INVITED PAPER[*]

Reconciling hydrology with engineering

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Abstract Hydrology has played an important role in the birth of science. Yet practical hydrological knowledge, related to human needs for water storage, transfer and management, existed before the development of natural philosophy and science. In contemporary times, hydrology has had strong links with engineering as its development has been related to the needs of the design and management of water infrastructures. In the 1980s these links were questioned and it was suggested that separating hydrology from engineering would be beneficial for both. It is argued that, thereafter, hydrology, instead of becoming an autonomous science, developed new dependencies, particularly on politically driven agendas. This change of direction in effect demoted the role of hydrology, for example in studying hypothetical or projected climate-related threats. Revisiting past experiences suggests that re-establishing the relationship of hydrology with engineering could be beneficial. The study of change and the implied uncertainty and risk could constitute a field of mutual integration of hydrology and engineering. Engineering experience may help hydrology to appreciate that change is essential for progress and evolution, rather than only having adverse impacts. While the uncertainty and risk cannot be eliminated they can be dealt with in a quantitative and rigorous manner.

> *The philosophers have only interpreted the world, in various ways;*
> *the point, however, is to change it (Karl Marx; Theses on Feuerbach, 1845)*

A brief history of hydrology and its links with engineering

Hydrology has played an important role in the birth of Science as the first scientific problems, put and studied as such, were about hydrological phenomena. It appears that the first geophysical problem formulated in scientific terms was the explanation of the flood regime of the Nile, then regarded a paradox, i.e. the fact that flooding occurs in summer when rainfall in Egypt is very low to non-existent (Koutsoyiannis et al., 2007, 2010). Thales of Miletus (640–546 BC, one of the Seven Sages of Greece and the father of natural philosophy and science), in addition to his scientific achievements on geometry, proposed an explanation of this "paradox". The historian Herodotus (Histories, 2.20), who lived more than a century later (ca.

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484–425 BC) relates this explanation and quotes additional ones by other Greek philosophers, including his own. Up to that time, all explanations were incorrect, but the important thing is that they were physical and thus scientific, contrary to the tradition of attributing natural phenomena to divine action.

Soon after Thales, the notion of what we call today the *hydrological cycle* was established. Specifically, Anaximander (c. 610–547 BC) understood that rainfall is generated from evaporation, Xenophanes (570-480 BC) described the whole hydrological cycle, while Aristotle (384–328 BC) in his book *Meteorologica* recognized the principle of mass conservation within the hydrological cycle (see the relevant extracts from classical texts in Koutsoyiannis et al., 2007). It is clear in *Meteorologica* that the ancient Greek natural philosophers formed a view of the hydrological cycle, which was generally consistent with the modern one, but also included some incorrect elements (as happens in the development of scientific knowledge all the time). Aristotle himself incorrectly asserted that vapour condensation occurs not only in the atmosphere, but also underground. For this assertion (as well as a passage from Plato's dialogue Phaedo; Koutsoyiannis et al. 2007) the modern hydrological literature charges these philosophers with vastly erroneous or fanciful views, providing a picture that is opposite to what they actually proclaimed, sometimes using "quotations" that do not actually appear in the original texts. The most significant advances in the science of the antiquity, as well as its marriage with technology, were made during the Hellenistic period (323–146 BC). For example, it was at that period that the "paradox" of the Nile was resolved by Eratosthenes (ca. 276–195 BC) who among other achievements also calculated the Earth's circumference with an error of less than 2%. During the same period, hydraulics was founded on a scientific basis (hydrostatics by Archimedes, ca. 287–212 BC; pressurized flow by Hero of Alexandria, ~150 BC) and was able to support large scale technological applications (e.g. the 3 km long inverted siphon of the Pergamon aqueduct; Koutsoyiannis et al., 2008).

Yet practical hydrological knowledge existed before the development of natural philosophy and science. This knowledge had its roots in human needs related to water storage, transfer and management. Thales's achievements include hydraulic engineering as he accomplished the diversion of the River Halys for military purposes. Nonetheless, hydraulic engineering achievements started in prehistory, in several civilizations in Mesopotamia, Egypt, India and Greece (Mays et al., 2007) and aimed to control the flow of water, initially for agricultural needs (irrigation) and later for urban needs (water supply and sewerage). Remains of prehistoric irrigation canals, as well as urban water systems still exist. The historical fact that technological applications to solve practical problems preceded the development of scientific knowledge is important to recognize and relevant when revisiting the current state of hydrology, as this paper attempts.

Substantial progress in hydraulic engineering occurred during Roman times, as demonstrated by the famous Roman aqueducts which advanced in scale and spread through Europe and beyond. This however was not accompanied by similar scientific progress. The latter had to wait until the Renaissance. Then, not only did the ancient scientific knowledge revive but it was further advanced by the Italian Renaissance scientists Leonardo da Vinci (1452-1519), Galileo Galilei (1564-1642) and Benedetto Castelli (1578-1643). The major breakthrough during the Renaissance was the recognition of the importance of the empirical basis in hydrological phenomena, acquired by observation, measurement and experiment. Leonardo da Vinci, the great artist, scientist and engineer, was also a great experimentalist and gave particular focus to water flow, as testified by his book *Del moto e misura dell' acqua*, written around 1500 (but published much later) and many of his manuscripts (see also Pfister et al. 2009). Also, Benedetto Castelli in his book *Della misura delle acque correnti*, published in 1628, explained how he installed a rain gauge in Perugia in order to provide a basis for estimating the variations in level of the Trasimeno Lake (Dooge, 2004) and controlling the discharge of its outlet. Interestingly, similar knowledge had been developed even earlier in other places of the world. Thus, the Korean King Sejo is attributed to have invented a rain gauging device in 1442 (Arakawa, 1956) while it is thought that rainfall measurements were taken also in ancient times in China and India (Montanari et al., 2013). Nonetheless, the oldest systematic and official rainfall measurements in the world were perhaps those made in Korea, in the 15th century, from which the records from the 18th century (namely after 1770) to date have survived (Koutsoyiannis and Langousis, 2011).

In the 18th century, Daniel Bernoulli (mostly known for the discovery of what we call Bernoulli's law) understood that the study of the motion of fluids needs advanced knowledge of mathematics and is very difficult:

> *"Admittedly, as useful a matter as the motion of fluid and related sciences has always been an object of thought. Yet until this day neither our knowledge of pure mathematics nor our command of the mathematical principles of nature have permitted a successful treatment"* (Bernoulli, in a letter to J. D. Schöpflin, Sept. 1734).

Despite spectacular progress in the next three centuries, there still remain issues for which the phrase "*until this day*" in this quotation could well represent present day.

The term *hydraulic* is used already in the Hellenistic period (by Hero of Alexandria in his *Pneumatica*, and later by Pliny). However, it seems that the term *hydrology* did not exist in the classical literature (neither a search in the archive of classical texts of www.perseus.tufts.edu, nor the Liddell and Scott, 1940, Lexicon provide any related entry). It only appeared towards the end of the 18th century, as a search on Google books testifies (Figure 1). In its first use, the term *hydrology* had a broad meaning and described a body of knowledge related to water and its links to other geophysical sciences, like geology, meteorology, climatology and natural history, as well as to botany, zoology, anthropology and health issues. Such links have been reflected in some of the first books and papers, published in the late 19th century, having the term *hydrology* in their titles:

- A Treatise on Physical Geography: Comprising Hydrology, Geognosy, Geology, Meteorology, Botany, Zoology, and Anthropology (Barrington and Burdett, 1850; see cover in Figure 2, left);
- Atlas of Physical Geography: Illustrating in a Series of Original Designs the Elementary Facts of Chartography, Geology, Topography, Hydrology, Meteorology, and Natural History (Johnston, 1852);
- On the Proceedings of the International Congress of Hydrology and Climatology at Biarritz, October 1886 (Symons, 1887).

Interestingly, in the last source, the related subfields (sections) covered in the 1886 Congress of Hydrology, are listed as: (i) Scientific Hydrology (water analysis, micro-organisms, collection of mineral water, geological influences, bathing apparatus); (ii) Medical Hydrology (physiological and medical questions); and (iii) Climatology, Scientific and Medical. One can then infer that the term *Scientific Hydrology*, which was used even in the name *International Association of Scientific Hydrology* of what is now called *International Association of Hydrological Sciences* (IAHS) aimed to distinguish it from *Medical Hydrology* (rather than distinguish it from charlatans' and simpletons' practices as generally thought; cf. ks360352.kimsufi.com/history/history.htm).

Other textbooks and manuals of the same period clearly manifest the link of hydrology with hydraulics and, through this, with engineering:

- Manual of Hydrology: containing I. Hydraulic and other tables: II. Rivers, flow of water, springs, wells, and percolation. III. Tides, estuaries, and tidal rivers. IV. Rainfall and evaporation (Beardmore, 1862; see cover in Figure 2, right);
- A Practical Treatise on Hydraulic and Water-supply Engineering: Relating to the Hydrology, Hydrodynamics, and Practical Construction of Water-works, in North America (Fanning, 1877).

These books contained hydraulic formulae and tables (Figure 3, upper) along with observational hydrological information (Figure 3, lower). They indirectly indicate that the reasons leading to hydrology becoming a quantitative science are related to engineering needs.

