ENVIRONMENTAL HYDRAULICS SERIES

Physical Processes and Measurement Devices

Edited by Jean-Michel Tanguy

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Environmental Hydraulics

volume 1

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Introduction [1]

This series on hydraulics is divided into five volumes. Volume 1 discusses the context for this environmental hydraulics treatise: the evolution of the different scientific and technical disciplines involved along with the space and time dimensions of the processes described. It evokes the importance of the global flood risk and outlines a first quantification approach of the impact of climate change on hydrology. It then describes in detail the physical processes relating to hydrology, hydraulics and river morphodynamics.

This continues with a part dedicated to describing the physical processes and the hydrosystems involved. The following part lists systems of measurements that may provide data for digital models:

– firstly focusing on estuarian processes, the tide, waves, storm surge and storm forecasting and on shore;

– then describing forecasting systems for weather parameters linked to the hydrological cycle, those necessary for the acquisition of topographical and bathymetric data, and for the characterization of soils and water in the soil. We then address the river field with systems of measurement of water levels and floods relative to the quality of water, to the measurement of ice thickness and coverage, to measurements of river sedimentology and in urban hydrology. We continue with the measurement of sea parameters: currents, swells and the sea level and by sedimentological measures in an inshore environment. The last chapter discusses new technologies arising from the spatial dimension.

Volume 2 focuses on mathematical modeling in hydrology and fluvial hydraulics, with a following part dedicated to the mathematical modeling of marine hydraulics, to transportation models and conceptual models.

Volume 3 discusses digital modeling.

Volume 4 shows examples of software applications in water engineering case studies.

Finally, Volume 5 describes a few operational software packages in the field of water engineering.

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1 Introduction written by Jean-Michel TANGUY.

PART 1

Floods and Climate Change

Chapter 1

Presentation of the Environmental Hydraulics Treatise [1]

1.1. Context

The management of water has become daily news, whether due to excess, with large devastating floods in the world, or due to scarcity with dry summers or the progression of semi-arid and arid areas that we know today. This pushes public authorities to enforce measures of protection and resource management. Climate evolution would appear to exacerbate extreme phenomena. According to the World Meteorological Organization (WMO) source (see also Chapter 2):

– approximately 1.5 billion people in the world were victims of floods from 1991 to 2000. Recently, an increase in the number of disasters associated with this phenomenon has been observed, mainly due to the development of land in floodplains and its densification. Natural disasters create a lot of suffering, particularly in developing countries with low income economies which are sensitive to the repetition of these events. It is true that the fact of living in a flood plain provides undeniable advantages in terms of richness of soils in order to obtain high agricultural yields;

– drought is probably the type of natural disaster with the most devastating effects. From 1991 to 2000, this phenomenon was responsible for more than 280,000 deaths in the world and caused billions of dollars of material damage. By 2025, it is expected that the population living in countries facing water shortage problems will increase from 1 to 2.4 billion people, representing 13% to 20% of the world population.

The World Summit on Sustainable Development held in Johannesburg in August and September 2002 underlined the need to "fight against drought and floods through better use of information, climate and weather forecasting, fast warning systems, better management of land and natural resources, agricultural practices and ecosystems conservation in order to reverse the current trends in soils and water degradation…"

In addition, because of global warming, an increased frequency of some extreme weather phenomena like heat waves and very heavy rainfalls is expected, but nothing is yet certain (see Chapter 3). We do not have enough hindsight in terms of climate change as yet to isolate evolutions caused by changes in natural conditions from those due to human activities. However, everything seems to contribute to an increase in greenhouse gas emissions. The global awareness of these problems has led to the ratification of major international protocols on climate change like Kyoto in 1997 or Bali in 2007 which laid the groundwork and then outlined the main principles of sustainable development. All this led to international or European initiatives which have since been outlined in regulations in each country. Moreover, it is in this context that in France the Environment Round Table (*Grenelle de l'Environnement*) was launched, which has given more emphasis to water conservation. This favorable context reminds us that water is a valuable resource and is of limited quantity, which should encourage developers to adopt an integrated approach by considering the impacts of each project in a much wider context and consider its actions both in the short and long term.

