRoque, 1967, p.108).

- 15 After briefly recalling the main theses on this subject as reported by some philosophers, among which there ~~are~~ is Aristotle, Seneca, Lydiat and Descartes, Perrault resumes that:

...all have remained in agreement about this rising of water or of aqueous vapors to the top of mountains; and this consensus, although based on different principles, is a fairly good sign of the truth of this fact (Perrault and LaRoque, 1967, p.109).

- 20 The fact that Perrault explains the hydrological cycle by ~~coming~~ going back to the ancient tradition, enlightens some intricate features of the Scientific Revolution, which did not proceed straight forward, but was characterised by alternative phases of advancement and uncertainty. Nevertheless, with his attitude at moving from the laboratory to the field, his research for shared methods of measurement, his ~~acceptation~~ acceptance of quantitative observations until they are not falsified ~~but~~ by other researchers, Perrault interprets the spirit of the Scientific Revolution ~~and~~. Moreover he seems to anticipate some themes which
- 25 are peculiar of the modern epistemology of the complexity. We should probably admit that, already in the XVII century, some scientists realised that the nascent paradigm of classical Physics, that focused on the perfect repeatability of an experiment, was inadequate to deal with some natural phenomena. Therefore, the birth of modern Hydrology implied not only the emergence of the scientific method, but also a supplementary epistemological reflection on the ~~limit of laboratory experiment~~ limits of laboratory experiments, thus going beyond the common image of the Scientific Revolution.
- 30 Apart from what is reflected in the *Origine*, is it possible to find witnesses of this supplementary epistemological reflection in Perrault's opus? Perrault's Cartesian appeal to simplicity, practice and common sense only apparently clashes with epistemological awareness. In fact, even a cursory look at the *Lettre à Mr. Hu[y]guens au sujet des experiences* (Letter to Mr. Huygens about experiments, written in 1672 and published as an appendix of the *Origine* two years later) demonstrates that

Perrault deeply reflected on the limits of the scientific method (Perrault and LaRoque, 1967, pp.146–157). In his letter to the great Dutch Physicist, Perrault defends two hypotheses which are wrong. Nonetheless, he presents arguments which are not devoid of interest from the epistemological point of view. Huygens warmly (and correctly) invites him to refuse the old idea of *horror vacui* as an explanation for the functioning of pumps and he also ~~suggests~~-advises him to discard attraction and repulsion as valid physical concepts. Perrault answers with claims which raise some ~~issues~~-questions for the nascent scientific method, as they call into question the risks of a blind faith in the experimental results. The core of Perrault's thesis can be briefly sketched as follows: a deep awareness of the limits of experience is essential to a thoroughly scientific approach, and the result of a single experiment must never lead the scientists to undue generalizations of their theses. Hereafter, we resume the main arguments he puts forward to support this claim.

10 First, according to Perrault, ~~the~~-a scientist must never declare himself satisfied with the results of an experiment before he has reached ~~the~~-a full agreement between experiences and ~~the~~-judgement:

For whatever experiments can be performed, one cannot stop there, if judgement and the senses all together do not agree about them: the senses are often mistaken when they act alone, and the judgement is often deceived also sometimes unless the senses set it right (Perrault and LaRoque, 1967, p.147).

15 Senses alone are necessary but not sufficient in order to obtain effective knowledge, and the same applies for judgement; ~~therefore~~. Therefore, it is wrong to consider ~~definitive-any-experiment~~-any experiment definitive, insofar as it leaves open the possibility of both different interpretation and further experience. The second argument concerns the concepts of cause and effect: according to Perrault, in Nature no effect is produced by a single cause, rather every effect is the consequence of a multiplicity of causes. He also introduces the distinction between internal causes (which are intrinsic to the dynamic of the

20 phenomena) and external causes (which play an accidental role in the determination of the effect):

It is certain that in Nature, no effect is produced by a single cause, and that on the contrary there is none without several causes, some of which are particular to the things on which the effects are produced, and the others are alien to them and come from the outside, and nevertheless take part in the production of their effects (Perrault and LaRoque, 1967, p.147).

25 The third argument calls into question what Perrault calls the “machines”, i.e. all the instruments which are used to measure the phenomena and to assemble the experimental model. As ~~far-long~~ as he considers the question of measurement as absolutely crucial for the success of the experiment, Perrault warns that the discrepancy of proportions between a laboratory model and a real natural process could compromise the generalisation of experimental results:

It appears that proportion is absolutely necessary in machines to make them yield the effects desired; and it is

30 likewise obvious that general conclusions cannot be drawn from many experiments that are made, and that all that may be learned from them, is merely that what they show us, can be done with the machines, the instruments and the materials which we have used; and at the same time to make us fear that in making them with other machines and of other proportions, or with other instruments, other materials and in other circumstances, they might have other results (Perrault and LaRoque, 1967, p.149).