It was only in the 1960s that hydrology acquired a clear, elegant and practically unquestionable, definition as a science:

> *"Hydrology is the science which deals with the waters of the earth, their occurrence, circulation and distribution on the planet, their physical and chemical properties and their interactions with the physical and biological environment, including their responses to human activity"* (UNESCO, 1963, 1964).

This definition complemented an earlier one by the US Ad Hoc Panel on Hydrology (1962), adding an essential element, the interaction of water with human activity. Sometimes the term, *hydrological science* has been used as a synonym but it conceals the fact that hydrology is strongly linked with engineering and technology. Besides, *hydrological sciences* (plural), although in common use for several decades, is ill-defined as it has not been explained which the constituent sciences are and perhaps indicates a misspecification of scientific branches of hydrology as sciences.

The above definition, however, does not explicitly recognize the link of hydrology with hydraulics and, more generally, with engineering. Because in the 20th century up to the 1970s the developed world was investing in building public infrastructures (Burges, 1979), hydraulics was a dominant and primary field in engineering and supported the design of hydraulic structures such as dams, canals, pipelines and flood protection works. At those times, hydrology was regarded as an appendage of hydraulic engineering (Yevjevich, 1968), again to support the design of hydraulic structures, especially in estimating their design discharges. The engineering aspect of hydrology was prominent also because it was part of the professional education in engineering schools. It is because of this aspect that hydrology made significant progress in developing a scientific approach to study natural variability and the implied uncertainty.

In other words, the close relationship of hydrology with engineering advanced it as a modern quantitative scientific discipline. Some of these advances are pertinent to both hydraulics and hydrology, such as those related to the flow in aquifers and in unsaturated soils, as well as the transport phenomena and the movement of sediments. Other advances in hydrology were not connected to hydraulics, yet they had a clear engineering orientation. These include the probabilistic and stochastic modelling of hydrological processes, the development of data processing methodologies, algorithms and computer tools, as well as of Monte Carlo simulation techniques, the reliability theory of reservoir storage, the linear systems approximations to flood routing (e.g. unit hydrograph), the systems analysis techniques used for assisting with water resources management, and the parameterization-optimization of the modelling of hydrological processes.

The involvement of stochastics in hydrology enabled a new type of prediction, the probabilistic prediction which replaces deterministic prediction when it becomes infeasible due to the very long prediction horizons in engineering planning and design. A basic premise in planning and design is that all engineering constructions are subject to uncertain loadings and are inescapably associated with risk.

Similarities, differences and interaction of hydrology and hydraulics

An informative analysis of the differences of hydrology from hydraulics has been made by Savenije (2009), who, inter alia, says:

> *“Hydraulic engineers describe the behaviour of water within well-defined boundaries. There is nothing wrong with that. The problem appears when hydraulic engineers start to apply their ‘physical laws’ to hydrology”.*

It could be added that, in hydraulics, the well-defined boundaries have also simple geometry, usually with rectangular, trapezoidal or circular cross-sections, and uniform longitudinal slope (Figure 4, upper). Once the geometry of, say, a canal is defined, there is no difference in the hydraulic characteristics whether the canal is in the Nile Delta or in the Po Valley. For this reason, hydraulics can proceed to construct abstract objects, which are generalizations of the natural objects. Actually, the structural simplicity enables repeatability (multiple copies of the same element), which is desirable in engineering constructions as, by studying only one element, we can infer the behaviour of all identical elements.

In contrast, with their complex geometry and structure (Figure 4, middle), the objects of hydrology are unique and non-repeatable (Koutsoyiannis et al., 2009). In hydrology, the Nile Delta and Po Valley are different entities, have different identities and, from a quantitative point of view, it looks impossible to devise an abstract concept that would generalize and unify both in one. In addition, hydrology deals with all three phases of water, solid, liquid, gaseous, and its domain includes the atmosphere, and the earth surface and subsurface (Figure 4, lower).

Hydrology is interrelated to hydraulics as well as to other disciplines that study flows including fluid mechanics and physics, as depicted in Figure 5. The schematic on the left shows the entire pyramid of knowledge and has been adapted from a book by Gauch (2003) on the scientific method. The schematic on the right focusing on hydrology and some of its relatives, tries to indicate that, on the one hand, the flow of water is represented by two disciplines: fluid mechanics—the more theoretical—and hydraulics—the more technological. On the other hand, the circulation of water on Earth is represented by a single discipline, hydrology. This should necessarily cover both the scientific domain and the technological domain. In addition, hydrology is associated with higher complexity in comparison to physics, fluid mechanics and hydraulics.

Physics and fluid mechanics often deal with complex phenomena, too. Among them, turbulence is the most characteristic that traverses all interrelated fields and is important also for hydrology, as exemplified in Figure 6. Almost all flows we deal with in practical problems are turbulent. Turbulence is a phenomenon that resists a deterministic description and its quantification demands a stochastic approach. Random fields of turbulent quantities, such as the flow velocity at a point and at a time, are much more complex than purely random fields. This more complex behaviour is manifested, inter alia, in the power spectrum of a turbulent time series, which is very different from the flat power spectrum of white noise. More importantly, a logarithmic plot of the power spectrum of turbulence indicates two scaling areas with different slopes for high and low frequencies, as seen in the Appendix. The frequencies most relevant to fluid mechanics and hydraulics are the highest (the time scales are the smallest), which define the turbulent (Reynolds) stresses. These are characterized by the Kolmogorov's 5/3 scaling law (spectrum slope = –5/3). But hydrology is more concerned about the largest time scales (the lowest frequencies), in which the Hurst-Kolmogorov dynamics applies, reflected in a milder slope (between 0 and –1; see Appendix). The different scales and scaling behaviours signify another dissimilarity between fluid mechanics and hydraulics, on the one hand, and hydrology, on the other hand.

The stochastic behaviour of turbulence does not enable accurate microscopic descriptions, but helps to develop good macroscopic descriptions for the temporal and spatial averages of the involved processes. In fluid mechanics the 5/3 law has helped the analytical and numerical modelling of turbulence. In hydraulics, this law can yield the celebrated Manning's equation for rectangular cross sections (Gioia and Bombardelli, 2002),

$$V = \frac{1}{n} R^{2/3} i^{1/2} \tag{1}$$

where V is the mean velocity of the cross section, n is a roughness coefficient, R is the hydraulic radius and i is the energy slope. The simplicity of Manning's equation is remarkable and it becomes more evident if we compare it with purely empirical and engineering-oriented Du Buat's equation of the 18th century, shown in Figure 3, which in metric units is written:

$$V = \frac{48.92\left(\sqrt{R} - 0.016\right)}{\sqrt{1\,/\,i} - \ln\sqrt{1/i + 1.6}} - 0.05\left(\sqrt{R} - 0.016\right) \tag{2}$$

We may notice that despite being more complicated and not consistent dimension-wise, the latter equation does not contain a roughness coefficient.

Yet Manning’s equation is neither an exact, nor a general physical law. The fact that the formula is not exact can be seen by inspecting its performance in open surface flow in conduits with circular cross sections, where an increase of *n* by up to 28% may be necessary to apply for medium flow depths (e.g. Koutsoyiannis, 2011b). The fact that it is not general can be inferred by inspecting the adaptation needed to describe the flow in composite (e.g. double trapezoidal) cross-sections (e.g. Papanicolaou, 2007) and the correction needed for meandering channels (Chow, 1959).

Even the very notion of the velocity in the equation is not strictly a deterministic physical quantity, whether we use a Lagrangian or an Eulerian type of description. It is a statistical quantity, a spatial and, simultaneously, a temporal average. In this respect, Manning’s equation is a statistical equation rather than a deterministic one. It does not describe the physics faithfully, yet it can perhaps be classified as a physical equation, if we accept that statistics is part of physics (the example of statistical thermophysics is characteristic of this type). It is a macroscopic equation, because of the assumed integration of the flow properties across the cross section, thus reducing the actual three-dimensional domain, where the flow occurs, into a one-dimensional domain.

It is useful to rethink how this equation is derived. Historically, it has not been established solely by theoretical reasoning and deduction, but is a result of several laboratory and field experiments. This is reasonable for a statistical equation. Given its basis on experiments and data, we can also call it an empirical equation. Alternatively, it can be derived as an approximation of the Darcy-Weisbach and Colebrook-White equations, which in principle are more accurate (albeit again not exact and of empirical type). Indeed, for pipes with rough walls, these equations practically switch to the Manning’s equation (Koutsoyiannis, 2008). In brief, measurement data, numerical methods and theoretical reasoning (as in Gioia and Bombardelli, 2002, mentioned above) are all useful approaches in this particular case, and in all other cases of complex phenomena. Obviously, among the three approaches, the one based on data offers the most precious information and can be used either to derive the equation or to validate it if it was derived by a more theoretical approach.

Can we retain anything from this analysis if we move from the typical domain of the Manning’s equation, i.e., a simple prismatic channel, to a hydrological system, such as a catchment with its unique characteristics? First of all, concerning the Manning equation per se, since it is a macroscopic equation, we may still use it for river channels. But we should have in mind that, as it is not exact even for prismatic channels, it will result in even greater errors in the irregular and varying cross sections of the river, which have also irregularly varying roughness.

