IDRA 2012 – XXXIII Conference of Hydraulics and Hydraulic Engineering
Brescia – Italy, 10-15 September 2012

Reconciling hydrology with engineering

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Abstract Hydrology has played an important role in the birth of Science in the antiquity. Indeed, the first scientific problems, put and studied as such, were about hydrological phenomena. 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. The term “hydrology” did not exist in the ancient literature and appeared only in the end of the eighteenth century to describe a body of knowledge related to water, on the one hand, and meteorological, climatological and health issues, on the other hand. However, it was the close relationship of hydrology with engineering that advanced it in a modern quantitative scientific discipline. This relationship is testified even in the first books bearing the name “hydrology” in their cover. These books, published in the second half of the 19th century, contained hydrological observational information along with hydraulic formulae and tables. It was only in the 1960s that, owing to UNESCO, hydrology acquired a clear, elegant and practically unquestionable until today, definition as a science. This definition places it among the geosciences and does not explicitly recognize a link with engineering. Nonetheless, hydrology continued its interaction with engineering and its development was related to the needs of the design and management of water infrastructures. In the 1980s this interaction was questioned and it was emphatically supported that cutting the umbilical cord between hydrology and engineering would be beneficial for both. Thereafter, hydrology, instead of becoming an autonomous science, it developed new umbilical cords, becoming a subservient to politically driven agendas, including green and, particularly, climate-related politics. This change of direction was dictated by the research funding opportunities, which disfavoured the autonomous character of hydrology and narrowed its role, for example in studying hypothetical or projected climate-related threats. Several negative experiences from the developments in the last years may make us think that reconciling hydrology with engineering could help hydrology to land again from the virtual reality into the real world, where data and facts are more important than models and predictions are tested against empirical evidence. Engineering experience may help hydrology to appreciate that parsimonious macroscopic descriptions are more powerful than inflationary detailed ones and that holistic approaches are more effective than reductionist ones. A fertilizing field of mutual integration of hydrology and engineering could be the study of change and the implied uncertainty and risk, which we cannot eliminate yet we can live with and cope with, in a manner that can be, and needs to be, quantitative and rigorous.

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 in the antiquity. Indeed, the first scientific problems, put and studied as such, were about hydrological phenomena. In particular, it appears that the first geophysical problem formulated in scientific terms was the hydrological "paradox" of the Nile, i.e. the fact that flooding occurs in summer when rainfall in Egypt is very low to non-existent (Koutsoyiannis et al., 2007, 2010). Thanks to Herodotus (Histories, Euterpe, 20), we know that Thales of Miletus (640–546 BC; one of the Seven Sages of Greece and the father of philosophy and science), in addition to his scientific achievements on geometry, proposed an exegesis of this "paradox". His attempt was followed by other Greek philosophers, including Herodotus. All exegeses were incorrect, but the important thing is that they were physical and thus scientific, contrary to the tradition of attributing natural phenomena to Gods' action.

Soon after, Greek philosophers, by studying natural phenomena, established the notion of what we call today "hydrological cycle", which is the domain of hydrology. Anaximander (c. 610–547 BC) from Miletus understood that rainfall is generated from the evaporation, Xenophanes of Colophon (570-480 BC) conceptualized 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 element (and perhaps a few other cases, such as a passage from Plato's dialogue Phaedo with symbolic meaning; see Koutsoyiannis et al. 2007) the modern hydrological literature charges these philosophers for 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.

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 the 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 fact that technological applications to solve practical problems preceded the development of scientific knowledge is important to recognize as a historical fact and is perhaps relevant in shaping up a progressive modern paradigm.

Likewise, during the Roman times, the substantial progress in hydraulic engineering, demonstrated by the famous Roman aqueducts which advanced in scale and spread all over Europe and beyond, 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 determinant breakthrough during the Renaissance was the recognition of the importance of the empirical basis in hydrological phenomena, acquired by observation, measurement and experiment. Thus, Leonardo da Vinci, the great artist, scientist and engineer, was also a great experimentalist and gave particular focus on 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). Hence, the oldest systematic and "official" rainfall measurements in the world were perhaps those made in Korea, in the 15th century, from which the records for the period after 1770 to date have survived (Koutsoyiannis and Langousis, 2011).