Lastly, Perrault recalls that nobody can exclude further explanations of ~~the~~ old problems, given the progress of both human mind and technical application, which will probably make ~~available~~ new interpretations and experimental models available:

... if these experiments have caused us to doubt so many things about which we were, so it seemed, very sure, they should cause us to doubt even more many things which we now believe are very certain, and cause us to fear
5 that some day posterity will give us the same treatment, and laugh at our Philosophy just as we laugh at that of Antiquity (Perrault and LaRoque, 1967, p.151).

Perrault's thesis about the *horror vacui* has been proved to be wrong, but the questions he ~~rises~~ raises are noteworthy from many points of view. Above all, in the letter there are neither direct references to his experiments reported in the *Origine*, nor to the basin hydrology, ~~but~~ However, the letter was written in 1672, just after the three years in which he was collecting data
10 about the water balance of the Seine river, and ~~probably it was~~ probably written during the composition of the book. If we consider these circumstances, it might be realistic to think that the hydrological studies of the *Origine* and the epistemological remarks of the letter deeply influenced each other.

What can be inferred by Perrault's remarks? As for the first argument, it is a classical *topos* of the Scientific Revolution, thus it does not depart from the XVII century's paradigm. On the contrary, Perrault's emphasis on the multiplicity of causes
15 may be connected to his studies to understand the hydrological cycle. It is important to stress that, according to Perrault, the multiplicity of causes does not represent an objection, but rather a stimulus for scientific enquiry. Furthermore, there is no contradiction between the epistemology of the letter and the scientific practice of the *Origine*. Indeed in the forethought of the *Origine*, which is dedicated to Huygens, Perrault states that:

What I have said in my letter to Mr. Hu[y]guens, which is at the end of this book, is not to criticize the experiments,
20 as has been said by a few who had already seen this letter: but only to say that there is no certainty to be drawn from the general conclusion of certain experiments, and on that basis to attribute to certain things certain effects rather than to others, and to exclude from them all other causes, known or unknown (Perrault and LaRoque, 1967, p.11).

~~As~~ Just as well, Perrault's awareness of the problem of proportions in the design of the laboratory model is remarkable: he is
25 in fact posing a problem that will be faced a ~~pair~~ couple of centuries later with the theory of hydraulic and mechanical models, based on dimensional analysis.

More generally, despite his undeniable faith in scientific progress, Perrault is significantly conscious of the risks involved in an acritical and dogmatic acceptance of experimental results. Not only he is aware that scientific results are strictly connected ~~with~~ to the opportunities offered by technical progress, ~~also he~~ but he also admits the possibility of new interpretations of the
30 achieved results, ~~thus showing~~ He therefore shows an understanding of science as an indefinitely open and perfectible field of knowledge. Although we can consider him as one of the founders of scientific soil hydrology and one of the progenitors of a modern scientific spirit, Perrault did not consider the experiment as an oracle. On the contrary, he clearly saw the ~~bait~~ risk of underestimating the complexity of the phenomena and the influence of the instruments on the object of observation. Far from being a naïve empiricist, he rejects the blind faith in ~~the~~ experimental results as well as the old appeal to authority.

To summarise, the *Lettre* is not only a proof of the individual guile and lucidity of the author ~~author~~ Author, it also demonstrates that the birth of quantitative ~~hydrology~~ Hydrology implied a deep epistemological reflection on the statute and on the limits of ~~experiment and laboratory model~~ experiments and laboratory models.

8 Conclusions

- 5 Perrault framed his main opus, the *Origine*, in a deeply novel epistemological approach, ~~which~~. This approach embraced the new experimental and Galilean method, rooted in the quantitative measurements, to integrate the traditional ~~one method~~, based on qualitative observations and on the discussion of conjectures. In the critical section of his opus he presents, in a few pages, a set of four experiments ~~with which~~. With these experiments he intended to test two main difficulties he found ~~with~~ in the modern understanding of the hydrological cycle, which at that time was about to be accepted. ~~These difficulties are~~
- 10 The difficulties were (a) whether the water may spontaneously rise in the soil and form springs, and (b) whether it may easily percolate through the soil ~~until it reaches to reach~~ an impervious layer, where a groundwater table will form and the water level will rise ~~until forming the to form~~ springs.