Second, it is even more useful in helping us perceive some characteristics and limitations of hydrology. Specifically, hydrology, with its much more complex, unique (not repeatable) objects is:

- macroscopic: it cannot (and need not) describe details;
- statistical/stochastic: it should use averages, standard deviations and probability distributions;
- empirical: it necessarily relies on field data, recognizing that deduction by theoretical reasoning is rather weak and should be complemented by induction based on

measurements (this is the philosophy behind, for instance, establishing stage-discharge curves at river cross sections, based on hydrometric data, instead of relying on application of Manning's equation or on three-dimensional hydrodynamic modelling of the river);
- not exact: errors and uncertainty will never be eliminated;
- difficult to generalize: different catchments may need different treatment as similarities may not be enough to allow accurate generalizations.

The modern change of perception

An impressive result of the combined effort of hydrology and hydraulics in an engineering frame is the transformation, through large-scale constructions such as dams, reservoirs and hydropower plants, of highly varying and uncertain natural flows into regular, often constant, outflows that satisfy the water and energy demands of society (see also Koutsoyiannis, 2011a). Up to the 1980s the engineering efforts had provided the basic infrastructure for reliable, technology-enabled, water resources to the developed world and allowed a high-quality hygienic lifestyle. As the infrastructures were completed to a large extent in the developed world, engineering started to lose importance and hydraulics lost its primary role as a scientific and engineering field.

Interestingly, at about the same time the link of hydrology with engineering was questioned. This was reflected in the discussions about the character of IAHS. The then president Vít Klemeš defined the focus of IAHS as:

> *"the development of hydrology as a strong geophysical (earth) science and the promotion of sound applications of this science on solving practical problems"* (Klemeš, 1987).

However, despite recognizing the importance of solving practical problems, he also asserted that water resources management is not a hydrological science and IAHS is not its professional home (Klemeš, 1987; see also Koutsoyiannis 2011e). He did not clarify in this text his view about the relationship of hydrology with engineering but this can be inferred from other texts, where he described himself as

> "*trying to cut the umbilical cord between [hydrologists and engineers], which [he saw] as inevitable and eventually beneficial to both*" (Klemeš, 1986).

A similar message was broadcast in a book by the US Committee on Opportunities in the Hydrological Sciences (1992) that has been regarded by some as the gospel of modern hydrology (and commonly referred to as the *Blue Book*). This gave the emphasis on the *understanding* of hydrological processes and asserted that:

> *"Development of hydrology as a science is vital to the current effort to understand the interactive behaviour of the earth system",*

as if hydrology was not a science till then and as if understanding was the primary goal of science. It also concluded that:

> *"graduate education in the hydrologic sciences should be pursued independently of civil engineering".*

The most frequently appearing words in US Committee on Opportunities in the Hydrological Sciences (1992) are shown in Figure 7 (left) in comparison with the frequencies of some engineering-related words. Clearly, Figure 7 reveals depreciation of engineering-oriented aspects of hydrology.

In fact, this trend did not concern merely hydrology. Rather it was part of a more general change of perspective, marked by a departure from a problem-solving approach that needs to be accompanied with engineering solutions. By definition, engineering deals with real-world problems and aims to change, transform or control natural processes, and to provide solutions to these problems. As manifest in the history of water engineering, it does not demand full understanding of the details of the processes and usually relies on a macroscopic view and an approximate description of such processes, provided that the degree of approximation is satisfactory for the purposes of the study.

Engineering solutions were also opposed during the last decades by the developing "green" ideology as well as by politico-economic agendas related to the climate-change movement (Klemeš, 2007, Koutsoyiannis, 2011a). The latter has been strong enough to determine the direction of research funding of national and international (e.g. European) bodies in a manner that hydrology would not have any share except in assisting with subjects dictated by the dominant political agendas (e.g. in studying hypothetical or projected climate-related threats and impacts). Thus, arguably, hydrology, instead of becoming an autonomous science with a broader domain, as envisaged, developed dependencies on politically driven agendas and this demoted its role accordingly.

The change of perspective was further supported by the notion of the so-called *soft water path* (Gleick, 2002, 2003; Brooks, 2005; Pahl-Wostl, 2007; Pahl-Wostl et al., 2008; Brooks et al., 2009), which,

> *"by investing in decentralized facilities, efficient technologies and policies, and human capital [...] will seek to improve overall productivity rather than to find new sources of supply [and] will deliver water services that are matched to the needs of end users, on both local and community scales"* (Gleick, 2002).

This has been promoted as a contrasting alterative to engineering solutions to problems that rely on infrastructure development, which Gleick (2002) calls the *hard path* and criticizes for:

> *"spawning ecologically damaging, socially intrusive and capital-intensive projects that fail to deliver their promised benefits"*.

Interestingly, the groups that discourage building new water projects and promote their soft path, at the same time highlight projections on threats like bigger floods and droughts of greater duration due to climate change, as well as the need for adaptation to climate change. The soft path concept has become popular in several countries and international organizations (Brooks et al., 2009). Thus, it was argued that some "*major shortcomings of conventional water management [are] avoided by using the 'soft path'*" (Wagner, 2008—an UNESCO publication) and that "*the soft path opens new avenues for accessing capital*" (Leflaive, 2008—an OECD publication). On the other side, in one of the rare instances that the concept was criticized, Stakhiv (2011) found it wholly inadequate for the needs of most of the developing world.

As the new promoted soft path approach is weakly connected to the material world, it encouraged a new culture in research procedures, which could be exemplified by the following approach in developing a research programme fully consistent with the modern socioeconomic emphasis on virtual reality: (a) we invent a problem that does not exist; (b) we coin a smart name to describe it; (c) we get plenty of money to study it; (d) we organize brain-storming meetings to define the problem; (e) we produce deliverables and publications to justify the funding received.

While the soft path was developing as a new dominant doctrine, the scientific developments in hydrology did not contest it. In particular, the new emerging areas of interest (in addition to the traditional branches such as hydrometeorology and hydrogeology) seem to comply with this doctrine. Some examples are:

- biohydrology: the study of the interactions between biological and hydrological systems (initially meant to be the study of catchment hydrology in conjunction with the microorganisms which the living populations of the catchment introduce into the various water flows; Feachem, 1974);
- ecohydrology: the study of the interactions between water and ecosystems within water bodies (Zalewski et al., 1997; Rodriguez-Iturbe, 2000);
- hydropsychology: the study of the transactions between humans and water-related activities (Sivakumar, 2011);
- hydrosociology: the study of human–water interactions (Falkenmark, 1979, 1997; Sivakumar, 2012);
- sociohydrology: "*the science of people and water, a new science that is aimed at understanding the dynamics and co-evolution of coupled human-water systems*" (Sivapalan et al., 2012).

The importance of the new knowledge acquired by these emerging fields should not be questioned. Particularly, ecohydrology, by shedding light on the interactions and feedbacks between hydrologic processes and terrestrial ecosystems (Porporato and Rodriguez-Iturbe, 2002; D'Odorico et al., 2010) has indeed offered useful knowledge. Also the importance of the interactions of humans with water, emphasized by hydropsychology, hydrosociology and sociohydrology, is not put in question. However, these interactions are already part of the domain of hydrology even according to the UNESCO (1964) definition, and thus introducing new labels and calling them new sciences is arguably pointless. In addition, the interaction of water and human societies can hardly be perceived without engineering means.

On the other hand, the mandate to make hydrology a science independent of engineering, combined with other socio-economic developments of the last decades, impelled hydrology (or part of it) to a virtual reality nexus, which deals with hypotheses, future projections and scenarios, and pays less attention to elements of reality. As stated in the beginning of this section, the late Vít Klemeš was one of the pioneers of this mandate. It is thus instructive to see his own view of the state of affairs that was gradually formed in the last decades. The following passages are from one of his lasts talks (Klemeš, 2007; emphasis added):

> *"[A] new infectious disease has sprung up—a WATER-BORN SCHIZOPHRENIA: on the one hand, we are daily inundated by the media with reports about water-caused disasters,*

> *from destructive droughts to even more destructive floods, and with complaints that 'not enough is done' to mitigate them and, on the other hand, attempts to do so by any* ***engineering means—and so far no other similarly effective means are usually available****—are invariably denounced as 'rape of nature' (often by people with only the foggiest ideas about their functioning), and are opposed, prevented, or at least delayed by never ending 'environmental assessments and reassessments'. In the present 'green' propaganda, all dams are evil by definition, ranking alongside Chernobyls, Exxon Valdezes, 'rape of the environment', AIDS, cancer and genocide".*
>
> *"I shall close with a plea to all of you,* ***hydrologists and other water professionals, to stand up for water, hydrology and water resource engineering****, to restore their good name, unmask the demagoguery hiding behind the various 'green' slogans. As in any sphere of human activity, errors with adverse effects were and will be made in our profession as well [...]. But, on the whole, our profession has nothing to be ashamed of – from the times of the ancient Mesopotamia, Greece and Rome to the present, it has done more good for mankind than all its critics combined".*

On understanding, misunderstanding and overstanding

It is interesting to observe that the period of the emphasis on the scientific, non-engineering, aspect of hydrology coincided with a bewildering over-optimistic view that data are not absolutely necessary in hydrological modelling, a view that is opposite to the above discourse. Specifically, it was hoped that, by cutting the hydrological systems into small nearly-homogeneous pieces and by describing the natural processes in each piece using differential equations, it would be possible to fully model the system behaviour in detail without the need of data. The differential equations could be, in principle, solved numerically thanks to the ever increasing computer power.