The term "hydraulic" (ὑδραυλικὸν) is used already in the Hellenistic period (by Hero of Alexandria in his "Pneumatica", a treatise on machines working on air, steam or water flow, and later by Pliny) and is related to "hydraulis" (ὕδραυλις), a hydraulic organ, invented by Ctesibius. However, the term "hydrology" did not exist in the classical literature and appeared only in the end of the eighteenth century. 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);
- 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”.

However, 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);
- A Practical Treatise on Hydraulic and Water-supply Engineering: Relating to the Hydrology, Hydrodynamics, and Practical Construction of Water-works, in North America (Fanning, 1896).

These books contained observational hydrological information along with hydraulic formulae and tables. They indirectly indicate that the reasons heading hydrology to become a quantitative, as opposite to speculative, science are related to engineering needs.

It was only in the 1960s that hydrology acquired a clear, elegant and practically unquestionable until today, definition as a science (UNESCO, 1963, 1964):

> *“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.”*

This definition complemented an earlier definition by a U.S. Ad Hoc Panel on Hydrology, (1962), adding an essential element, the interaction of water with human activity, whose absence rendered this preceding definition incomplete.

The UNESCO definition of hydrology does not explicitly recognize its link with hydraulics and, more generally, with engineering. Because up to the 1970s, the developed world was busy in building public infrastructures, 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. Despite that, hydrology made significant progress in developing a scientific approach to study natural variability and to tame uncertainty.

In fact, it was its close relationship with engineering that advanced hydrology in 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 are purely hydrological, yet with clear engineering orientation, such as the probabilistic and stochastic modelling of hydrological processes, the development of data analysis tools and 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 for 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 serves very well engineering purposes, when deterministic prediction methods become 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. Hydrological stochastics has certainly contributed in the quantification of uncertainty and the management of the risk.

The interaction of hydraulics and hydrology within an engineering frame had impressive results, which transformed the living style and improved the quality of life, the public health and the civilization in developed parts of the world. One impressive example is the transformation, through large-scale hydraulic 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 the society (see also Koutsoyiannis, 2011a).

The modern change of perception

Up to the 1980s the engineering efforts had provided 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 has lost 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. Moreover, it was emphatically asserted that cutting the umbilical cord between hydrology and engineering would be beneficial for both (Klemeš, 1986). This trend 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"*.

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). Not surprisingly, his message instigated a strong debate from others (Shamir, 1988) who regarded water resource systems as an essential section of IAHS.

A similar message was broadcast in the US, as manifested in a text by the US Committee on Opportunities in the Hydrological Sciences (1992) that has been widely regarded as the gospel of modern hydrology. This gave the emphasis on "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".*

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 contents in 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. The latter has been as strong as 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 as an assistant in subjects dictated by the dominant political agendas (e.g. in studying hypothetical or projected climate-related threats and impacts). Thus, hydrology, instead of becoming an autonomous science with a broader domain, as envisaged, it developed new umbilical cords, becoming a subservient to politically driven agendas, and its role was narrowed accordingly.

The change of perspective was further supported by the notion of the so-called "soft water path" (Gleick, 2002), 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".*

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 project threats like bigger floods and droughts of greater duration due to climate change, and highlight the need for adaptation to climate change, are the same groups that discourage building new water projects and promote their "soft path" for developing nations.

As the new promoted "soft path" approach is weakly connected to the material world, it encouraged a new culture in research transactions, which could be exemplified by the following approach in developing a research programme: (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 funding.

As the “soft path” was shaping up as a new dominant doctrine, the scientific developments in hydrology were in line with 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);
- 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.

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 nexus of ‘sciences of virtual reality’, which deal with hypotheses, future projections and scenarios, paying 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 interesting and didactic 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; my emphasis)

> *“[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".*

The interaction of hydraulics and hydrology

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".*

We could also add that, in hydraulics, the well-defined boundaries have also simple geometry, usually with rectangular, trapezoidal or circular cross-sections, and uniform longitudinal slope. 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 know the behaviour of all identical elements.

In contrast, with their complex geometry and structure, 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, there is no point in devising an abstract construction that would generalize and unify both in one. Yet hydrology and hydraulics are interrelated and it is possible to draw some lessons from hydraulics that would be useful for hydrology.