- The experiments are precisely described and most of the ~~measures~~ measurements are detailed, so that we are able both to repeat them in the laboratory, and to recognize incomplete data and missing information. Perrault's idea was therefore not only
- 15 to experience his conjecture, but also to make his experiments repeatable, and in this sense we may regard ~~at~~ them as probably the first modern hydrological experiments. Yet two of his observations misled his interpretation of the hydrological cycle: at first he tried to onset a spring above what would have been the groundwater table, then he did not recognize the importance of the capillary barrier ~~he realised in the experiment~~, in confining the water percolation, and in reducing the consequent recharge of the groundwater. The repetition of the experiments and the discussion about ~~its~~ their interpretation provide interesting cases;
- 20 ~~useful to let hydrology students train themselves both with the understanding of~~. These are useful in allowing hydrology students to learn about the fundamental aspects of epistemology ~~and of~~, and to understand the modern theoretical framework of soil hydrology.

- Perrault's misinterpretation of the hydrological cycle also opens up a discussion ~~of some interesting about some attractive~~ epistemological issues. At first Perrault ~~comes~~ goes back to accept the undemonstrated theory, rooted in the Aristotelian
- 25 thought, according to which the hydrological cycle is mainly the effect of an evaporation and condensation process that takes place in the center of the Earth. This provides some evidence that the Scientific Revolution is not a straightforward line, but, as a great cultural movement, is articulated in alternative phases of advancement and uncertainty. Then, the problems posed by soil hydrology, even at an early stage, appear irreducible to the classical paradigm of the Scientific Revolution. Even if the ~~experiment~~ experiments designed by Perrault has proved to be repeatable, an in-depth analysis of them shows that the ques-
- 30 tions posed on the hydrological cycle ~~and on the soil hydrology~~ are hardly reproducible by means of a controlled laboratory model.

Perrault's scientific practice, which was many-sided, confronted him with complex issues, such as the hydrological cycle and the catchment ~~are~~ water balance. This objective complexity seems to be reflected in his letter to Huyguens which, although

often disregarded, contains remarkable ideas anticipating a modern epistemology. Perrault should therefore be considered not only as an amateur scientist, but also as a refined scholar who worked at a turning point within the developing epistemology of the Scientific Revolution, being aware of its uncertainties and conflicts. In one of his essays, the novelist and literary critic Italo Calvino gave several definitions of what in his opinion is a classic. Among these, the sixth one is: “A classic is a book which has never exhausted all it has to say to its readers” (Calvino, 1991, p.5). As-a-In conclusion we may state that Perrault’s *Origine* attractively meets this definition, as-so-and many years after its first appearance it still deserves intriguing stimuli and suggestions.

Data availability. Data of the experiment will be fully reported in the technical report Berta and Barontini (in preparation) available at the Università degli Studi di Brescia, Dipartimento di Ingegneria Civile, Architettura, Territorio, Ambiente e di Matematica

10 Appendix A: Relationships used to characterize soil hydrological properties

A1 Hydraulic conductivity at soil saturation

The hydraulic conductivity K_s at soil saturation was estimated by means of Kozeny and Carman’s relationship:

$$K_s = \frac{\gamma}{\mu} \frac{\tilde{d}^2}{180} \frac{\phi^3}{1 - \phi^2}, \quad (\text{A1})$$

in which $\gamma [MLT^{-2}L^{-3}]$ is the water unitary weight, $\mu [ML^{-1}T^{-1}]$ is the dynamic water viscosity, and the term:

$$15 \quad k_p = \frac{\tilde{d}^2}{180} \frac{\phi^3}{1 - \phi^2} \quad (\text{A2})$$

is the intrinsic permeability $k_p [L^2]$. In Eq. (A2) $\tilde{d} [L]$ is a characteristic grain diameter of the soil and $\phi [L^3L^{-3}]$ is the soil porosity. Knowing the grain size distribution curve of the soil, the characteristic diameter \tilde{d} was estimated by means of the weighted-weighed harmonic average of the grain size distribution curve diameters d_i :

$$\tilde{d} = \frac{1}{\sum_i (W_{i+1} - W_i) \frac{1}{2} \left(\frac{1}{d_{i+1}} + \frac{1}{d_i} \right)}, \quad (\text{A3})$$

20 where the weights $W_i [MM^{-1}]$ are the fraction of the soil passing throw-through the sieve with diameter d_i . Therefore $W_{i+1} - W_i$ is the soil fraction retained by the sieve $d_i < d_{i+1}$ and $\sum_i (W_{i+1} - W_i) = 1$.

A2 Soil–water retention relationships

The effective soil saturation $s [1]$ is firstly introduced as:

$$s = \frac{\theta - \theta_r}{\phi_e}, \quad (\text{A4})$$

in which $\theta [L^3 L^{-3}]$ is the volumetric soil–water content, $\theta_r [L^3 L^{-3}]$ is the residual (volumetric) soil water content, $\phi_e = \theta_s - \theta_r [L^3 L^{-3}]$ is the effective porosity, being $\theta_s [L^3 L^{-3}]$ the (volumetric) water content at soil saturation.