This reductionist philosophical view constituted the basis of the so-named "physically-based" hydrological modelling (e.g. Abbott et al., 1986) and was highly promoted in the initial document of the decade-long IAHS initiative for Prediction in Ungauged Basins (PUB). The idea was that a new generation of models would not need calibration and, hence, data and, simultaneously, would radically reduce uncertainty (Sivapalan et al., 2003). However, pragmatism and experience help us see that the more complex and detailed an approach is, the more data it needs to calibrate. Also, common sense helps us understand that it is infeasible to estimate the evapotranspiration of a forested area by examining each tree separately and then by further modelling the transpiration of each maple or pine leaf individually. History of science teaches that feasible and convenient macroscopic views can better be achieved using principles of probability theory like the law of large numbers and the principle of maximum entropy or even by conceptual and systems approaches.

Parsimony in process description is paramount (Rosbjerg and Madsen, 2005). There are several examples where simpler and more parsimonious models gave better fits and better predictions in complex hydrological systems. It is worth mentioning just one, which refers to a karstic basin in Bosnia and Herzegovina with a complex system of surface poljes and underground natural conduits. Three different research teams modelled it working independently from each other and adopting different approaches. One of those was of the type commonly referred to as “physically-based”, one was based on a detailed conceptual description of the processes and the third was a toy model, lumping similar elements of the system into a single substitute element. Interestingly, the toy model performed best, while the “physically-based” model gave the worst predictions (Makropoulos et al., 2008).

One could say that, despite giving worse predictions, a physically-based model by providing distributed information across the entire basin may eventually be preferable. This argument seems to have some merit, particularly if we target at understanding the hydrological system. Understanding seems to have become the Holy Grail of modern science, not excluding hydrology, as testified by the frequent and emphatic use of this word in scientific papers. For example, a Google Scholar search reveals that out of 31 200 papers published since 2009 that contain the word *hydrologic* (as of January 2012), 64% also contain the word *understanding*. This is a negative development, because understanding is a vague and obscure term. In particular, understanding is a subjective cognitive procedure rather than anything objective. Perhaps a more relevant term is *interpretation* (cf. the motto in the beginning), which is also subjective, but more honest in admitting the subjectivity: while fans of the term *understanding* would pretend to target a unique type of understanding (characterizing other views as misunderstanding), they would be less reluctant to allow multiple interpretations of a phenomenon as legitimate. In addition, as understanding is typically used within a deterministic point of view, which is more familiar to the majority of scientists, it leaves out important targets as the understanding of uncertainty. And as it is used to mean detailed views of phenomena, it may lead to failure in constructing the big picture; for the latter the term *overstanding* has been coined (Koutsoyiannis, 2010) which highlights the importance of macroscopic views of complex phenomena. (Note that a literal translation of the Greek word *episteme* would be overstanding).

A characteristic effect of this misleading approach (detailed physically-based modelling in a hopeless attempt to achieve a correct understanding and produce analytical and insightful calculations of the detailed dynamics at the finest scales) is that most hydrological models are for natural (intact) conditions, while most of the catchments have been modified by humans. In modified catchments it is misleading to study the hydrological behaviour independently of their management or even in a serial approach where a management model is fed by the outputs of a hydrological model. A more consistent approach would admit a two-way interaction of hydrological processes and management practices (Nalbantis et al., 2011).

In an engineering approach, understanding is not necessarily of primary importance. Rather, the primary target depends on the pragmatic objectives of the problem which we study (cf. Littlewood, 2010, who compares utility versus process understanding and Rosbjerg and Madsen, 2005, who suggest that the development or selection of a model should reflect the actual needs for modelling results). As history teaches, full understanding has not been a prerequisite to act. Furthermore, the spatially distributed information provided by such approaches may be misleading or even wrong if it is not controlled through real world data, which provide the final judge for the entire modelling exercise.

Furthermore, contemplating the complexity, heterogeneity, non-repeatability and uniqueness of hydrological systems, one can easily conclude that a target of uncertainty elimination or radical reduction would be infeasible (Koutsoyiannis, 2010). Instead, a feasible target would be to quantify uncertainty. Admitting this, we can extend the notion of a physically-based or conceptual model to incorporate the estimation or description of uncertainty into the model (Jakeman et al. 1990). In this respect, Montanari and Koutsoyiannis (2012) emphasize the need for unification of hydrological modelling and total uncertainty assessment, and outline a blueprint for process-based modelling of uncertain hydrological systems.

As noted above, uncertainty and risk have been fundamental notions in engineering as there cannot be risk-free human constructions. Also, in science, uncertainty is increasingly appreciated as a fundamental, intrinsic feature of Nature, which we have to study and accept, rather than try to eliminate.

Hydrology and the major problems of the 21st century

As already described, current dominant ideological views have obscured real contemporary problems and their real causes. For example, anthropogenic global warming cannot be regarded anything more than a symptom—and not the major one—of other changes. The real problems are related to the demographic change (overpopulation in developing countries, overconsumption and immigration in developed countries), energy change (intense fossil fuel use) and environmental change (urbanization, deforestation, pollution) (Koutsoyiannis et al., 2009). In the current conditions marked with these three historical changes, water supply, food security, energy security, natural hazard prevention and environmental recovery are among the major real challenges of the 21st century. All these five challenges are related to engineering hydrology.

As urbanization increased, and big cities and megacities were created, sometimes without proper water infrastructure (in developing countries) and sometimes with old infrastructure (in developed countries), it has become a big challenge to create or modernize the urban water systems to serve the needs of the population, while minimizing the damages to the environment. This challenge calls for engineering means and hydrology has certainly a big role to play in this.

Food security is more vulnerable in areas with high evapotranspiration, which necessitates irrigated agriculture. Population density, land availability, crop types, water resources availability and irrigation efficiency are the controlling factors for this challenge. Obviously, the last two are related to engineering hydrology.

As we are approaching the time of the so-called peak oil production (Hubbert, 1982), the importance of the renewable energy sources becomes increasingly higher. With the exception of hydroelectric energy from large-scale infrastructures that include reservoirs, all other renewable energy forms are highly variable, depending on hydrometeorological conditions, unpredictable and unavailable at the time of energy demand. Therefore regulation of energy production through energy storage is necessary. The only available technology for large-scale storage of energy is provided by reversible hydropower plants, i.e., by pumping water to an upstream reservoir in periods of excessive energy availability and recovering it producing electric energy as stored water is moved downstream. For large-scale plants, the efficiency of the two-step cycle is extremely high, reaching 85% (Koutsoyiannis 2011a). Again here engineering hydrology, with its particular experience in studying and managing natural variability can substantially help.

With respect to natural hazards, hydrology and hydraulics are the scientific fields most pertinent to the study and management of the flood risk both in real time and in planning and design time horizons. While soft-path low-cost means, like public awareness building and flood warning systems, are pertinent for mitigation of the flood risk (Di Baldassare et al., 2010), engineering means (including structural solutions and urban planning) remain the most powerful weapon in flood protection.

Creation of technological infrastructure is inevitably accompanied by environmental problems. Modernizing management practices of traditional human activities (e.g. agriculture) also create similar problems like pollution and degradation of ecosystems. Envisaging a regression and recovery of the traditional conditions would be utopian, unless it were combined with mass reduction of the population and return to the agrarian age—and hopefully no one supports such vision. Therefore, technology and engineering solutions for existing pollution problems and for minimizing adverse effects in new infrastructures should be the way forward. Engineering hydrology has again a role to play.

The above engineering challenges are particularly relevant to the developing countries in South America, Asia and, above all, Africa, where the level of infrastructure development is lower. But this does not necessarily mean that there are no similar challenges in Europe and North America. While it is true that the level of infrastructure development in the latter areas has been high since a few decades ago, human constructions have a limited life cycle and need good management, maintenance, adaptation to changing conditions and, at times, replacement. In this respect, planning and design of engineering infrastructures are not once-and-for-all actions but perpetual processes.

Perhaps this has not been appreciated by the hydrological community, which, as described above, in the last decades seems to have proceeded to a divorce from engineering, which also led to divergence of hydrologists in academia from professional engineers. Certainly this is an unfortunate development as both scientific and engineering aspects of hydrology are equally important if we wish to deal with real-world problems.

At the same time, part of the hydrological community preferred, over the real-world problems, its engagement to the virtual reality of climate models. Certainly, assisting in climate impact studies provides funding opportunities. The reasons are understandable as without the cooperation of hydrologists, without involving extreme floods and droughts, the necessary prediction of future threats and catastrophes is not frightening enough. However, the entire endeavour may be in vain given the generally admitted, even by climate modellers, failure of climate models to simulate processes relevant to hydrology (see Kundzewicz and Stakhiv, 2010; Anagnostopoulos et al., 2010; Koutsoyiannis et al., 2008, 2011; Stakhiv, 2011). On the other hand, the irony is that anthropogenic effects other than CO_2 emissions, for example land use changes, deforestation and urbanization, have major impacts on hydrological processes and are more predictable (e.g. Ranzi et al., 2002).

Will hydrology keep on walking on those trails formed in the last three decades? It is very probable and an indication is already provided by a recent update of the 1992 document mentioned above by the US Committee on Challenges and Opportunities in the Hydrologic

Sciences (2012). As shown in the right panel of Figure 7, the engineering-related words that had appeared infrequently in the 1992 document have almost disappeared from the 2012 document.

It can be speculated that the current trails are consistent with the targets of the classe politique and the related socio-economic interests. However, it would be more beneficial for the future of hydrology:

- if it revisited its strong technological and engineering roots,
- if it took advantage from the historical fact that hydrology has studied natural uncertainty better and in greater depth than other disciplines,
- if it recognized again that change, uncertainty and risk are intrinsic and interrelated properties of this world and are not eliminable, but are quantifiable and manageable,
- if it appreciated that, in studying catchment scale problems, parsimonious macroscopic descriptions are more powerful than inflationary detailed ones and that holistic approaches are more effective than reductionist ones, and
- if it identified its role within the real and pressing problems of the contemporary world.

In conclusion, reconciling hydrology with engineering could help hydrology to come back from the virtual reality into the real world, where data and facts are more important than model simulations, where predictions are tested against empirical evidence, and where uncertainty and risk dominate. In the real world change is the rule rather than an adverse property that should be opposed (see also Koutsoyiannis, 2013; Montanari et al., 2013). Therefore engineering as a means of planned and sophisticated change is essential for progress and evolution. Thus, the study of change, natural and engineered, as well as the implied uncertainty and risk, can constitute the field of mutual integration of hydrology and engineering.

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Figures

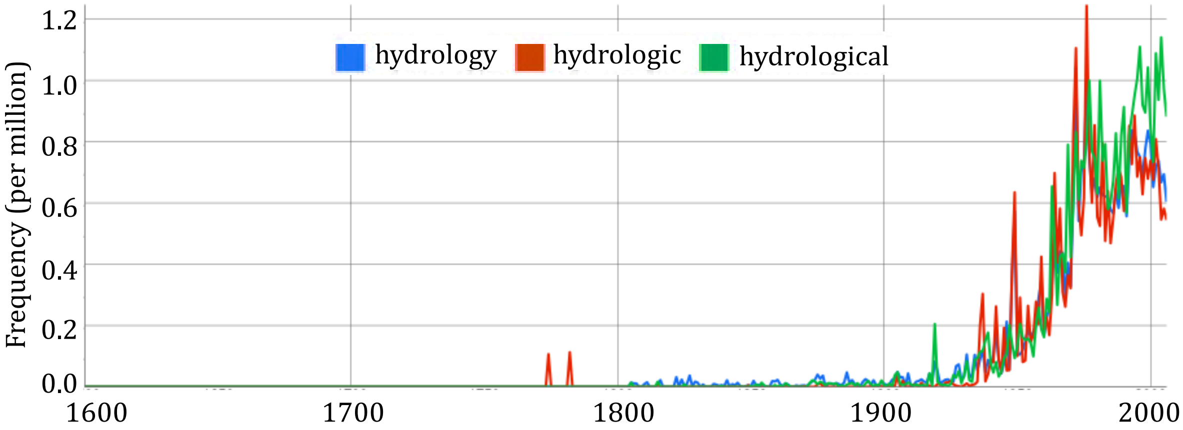
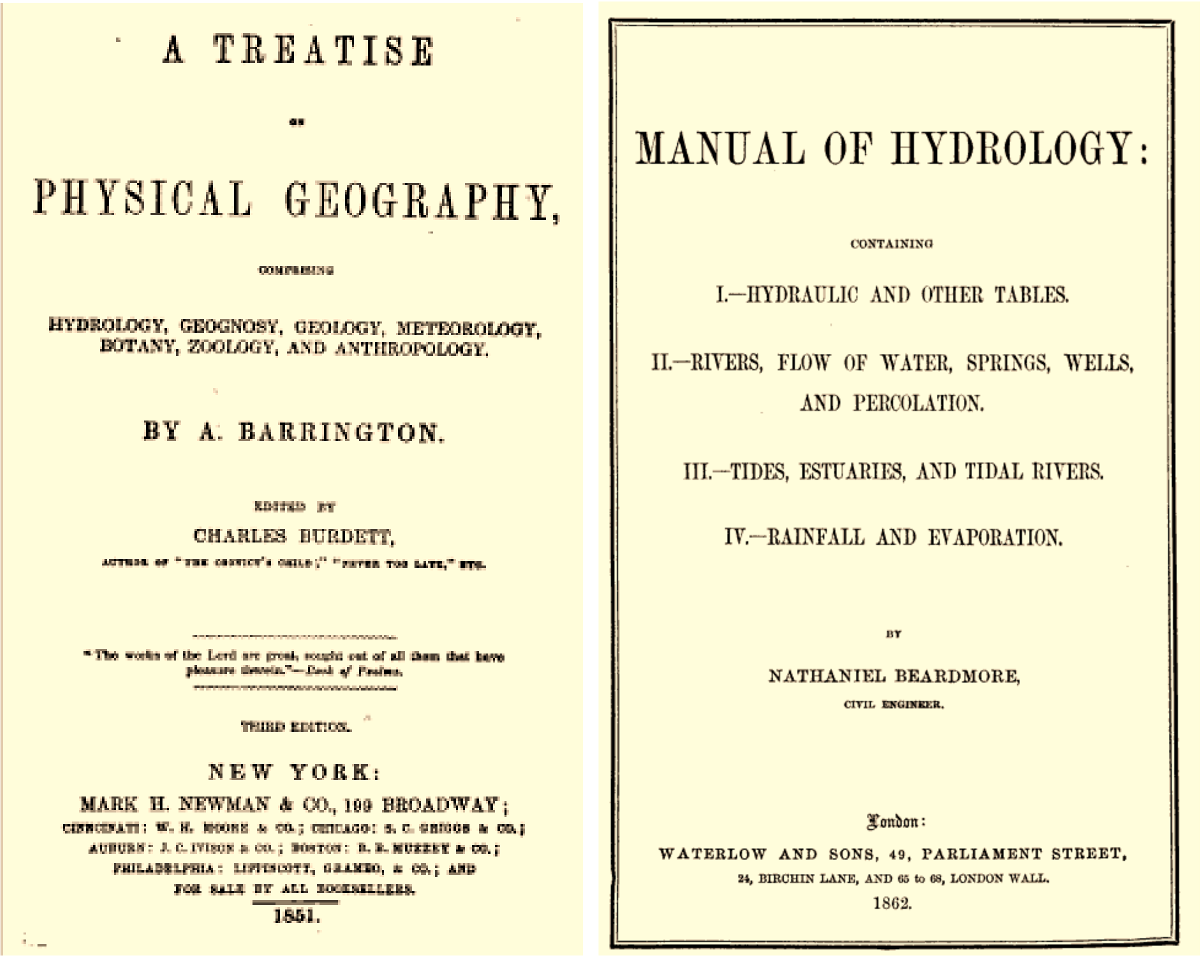


Figure 1 Evolution of the frequency per year of the indicated words, as found in millions of books digitized by Google (data and visualization by Google books: books.google.com/ngrams⁄; see also Mitchel et al., 2011).



A TREATISE

ON

PHYSICAL GEOGRAPHY,

COMPRISING

HYDROLOGY, GEOGNOSY, GEOLOGY, METEOROLOGY,
BOTANY, ZOOLOGY, AND ANTHROPOLOGY.

BY A. BARRINGTON.

EDITED BY
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II.—RIVERS, FLOW OF WATER, SPRINGS, WELLS,
AND PERCOLATION.

III.—TIDES, ESTUARIES, AND TIDAL RIVERS.

IV.—RAINFALL AND EVAPORATION.

BY

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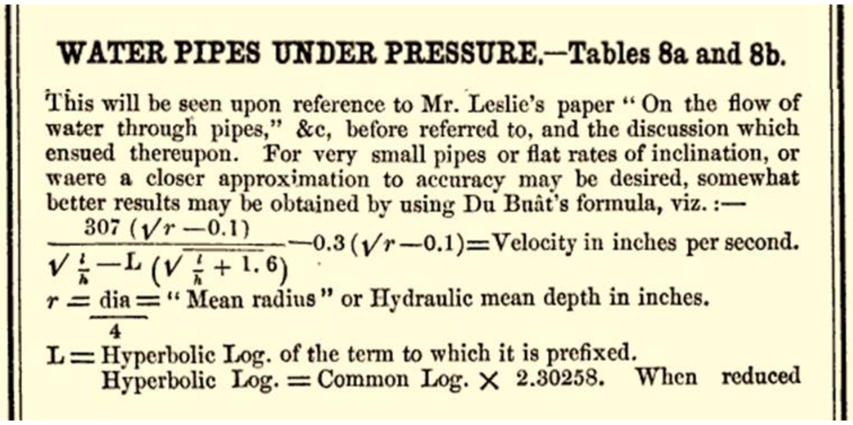
CIVIL ENGINEER.

London:
WATERLOW AND SONS, 49, PARLIAMENT STREET,
24, BIRCHIN LANE, AND 65 to 68, LONDON WALL.
1862.

Figure 2 Covers of two of the earliest books whose title includes the term “hydrology”.



WATER PIPES UNDER PRESSURE.—Tables 8a and 8b.

This will be seen upon reference to Mr. Leslie's paper "On the flow of water through pipes," &c, before referred to, and the discussion which ensued thereupon. For very small pipes or flat rates of inclination, or waere a closer approximation to accuracy may be desired, somewhat better results may be obtained by using Du Buât's formula, viz.:—

$$\frac{307\,(\sqrt{r}-0.1)}{\sqrt{\frac{l}{h}}-\mathrm{L}\left(\sqrt{\frac{l}{h}}+1.6\right)}-0.3\,(\sqrt{r}-0.1)=\text{Velocity in inches per second.}$$

$r = \frac{\text{dia}}{4} =$ "Mean radius" or Hydraulic mean depth in inches.

L = Hyperbolic Log. of the term to which it is prefixed.
Hyperbolic Log. = Common Log. × 2.30258. When reduced

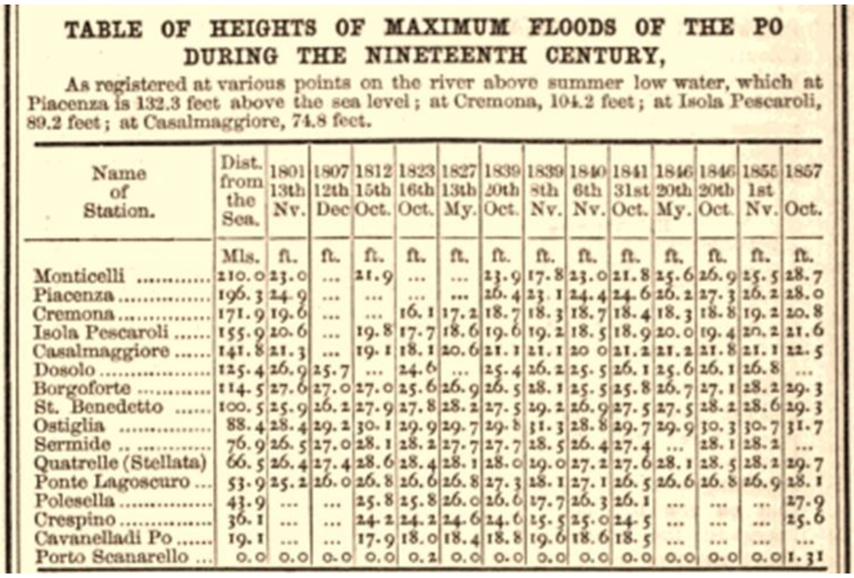


TABLE OF HEIGHTS OF MAXIMUM FLOODS OF THE PO DURING THE NINETEENTH CENTURY,

As registered at various points on the river above summer low water, which at Piacenza is 132.3 feet above the sea level; at Cremona, 104.2 feet; at Isola Pescaroli, 89.2 feet; at Casalmaggiore, 74.8 feet.

Name of Station.	Dist. from the Sea.	1801 13th Nv.	1807 12th Dec	1812 15th Oct.	1823 16th Oct.	1827 13th My.	1839 20th Oct.	1839 8th Nv.	1840 6th Nv.	1841 31st Oct.	1846 20th My.	1846 20th Oct.	1855 1st Nv.	1857 Oct.
	Mls.	ft.	ft.	ft.	ft.	ft.	ft.	ft.	ft.	ft.	ft.	ft.	ft.	ft.
Monticelli	210.0	23.0	...	21.9	...	...	23.9	17.8	23.0	21.8	25.6	26.9	25.5	28.7
Piacenza	196.3	24.9	...	...	...	...	26.4	23.1	24.4	24.6	26.2	27.3	26.2	28.0
Cremona	171.9	19.6	...	...	16.1	17.2	18.7	18.3	18.7	18.4	18.3	18.8	19.2	20.8
Isola Pescaroli	155.9	20.6	...	19.8	17.7	18.6	19.6	19.2	18.5	18.9	20.0	19.4	20.2	21.6
Casalmaggiore	141.8	21.3	...	19.1	18.1	20.6	21.1	21.1	20 0	21.2	21.2	21.8	21.1	22.5
Dosolo	125.4	26.9	25.7	...	24.6	...	25.4	26.2	25.5	26.1	25.6	26.1	26.8	...
Borgoforte	114.5	27.6	27.0	27.0	25.6	26.9	26.5	28.1	25.5	25.8	26.7	27.1	28.2	29.3
St. Benedetto	100.5	25.9	26.2	27.9	27.8	28.2	27.5	29.2	26.9	27.5	27.5	28.2	28.6	29.3
Ostiglia	88.4	28.4	29.2	30.1	29.9	29.7	29.8	31.3	28.8	29.7	29.9	30.3	30.7	31.7
Sermide	76.9	26.5	27.0	28.1	28.2	27.7	27.7	28.5	26.4	27.4	...	28.1	28.2	...
Quatrelle (Stellata)	66.5	26.4	27.4	28.6	28.4	28.1	28.0	29.0	27.2	27.6	28.1	28.5	28.2	29.7
Ponte Lagoscuro ...	53.9	25.2	26.0	26.8	26.6	26.8	27.3	28.1	27.1	26.5	26.6	26.8	26.9	28.1
Polesella	43.9	...	...	25.8	25.8	26.0	26.6	17.7	26.3	26.1	...	...	...	27.9
Crespino	36.1	...	...	24.2	24.2	24.6	24.6	15.5	25.0	24.5	...	...	...	25.6
Cavanelladi Po	19.1	...	...	17.9	18.0	18.4	18.8	19.6	18.6	18.5	...	...	...	...
Porto Scanarello ...	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.31

Figure 3 Images from pages of the book by Beardmore (1862) whose cover is shown in on Figure 2, right; (upper) Du Buât's formula for water pipes; (lower) observations of maximum water level of the Po River.

Figure 4 (Upper) An irrigation canal as a typical, simple and repeatable, object representative of hydraulics (Lugagnano, Verona, Italy; photo from www.panoramio.com/photo/40777649); (Middle) The Po River basin illustrating the complex and unique objects of hydrology (map from Wikipedia); (Lower) A satellite image of the same basin (from visibleearth.nasa.gov/view.php?id=55161) suggestive of the fact that hydrology deals with all three phases of water, solid, liquid, gaseous, and its domain includes the atmosphere, and the earth surface and subsurface.

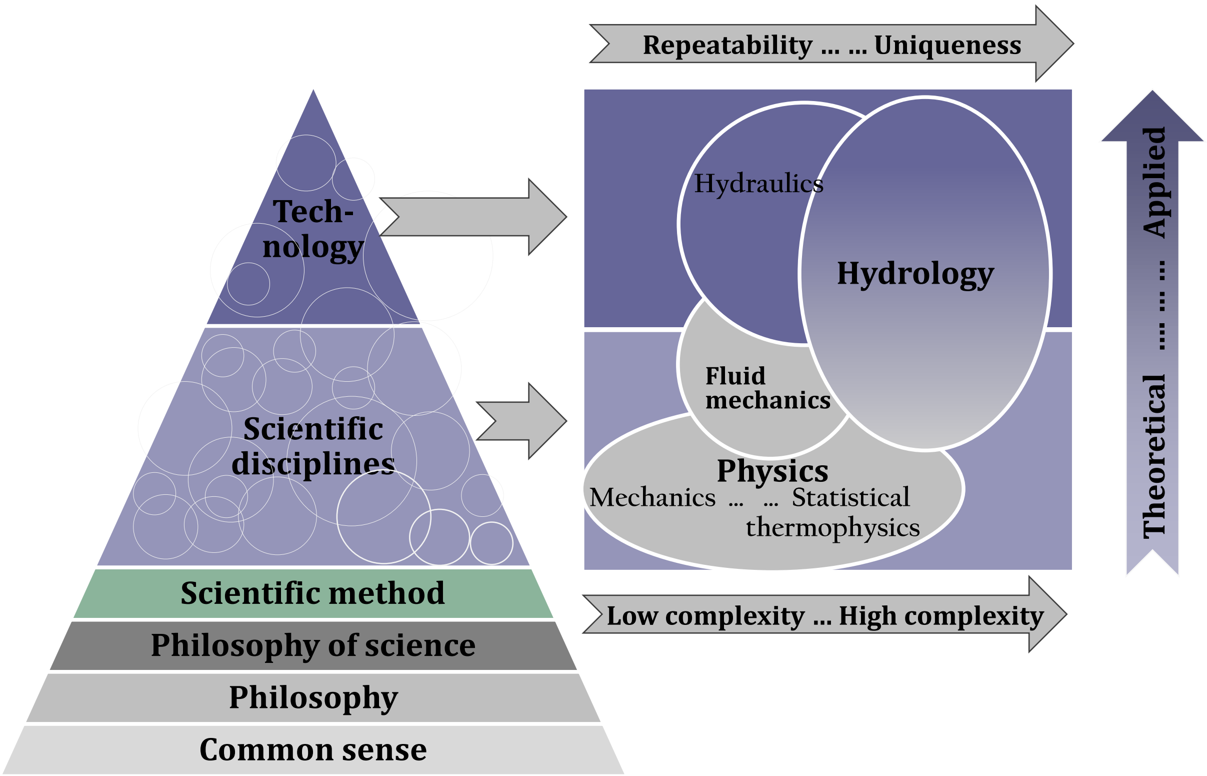


Figure 5 A schematic depiction of the domain of hydrology and some of its relatives, hydraulics, fluid mechanics and physics, within the pyramid of knowledge as suggested by Gauch (2003).

Figure 6 A photo of a junction of two branches of the Karpenisiotis river, tributary to Acheloos in SW Greece; suspended sediment transport, evident on the right branch, would not be possible without turbulence (photo by author).

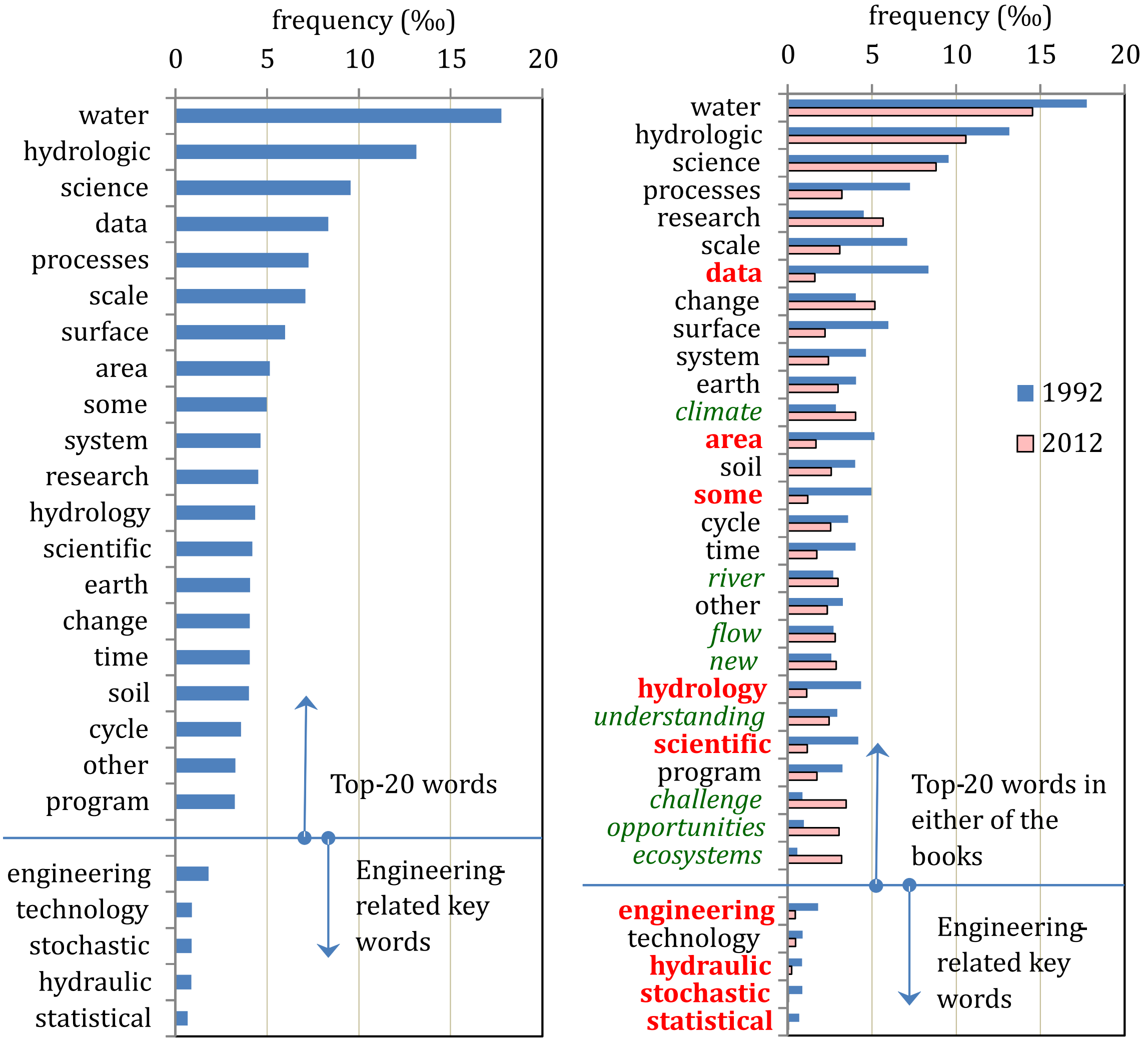


Figure 7 Most appearing words (top 20) and their frequencies in: (left) US Committee on Opportunities in the Hydrological Sciences (1992) and (right) its recent update, US Committee on Challenges and Opportunities in the Hydrologic Sciences (2012). In both graphs the frequencies of some engineering-related words are also shown for comparison. In the right panel (2012 book) the words loosing frequency, by more than 50%, in comparison to the 1992 book, are printed in red, while the words entering the top-20 list in the 2012 book or gaining frequency by more than 100% are printed in green.

Appendix
Turbulence from fluid mechanics to hydrology: different scales and scaling behaviours

A high-resolution time series of turbulence is shown in Figure A1. Specifically, the plot of the upper panel shows velocity fluctuations from a laboratory experiment in a wind tunnel at a millisecond scale for a period of 30 s. For comparison, a purely random synthetic time series with mean and standard deviation equal to those of the turbulent velocity time series is also plotted (lower panel). The differences become more visible on aggregate time scales (k = 0.1 and 1 s in Figure A1).

In particular, it is visually recognizable that the variability at higher time scales is higher in the turbulent time series than in the random one. The variability is quantified by the statistical concept of standard deviation. We can estimate the standard deviation $\sigma(k)$ of the time-averaged process at any time scale k, from the initial time step of the time series to, say, one tenth of its total length. The (typically logarithmic) plot of $\sigma(k)$ vs. k has been termed the climacogram (Koutsoyiannis, 2010) and it is one-to-one related to the autocovariance function and the power spectrum. The climacogram of the time series of observed turbulent velocities of Figure A1 is shown in Figure A2 (upper) along with the theoretical climacograms of four models. We can see that the turbulent velocity process differs from random noise at all time scales. It also differs from the well-known Markov model, whose climacogram is given by (Koutsoyiannis, 2011c):

$$\sigma^2(k) = \frac{\lambda_0}{k/\alpha_0}\left(1 - \frac{1-e^{-k/\alpha_0}}{k/\alpha_0}\right) \tag{A1}$$

where α_0 denotes a characteristic time scale, and $\lambda_0 = \sigma^2(0)/2$ (half the variance of the instantaneous process). Two more realistic models are additionally fitted, Models 1 and 2, which have climacograms, respectively,

$$\sigma^2(k) = \frac{\lambda_1}{1+(k/\alpha_1)^{2/3}} \tag{A2}$$

$$\sigma^2(k) = \frac{\lambda_2}{\left(1+(k/a_2)^{2/3}\right)^{\frac{2-2H}{2/3}}} + \frac{\lambda_3}{1+k/a_3} \tag{A3}$$

The time scale parameters (in s) in the models fitted to the empirical data are α_0 = 0.01347, α_1 =0.03831; α_2= 0.007346; α_3 = 0.03518; the variance parameters (in $\mathrm{m}^2/\mathrm{s}^2$) are λ_0 = 6.776, λ_1 =3.624, λ_2= 1.283, λ_3 = 2.316; for Model 2 the dimensionless Hurst parameter H is 0.87.

A common characteristic of the purely random (white noise) and the Markov models is that their climacograms have the same asymptotic slope, –1/2, for large scales k (this can be proved by deduction) and this is inconsistent with the empirical slope. Models 1 and 2 give milder slopes, –1/3 and –0.13, respectively, which suggest long-term persistence, else known as Hurst-Kolmogorov behaviour, with Hurst parameter H = 2/3 (Model 1) and 0.87 (Model 2). We recall that the Hurst parameter indicates how strong the long-term persistence is, or equivalently, how large the predictive uncertainty is at large time scales (Koutsoyiannis, 2011c, d). The closer the Hurst coefficient to the value 1 (which is the highest possible), the greater the uncertainty at large scales.

At small time scales, the Markov model as well as Models 1 and 2 appear to have indistinguishable climacograms. However, there are differences which can better be seen in the power spectra of the three models shown in the lower panel of Figure A2. Small scales appear here as high frequencies, and indicate a different scaling behaviour with slope –2 for the Markov model and –5/3 for Models 1 and 2. The latter is consistent with the well-known Kolmogorov’s 5/3 law of turbulence combined with Taylor’s frozen turbulence hypothesis. Note that an asymptotic slope in the spectrum steeper than –1 is mathematically feasible for high frequencies, but it is mathematically infeasible for frequency tending to zero. This results in the necessity of a break of scaling, which is evident in Figure A2. In some way, this break of scaling indicates a rough border between fluid mechanics and hydraulics, on the one hand, which focus on high frequencies (small time scales) and hydrology, on the other hand, which is more interested on small frequencies (large time scales).

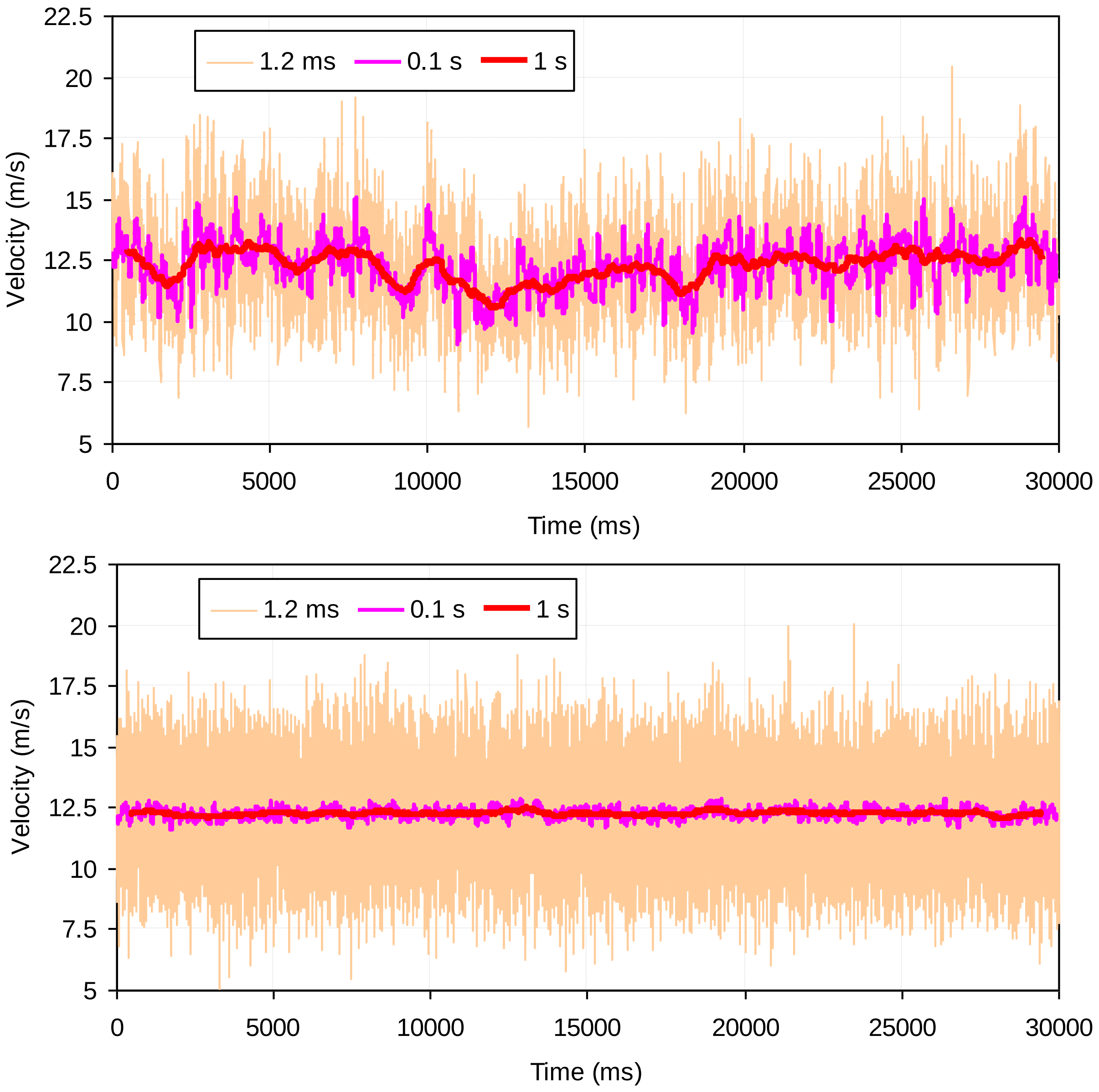


Figure A1 (Upper) Laboratory measurements of velocity fluctuations in nearly isotropic turbulence at a high Reynolds number; each data point represents the average velocity every 1.2 ms, while time averages at time scales of 0.1 and 1 s are also plotted (the original data, available on line at www.me.jhu.edu/meneveau/datasets/Activegrid/M20/H1/m20h1-01.zip, are measurements by X-wire probes with sampling rate of 40 kHz, here aggregated at 0.833 kHz, from an experiment at the Corrsin Wind Tunnel; Kang et al., 2003). (Lower) A purely random synthetic time series with mean and standard deviation equal to those in the upper panel. (Reproduced from Koutsoyiannis, 2013).

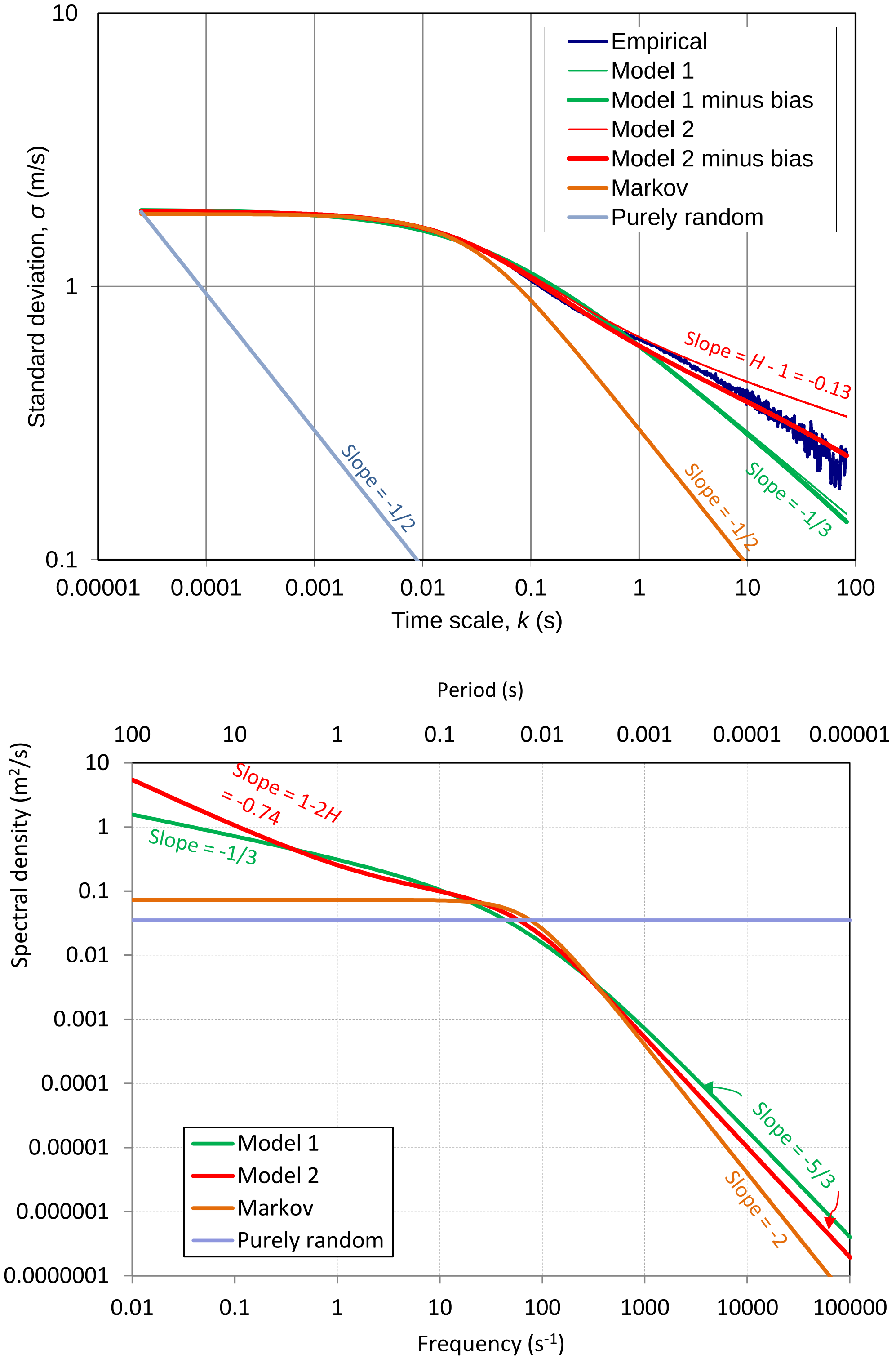


Figure A2 (Upper) Empirical climacogram of the turbulent velocity time series shown in Figure A1 upper, along with the four models (purely random, Markov, and Models 1 and 2) outlined in text, fitted to the empirical climacogram; statistical bias in standard deviation was accounted for in the fitting. (Lower) Theoretical power spectra of the four models; Models 1 and 2 on the left (low frequencies, most relevant to hydrology) indicate the Hurst-Kolmogorov behaviour and on the right (high frequencies, most relevant to fluid mechanics and hydraulics) are consistent Kolmogorov’s 5/3 law of isotropic turbulence; the purely random and the Markov model fail to capture both behaviours.