In hydraulics we know that 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. Furthermore, it is well known that the 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 with flat power spectra, or even than Markov-type random fields with short-term correlations. Kolmogorov's "5/3 law", determining a slope equal to –5/3 in the power spectrum, provides the stochastic behaviour of turbulence at relatively high frequencies (or wave numbers). Yet it leaves unexplained what happens at low frequencies, where it can be proved that the power spectrum should necessarily have a milder slope. The stochastic behaviour of turbulence does not enable accurate microscopic descriptions, but helps to develop good macroscopic descriptions for the temporal and/or/ spatial averages of the involved processes.

Let us take as an example the celebrated Manning's equation in hydraulics of steady flow, $V = (1/n)\, R^{2/3}\, i^{1/2}$, 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. We are usually tempted to think of this equation as an exact and general physical law. However, it is neither exact, neither general and to call it a physical law we should broaden the definition telling what a physical law is. The fact that the formula is inexact can be seen by inspecting its performance in open surface flow in 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).

Manning's equation can hardly been derived from first principles. Even the very notion of the velocity in the equation is not strictly a 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 and didactic 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 inexact and of empirical type). Indeed, for pipes with rough walls, these equations practically switch to the Manning's equation (Koutsoyiannis, 2008). Furthermore, a more theoretical derivation, based on Kolmogorov's theory of turbulence, is possible for rectangular channels (Gioia and Bombardelli, 2002). In conclusion, measurement data, numerical methods and theoretical reasoning 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 at river branches. But we should have in mind that, as it is inexact 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, we can understand that only in situ measurement data can help reduce the large error. We have seen that even in non-rectangular prismatic channels deduction by theoretical reasoning is rather weak and should be complemented by induction based on measurements. In hydrological systems, we can expect that quantification with acceptable error cannot stand without induction. 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, worse, on three-dimensional hydrodynamic modelling of the river.

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 an 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, thus, would be data free, and simultaneously would radically reduce uncertainty (Sivapalan et al., 2003). However, pragmatism and experience may help us see that the more complex and detailed an approach is, the more data it needs to calibrate. Also, common sense may help 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 only be achieved using principles of probability theory like the law of large numbers and the principle of maximum entropy.

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 "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. Naturally, 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. This is an infelicitous development, because "understanding" is a vague and obscure term per se. In particular, "understanding" is a subjective cognitive procedure rather than anything objective. Perhaps a more relevant term is "interpretation", 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.

In an engineering approach, “understanding” is a secondary target, while the primary target depends on the pragmatic objectives of the problem which we study. As history teaches, full understanding has not been a prerequisite to act. Furthermore, the 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 of radical reduction would be infeasible (Koutsoyiannis, 2010). Instead, a feasible target would be to quantify uncertainty. Admitting this, we can take a step of extending the notion of a physically-based model, so as to incorporate the estimation or description of uncertainty into the model (Montanari and Koutsoyiannis, 2012). This constitutes a step forward, both from engineering and scientific point of view. 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 described above, currently dominant ideological views have obscured the real contemporary problems and their real causes. For climate change 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 and environmental recovery are among the major real challenges of the 21st century. All these four challenges are related to engineering hydrology.

As urbanization increased and big cities and megacities were created, sometimes without proper water infrastructure (in the 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, exceeding 90% (Koutsoyiannis 2011a). Again here engineering hydrology, with its particular experience in studying and managing natural variability can substantially help.

Creation of technological infrastructure is inevitably accompanied by environmental problems, and 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 “lump sum” actions but perpetual processes.

Perhaps this has not been appreciated by the hydrological community, which in the last decades seems to have proceeded to a divorce from engineering, which also led to a departure of hydrologists in academia from professional engineers. In turn, hydrological research in universities has been depreciated by professional engineers and decision makers. Certainly thus 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, to regain some practical importance the hydrological community preferred, over the real-world problems, its engagement to the virtual reality of climate models as a willing assistant for climate impact studies, despite 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). 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. 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).

Also, hydrologists preferred espousing 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. A characteristic effect of this misleading approach is that most hydrological models are for intact conditions, while most of the catchments are 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).

Will hydrology keep on walking on these trails formed in the last three decades? It is very probable, given the inertia of the scientific community, 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 any other discipline,
- 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 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 land again from the virtual reality into the real world, where data and facts are more important than models, where predictions are tested against empirical evidence, and where life is in a continuous dialogue with uncertainty and risk. In the real world, change is the rule, rather than an adverse property that should be opposed, and, 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 a fertilizing field of mutual integration of hydrology and engineering.

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