Soil–water retention relationships were represented in the forms proposed by Brooks and Corey (1964) and by van Genuchten (1980). Brooks and Corey’s relationship is:

$$s = \begin{cases} \left(\frac{\Psi}{\Psi_b} \right)^{-\lambda} & \Psi \leq \Psi_b \\ 1 & \Psi_b < \Psi \leq 0 \end{cases}, \quad (A5)$$

where s is the effective soil saturation, $\Psi [MLT^{-2}L^{-2}]$ is the soil–water pressure, which may be expressed also in potential form i.e. with $[L]$ –dimension, Ψ_b is the bubbling pressure (with the same dimension as Ψ), i.e. the minimum value of the pressure potential for which the gaseous phase is discontinuous, and λ is the pore–size distribution index. Generally the greater λ , the greater is the soil–grain uniformity.

10 Van Genuchten’s relationship is:

$$s = \frac{1}{\left[1 + \left(\frac{\Psi}{\Psi_1} \right)^n \right]^m} \quad (A6)$$

where s is again the effective soil saturation, Ψ is the soil–water pressure or pressure potential, Ψ_1 is a scaling factor (with the same dimension as Ψ) and n, m are shape coefficients. According to van Genuchten (1980), in order to analytically integrate Mualem’s predictive form for the conductivity of the unsaturated soil, the shape coefficients are constrained by the relationship:

15

$$m = 1 - \frac{1}{n}. \quad (A7)$$

If m and n are not constrained, the soil–water retention curve (A6) has an inflexion point Ψ_f at:

$$\frac{\Psi_f}{\Psi_1} = \sqrt[n]{\frac{n-1}{mn+1}}. \quad (A8)$$

In case Eq. (A7) holds, the relationship (A8) takes the form:

$$20 \quad \frac{\Psi_f}{\Psi_1} = \sqrt[n]{\frac{n-1}{n}} \equiv m^{\frac{1}{n}}. \quad (A9)$$

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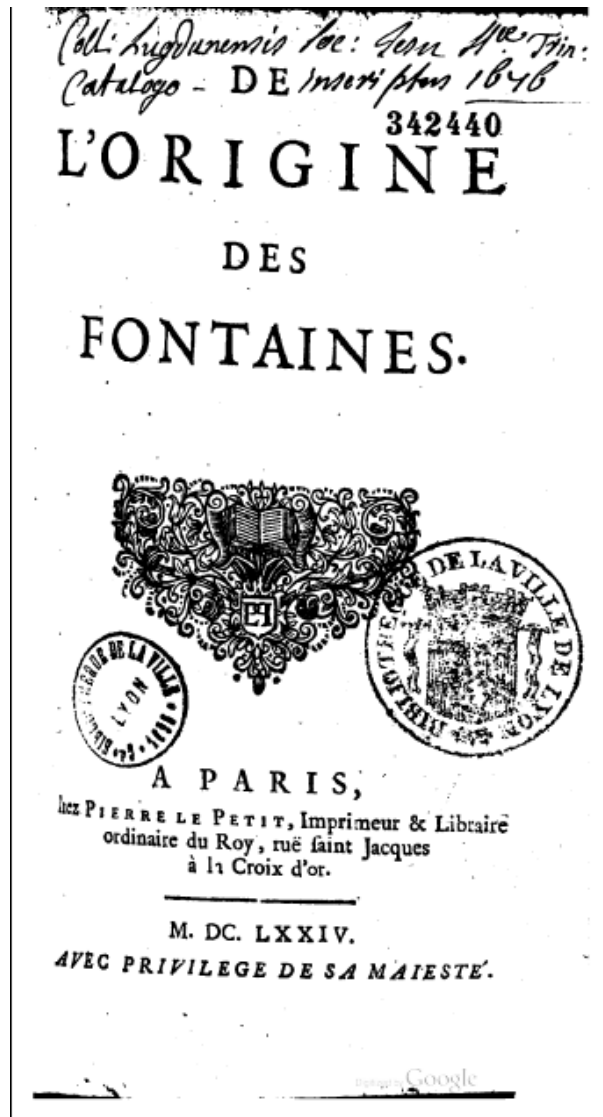


Figure 1. Front matter of Perrault's opus *De l'origine des fontaines* (Perrault, 1674, source: <https://books.google.com>, Library Project, accessed 12/8/2019)

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REGISCURIANI E SOCIETATE
JESU

ANATOMIA
PHYSICO-HYDROSTATICA
FONTIUM AC FLUMINUM,
Libris VI, explicata, &
Figuris æri incilis exornata;

*Quibus, præmissâ fontium ac fluminum
hystoriâ, primò eorundem principium & ma-
trix accuratò scrutinio inquiritur; deinde modus
quo à matricè præcipua (quæ Mare est) oriuntur, ex
sacra Scriptura, Philosophia naturalis, & Hydrosta-
tica principijs detegitur; postremò varia pro-
prietates ac veluti miracula in varijs
fontibus elucescentia di-
scutiuntur.*

Accedit in fine

Appendix de vera origine Nil.

Cum privilegio Casareo, & facultate Superiorum

Sumptibus Viduæ Jo. GODEFRIDI

SCHÖNWETTERI Bibliopolæ

Francofurtensis,

HERRIPOLI

Excudit JOHVS HERTZ Bibliopola &

Typographus Herbipolensis

ANNO M. DC. LXIII.

Figure 2. Front matter of Schott's opus *Anatomia physico-hydrostatica fontium ac fluminum* (Schott, 1663, source: <https://books.google.com>, Library Project, accessed 12/8/2019)

les objections que j'ay faites sur les autres, & n'en omettray aucune autre si je puis que je ne me fasse, & à laquelle je ne réponde de bonne foy. Je souhaite qu'il vienne quelqu'un qui la rejette, comme j'ay rejeté les autres, & qui en mesme temps en ouvre vne autre toute nouvelle qui soit meilleure, puis que je n'ay dessein de la soutenir, qu'autant que je la croiray soutenable.

OPINION DE L'AVTEVR.

MOn opinion est donc que les eaux des pluyes & des neiges qui tombent sur la Terre, sont la cause & l'origine des Fontaines. Ce sentiment est le plus ordinaire & le plus suivy : Neanmoins de la façon que je conçois la chose, il y a vne différence extrême entre ma pensée & celle de ceux qui suivent ce sentiment ordinaire. Car ils croient que les eaux des pluyes & des neiges fonduës tombant sur la Terre, la penetrent jusques à ce qu'elles ayent rencontré de la terre grasse ou autre chose qui les arreste ; surquoy elles coulent vers

Figure 3. Statement of Perrault's opinion (Perrault, 1674, p.148, source: <https://books.google.com>, Library Project, accessed 12/8/2019)



Figure 4. Figure XI from Schott's opus *Anatomia physico-hydrostatica fontium ac fluminum* (Schott, 1663, source: <https://books.google.com, Library Project>, accessed 12/8/2019)

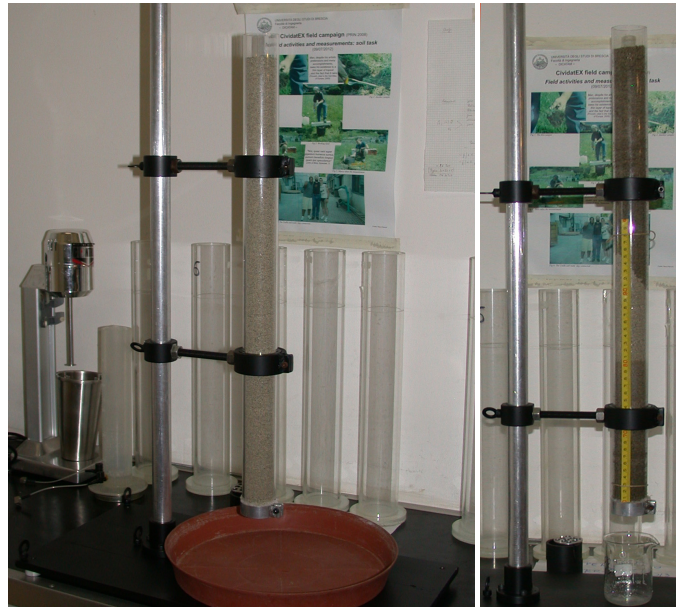


Figure 5. Laboratory setup of the soil column (left) and the soil column during the second part of the first experiment, when the top and the bottom imbibition fronts meet (right)

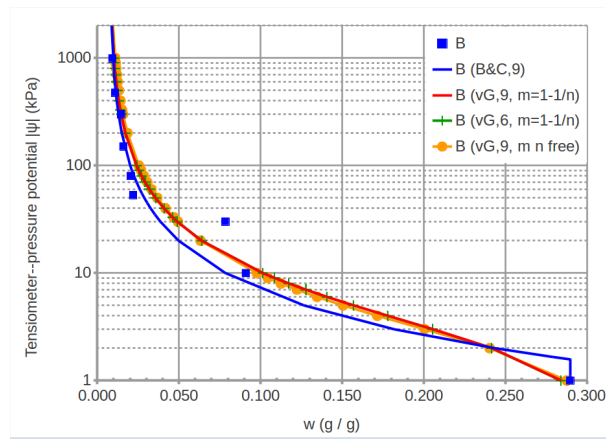


Figure 6. Experimental and interpolated soil–water retention relationships of one of the sandy soils used to repeat Perrault’s experiments.
Legend: B = Soil identificative, \square = Experimental data, B&C = Brooks and Corey’s curve, vG = van Genuchten’s curve; 6 and 9 are the number of experimental points which were used to interpolate the analytical curves

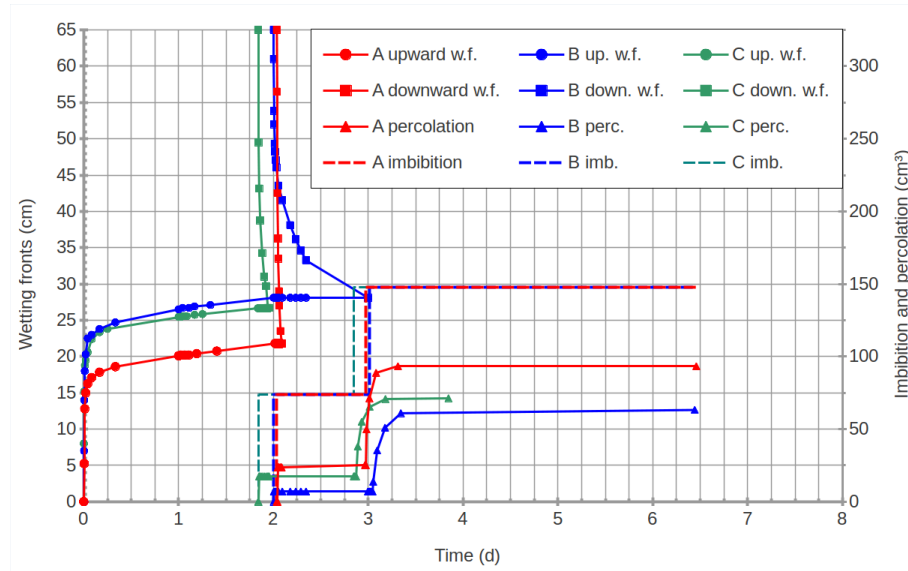


Figure 7. Measures of the position of the water fronts, of imbibition and of percolation collected during the three repetitions of the first experiment. The unitary volume of a vial was estimated equal to 74cm^3 for all the soils, according to Barontini et al. (2013). Legend: A, B, C = Soil identificative, \circ = Upward moving water front, \square = Downward moving water front, \triangle = Percolation volume, Dashed line = Imbibition volume

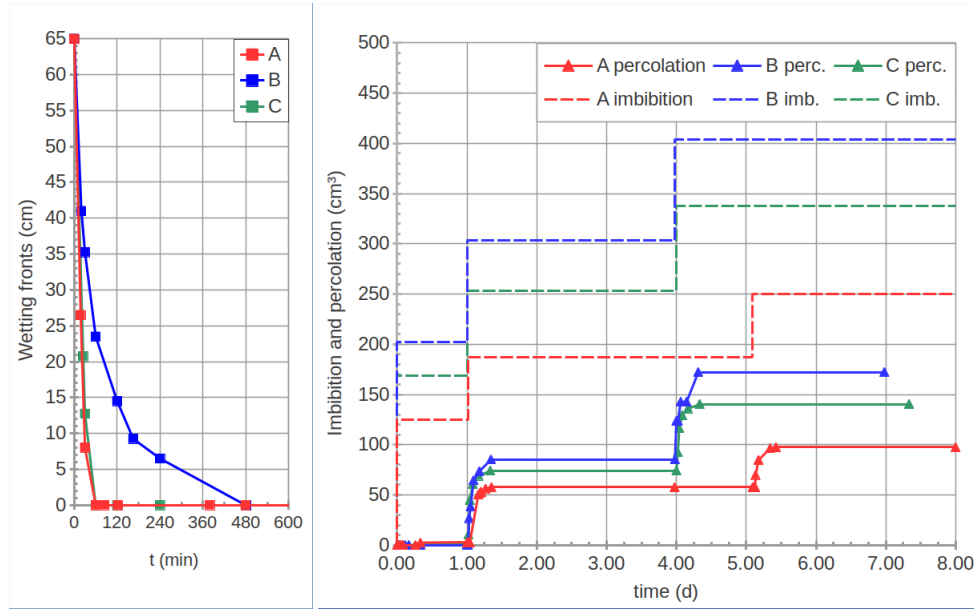


Figure 8. Measures collected during the three repetitions of the third experiment: depth of the imbibition fronts (left) and volumes of imbibition and percolation (right). The unitary volume V_i of a vial was estimated equal to $V_i = 31.3, 50.5, 41.0 \text{ cm}^3$ for soil A, B, and C, respectively, according to the procedure described in Section 5. Legend: A, B, C = Soil identificative, \square = Downward moving water front, \triangle = Percolation volume, Dashed line = Imbibition volume