1.2. Origin of environmental hydraulics

In this critical context, it seemed necessary to establish a state of knowledge regarding hydraulics in a broad sense, so as to inform policy makers by providing overwhelming evidence not only on the behavior of water and its richness, but also on its fragility. This treatment of environmental hydraulics deals with the physical processes of water from a raindrop all the way to the sea. Its publication stems from a number of motivations:

– the lack of works covering this subject in its *global nature*. The literature is rich in works covering meteorology, hydrology, hydraulics or hydrogeology on the one hand and mathematical modeling and numerical methods on the other hand. These works are often very theoretical and do not grant enough space for illustrations and practical examples. We want to present these fields in an integrated manner, starting from the description of physical processes through mathematical theories and by illustrating our comments with examples of applications and the description of software;

– the evolution of current knowledge in the areas of *water resource management* and *risk management*. Public authorities implement policies to protect people and goods combining prevention, protection and anticipation. New tools must be developed to implement and evaluate these policies;

– the necessary *networking of teams and dissemination of knowledge*. The hydrological community (in a very broad sense) has been structured for several years around national, European or international projects. Researchers and professionals in this field have developed a project culture that requires the sharing of common knowledge laterally. The publication of this work should be brought to the forefront of expertise in this field;

– the authors also identified the need to reinstate the different approaches in terms of modeling processes within a unified conceptual framework, thus meeting the needs of experts who use simulation tools that seem at first glance to be of different origins, but that result from the same theories;

– at an international level, it was felt that there was a need for a reference work which could be shared by the entire scientific community. In this regard, the World Meteorological Organization (WMO), which works in the field of hydrology through the Commission for hydrology, has a number of guides, including “Guide to hydrological practices.” The treatment of environmental hydraulics presented herein, promoted by the WMO, directly complements these existing guides.

All these reasons prompted the coordinator of this series to propose initially to a small group of authors, to be associated with writing a reference document not only for professionals in the field (in the broad sense), but also for students and professors involved in the technical and scientific fields dealing with the water cycle. The boundaries of this work are thus, naturally: from a raindrop (meteorology) to the sea (maritime morphodynamic) following the paths of water either on the surface or in the subsoil, of the drainage basin into the sea. This group was then expanded considerably in order to collect descriptive case studies illustrating the use of numerical models in all of the areas covered by this work.

1.3. Modeling at the crossroads of several sciences

What exactly do we mean by modeling and why should we seek to model?

The need for modeling stems from the necessity of reproducing phenomena in order to better study them. Numerical modeling uses computer-based tools, but there are other ways to reproduce natural phenomena, in particular using physical models. The aforementioned models are of great assistance to the physicist, enabling him to study and quantify some processes that are good *benchmarks* in order to validate numerical models.

By skimming through the different scientific and technical disciplines which are concerned with the water cycle, it is surprising to see the very strong heterogeneity which characterizes the level of development of the various disciplines concerned:

– meteorology;

– river hydraulics and maritime hydraulics;

– hydrogeology;

– computing;

– numerical methods.

We will thus show that the disciplines are all interrelated and that the recent development in computing has given them a “boost.”