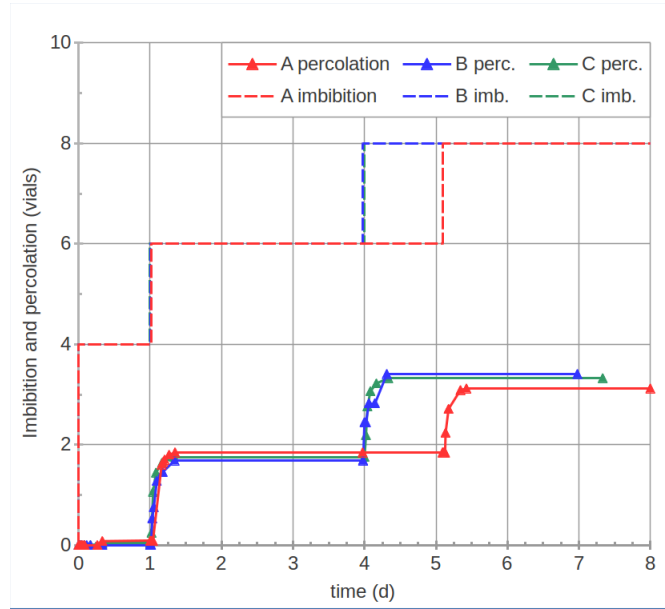


Figure 9. Imbibition and percolation volumes during the three repetitions of the third experiment expressed as the number of vials. The ~~volumes are divided for the~~ unitary volume V_i of a vial was estimated equal to $V_i = 31.3, 50.5, 41.0 \text{ cm}^3$ for each soil A, B, and C, respectively, according to the procedure described in Section 5. Legend: A, B, C = Soil identificative, \triangle = Percolation volume, Dashed line = Imbibition volume

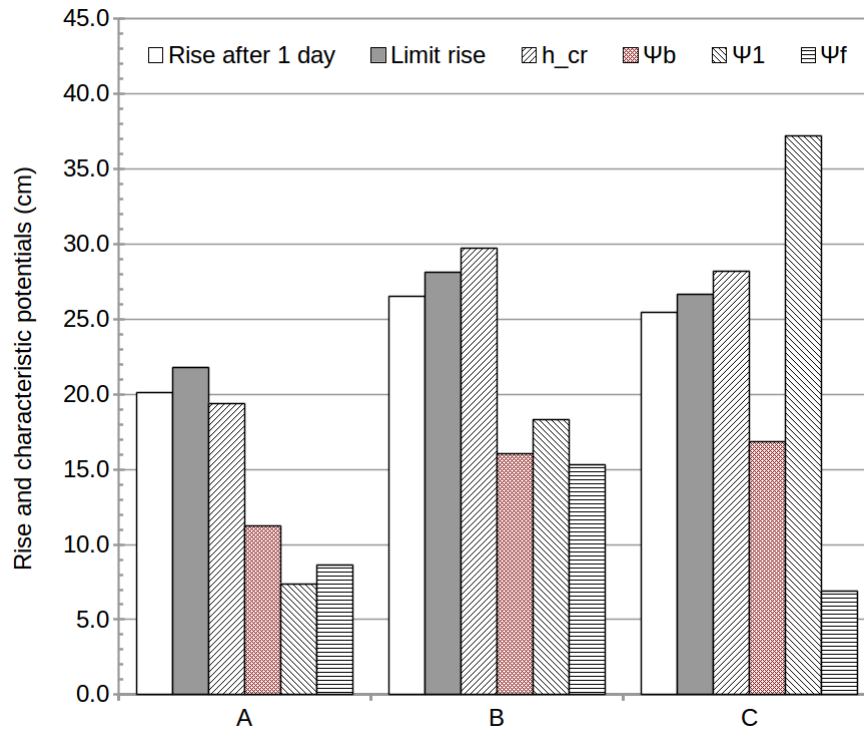


Figure 10. Comparison between the measured height of capillary rise after 1 day, the limit height of capillary rise, the height of capillary rise h_{cr} estimated by means of the Polubarinova–Kochina formula and the absolute values of the characteristic potentials Ψ_b , Ψ_1 , Ψ_f for the three soils used to repeat Perrault’s experiments

Table 1. List of previous scholars referred to by Schott (1663) and by Perrault (1674)

Scholar	Schott (1663)	Perrault (1674)
Agricola	p.110	p.48
Albertus Magnus	pp.117–121	
Aristotle	pp.66–76	pp.13–21
Cabeus Nicolas	pp.111–114	
Cardano		pp.40–49
Coimbran philosophers	pp.106–109	pp.35–38 (together with Thomas Aquinas)
Cornelius a Lapide	pp.114–117	
Davity		pp.89–90
Descartes	pp.82–84	pp.90–97
Dobrzanski de Nigro Ponte		pp.49–51
Du Hamel		pp.117–124
Epicurus		pp.21–22
Froidmond Libert	pp.109–110	
Gassendi		pp.116–117 ‡
Holy Scriptures and Patristics	pp.88–102	
p. (père) Jean François		pp.142–145‡
p. (père) Lennart Leys (Leonardus Lessius)	pp.77–78	
Lucretius	pp.96–99	
Maignan	pp.126–128	(see Schott)
Palissy		pp.145–146 ‡
Papin		pp.97–116
Presocratic philosophers	p.74	
Plato	pp.49–53, 78	p.8
Plinius		pp.32–35
Rohault		pp.138–142
Scaliger (Julius Caesar Scaliger)		pp.38–40
Schott		pp.115, 124–138
Scotus Duns	pp.121–125	
Seneca	pp.77, 86–88	pp.24–32
Other scholars reported by Seneca	p.85	pp.27–30
Thomas Lydiat	pp.129–130	pp.72–88
Vallès Francisco (Vallesius)	pp.103–106	pp.33–34
Vitruve		pp.22–24 ‡
von Helmont		pp.51–72

‡ Authors referred to as *Opinion Commune* by Perrault

Table 2. Measurement systems used in the XVII–century France (Blamont, 2001)

Measurement unit	<i>pied du roi</i>	<i>Toise de l'Écritoire</i> (before 1667)	<i>Toise du Châtelet</i> (since 1668)
<i>point</i>	1/1728	0.189 mm	0.188 mm
<i>ligne</i>	1/144	2.268 mm	2.256 mm
<i>pouce</i>	1/12	2.722 cm	2.707 cm
<i>pied du roi (pied)</i>	1	32.660 cm	32.484 cm
<i>toise</i>	6	1.959 m	1.949 m

Table 3. Perrault’s description of the soils used during the first and second experiment

	Perrault’s description
1 st	Dry river sand, passed with coarse sieve
2 nd	Sand with gravel
3 rd	Crumbled and sieved sandstone
4 th	Crumbled granular soil

Table 4. ~~Capillary~~ Height of capillary rise and characterization of Perrault’s soils (1st, 2nd, 3rd, 4th) and of the soils used for the repetitions of the first experiment (A, B, C). Legend: ϕ porosity, d_{10} characteristic diameter for the Polubarinova–Kochina’s relationship, \tilde{d} characteristic diameter for Kozeny and Carman’s relationship, h_{cr} Polubarinova–Kochina’s capillary rise, k_p Kozeny and Carman’s intrinsic permeability, K_s Kozeny and Carman’s hydraulic conductivity at saturation. Perrault’s soils are ~~describ~~ described in Table 3

	ϕ	d_{10}	\tilde{d}	Height of capillary rise			h_{cr}	k_p	K_s
				Perrault’s	After	Limit			
				data	one day	rise			
	cm ³ /cm ³	cm	cm	pouces	cm	cm	cm	cm ²	m/s
1 st	0.333	0.0185	(0.0185)	18	48.7			1.58E-07	1.55E-04
2 nd	0.333	0.0332	(0.0332)	10	27.1			5.11E-07	5.01E-04
3 rd	0.333	0.0332	(0.0332)	10	27.1			5.11E-07	5.01E-04
4 th	0.333	0.0185	(0.0185)	18	48.7			1.58E-07	1.55E-04
A	0.463	0.0268	0.0444		20.1	21.8	19.4	3.77E-06	3.70E-03
B	0.478	0.0165	0.0241		26.5	28.1	29.7	1.29E-06	1.27E-03
C	0.440	0.0198	0.0340		25.45	26.65	28.2	1.74E-06	1.71E-03

Table 5. Imbibition and percolation volumes measured during the first experiment. Data are reported as the number of vials, in order to make a comparison with Perrault’s data. The unitary volume of a vial was estimated equal to 74cm^3 for all the soils, according to Barontini et al. (2013)

Imbibition (vial)	Perrault’s data (vial)	A (vial)	B (vial)	C (vial)
1	0.75	0.34	0.09	0.24
1	1	0.92	0.76	0.73

Table 6. Imbibition and percolation volumes measured during the third experiment. Data are reported as the number of vials, in order to make a comparison with Perrault’s data. The unitary volume V_i of a vial was estimated equal to $V_i = 31.3, 50.5, 41.0\text{cm}^3$ for ~~the~~ soil A, B, and C, respectively, according to the procedure described in Section 5

Time (d)	Imbibition (vial)	Perrault’s data (vial)	A (vial)	B (vial)	C (vial)
0	4	0.33	0.09	0	0.04
1	2	2	1.76	1.69	1.72
4	2	1.75	1.36	1.72	1.61