1.3.1. *Meteorology*

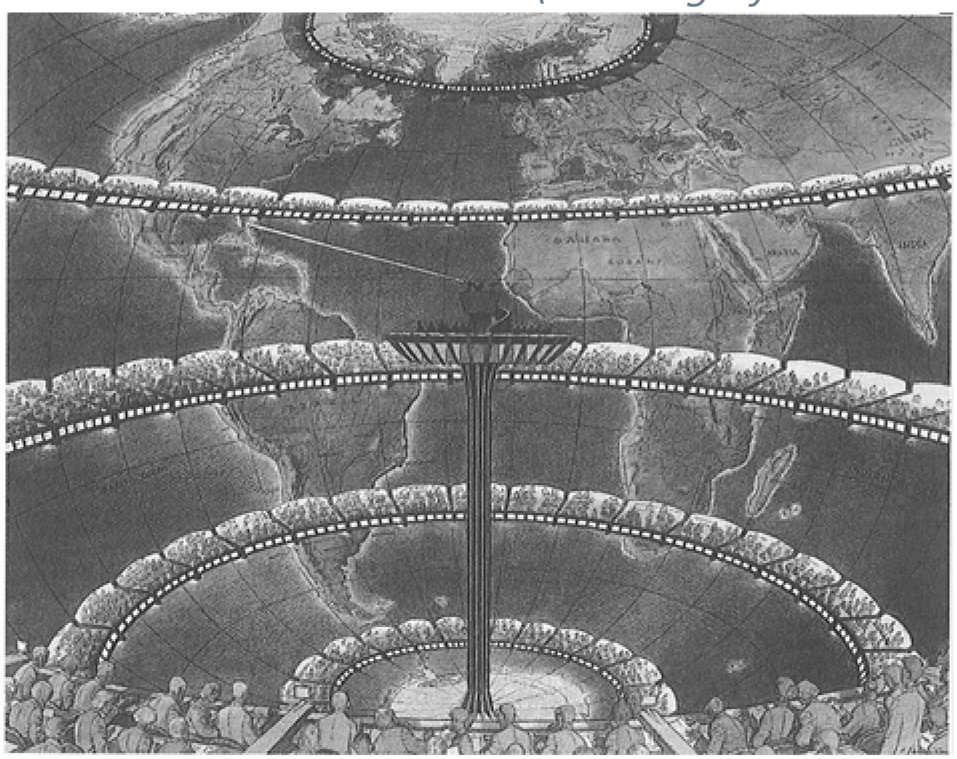
Modern meteorology in France arose from an accident or rather from a shipwreck. During the Crimean War, on November 14th 1854, a violent storm caused the death of 400 sailors and the loss of 38 French ships. Following this disaster, French War Minister Marshal Vaillant, charged the astronomer Le Verrier to study the causes of such a disaster. He realized that the storm in question had crossed over the whole of Europe from 10th to 14th November. The minister then made the decision to establish a monitoring network in charge of indicating dangerous phenomena. At that time, the French network included 24 stations.

This discipline is in a very advanced level of modeling. It has obviously taken advantage of the strategic nature of the knowledge of time and anticipation of upcoming events (see historical insert below). Moreover, it was developed according to the dimensions of the planet. In history, meteorologists were confronted very quickly with the need to have measurements across the globe in order to develop quality forecasting for their own country.

The data which comes from radiosondes, from observations on land and sea, has been exchanged since the emergence of this science, and an astonishing fact of history is that this data continues to be exchanged during conflicts and wars. Meteorologists have thus been able to develop efficient modeling tools across the globe, and weather forecasting has become an international issue. It has been necessary to work with very sophisticated models: 3D, transient and rapid execution models.

Between 1916 and 1922, the Briton, Lewis Fry Richardson [RIC 65], tried to manually solve the primitive (unfiltered) weather forecasting equations in an approximate way. He used a horizontal grid of 200 km, with four layers along the vertical, and centered on Germany. The forecastings he obtained were completely unrealistic because of poor initial conditions and because they did not respect the stability condition which was developed a few years later by Courant, Frierichs and Lewy (CFL condition). This first unsuccessful test penalized numerical predictions for several years, but it nevertheless marked a major step in the evolution of this discipline. Richardson imagined that a factory of 64,000 human calculators would be necessary to get ahead of the changing weather throughout the globe (Figure 1.1). This modeling dream partly became a reality in 1950 thanks to J. Charney, R. Fjörtoft and von Neumann who achieved the first numerical predictions using a computer. The results obtained were completely encouraging and this historical experiment marks the starting point of modern weather forecasting.

Figure 1.1. *Richardson's dream (drawing by F. Schuiten)*



The first numerical models used the geostrophic approximation (time-independent relationship between pressure and wind). This approximation has the advantage of having only slow waves (Rossby waves) as a solution and of enabling large time steps (filtered approximations).

These models were operational until the 1960s. The increase in the capacity of computers made it possible to revert to hydrostatic primitive equations which enable inertia-gravity waves to be alternative solutions.

In conjunction with grid point models using the finite difference method, spectral models were also developed, in which the defined fields are represented on the sphere using a decomposition based on orthonormal functions.

Along with the use of global models (several tens of kilometers in resolution), it proved necessary to work on smaller areas at a sufficiently fine scale to correctly simulate the processes that develop at smaller scales, in particular because of the presence of relief but also to better represent certain physical phenomena such as water phase transfer. These initially hydrostatic models have evolved into more sophisticated models, non-hydrostatic with fine mesh (a few kilometers in plan). Their boundary conditions are extracted from global models.

A major technological innovation in meteorology comes from the assimilation of data which enables the determination of the state of the atmosphere, taking into account the various meteorological observations available. This method known as 3D-VAR (developed from optimal control methods) has been extended to 4D-VAR to take into account the data distributed in time and space.

Another problem appeared with the date of prediction that could not be postponed. In the early 1960s, Lorentz made a significant discovery: by modifying the boundary conditions of his model, he obtained very different predictable states of the atmosphere within a few days of the date. The idea then came to him to launch the deterministic model several times by varying the initial conditions (the ECMWF model is launched 50 times). This method known as *Quantitative Precipitation Forecasts* (QPFs) presents a probabilistic approach, for example it assesses what percentage an overall prediction will forecast precipitation at a given point.

Developments will certainly continue in the future. Some authors [COI 00] predict an improvement of fine models towards very fine models, data assimilation, ocean-atmosphere coupling, adaptive measuring systems (reinforced spatially during errors of models), all this is made possible by international cooperation regarding measurement systems and modeling.

1.3.2. *Operational hydrology*

Operational hydrology appears to be the poor relation of the family with respect to modeling. Although many observations have been recorded in works since antiquity by famous names such as Thales or Aristotle, hydrology as an independent scientific discipline is only around 100 years old. The main cause of the very limited development in modeling disciplines is certainly due to the fact that the considered media are very heterogeneous and less observable, especially anything which concerns the subsurface which explains a large part of the overall behavior of drainage basins.

Without repeating the history of hydrology in detail, let us specify that the first ancient speculations were turned towards the origin of the source of water and its fate: everything that was underground, and therefore hidden, gave rise to speculative discourse. Bernard Palissy is regarded by the hydrologist community as the founder of the discipline with his work Discours admirables de la nature des eaux et fontaines tant naturelles qu'artificielles (admirable discourse of water and fountains) [PAL 80]. He expresses his “firm conviction” that sources and rivers originate from the rain and not as the first theories supported from the sea (Musy online course). He recommended the taking of many measurements and devoted himself to carrying out many measurements and to comparing rainfall and flow on the basin of the River Seine. François Le Père in his work “on the origin of springs” in 1653 extrapolated the idea of Palissy to the entire planet, thus initiating a comprehensive view of the water cycle. In order to tackle the behavior of water underground, he recommended complementing surface measurements with measurements of groundwater fluctuations; this was quite innovative for its time.

Traditionally, we recognize that Perrault [PER 74] and Mariotte [MAR 86] established the first quantitative approaches in terms of a balance sheet, on the Coquille River, a tributary of the Seine and on the upstream of the Seine basin, respectively. The first balance sheets indicated that the surface flow represented only one sixth of the rainfall.

To complete the understanding of the water cycle and to integrate the exchanges with the sea, a major contribution was made by Halley who explained the origin of atmospheric water vapor by evaporation and then condensation (his discovery came from the condensation on his telescope). Dalton proved this theory by measurement.

In situ measurements then began to develop. Thus, by the middle of the 17th century, observations had been made on the level of the River Seine as well as the first gauging. Rainfall was also measured at the Paris observatory, and in 1719 a flooding scale was installed at the Tournelle Bridge.

Thereafter, many developments were made in the field of hydraulics and hydrogeology (treated separately in this section), but few big discoveries have been made in the hydrology field since these pioneers of the 17th century.

The hydrological functioning of drainage basins remains in many ways not well known. B. Amboise [AMB 99] points out that two issues have not yet been completely solved by hydrology: