Solute transport in complex natural flows

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The most innovative hydraulic research flows from the needs of applications in diverse, very often complex settings. The aim of this preface is to provide a brief overview on mass transport in complex natural flows, highlighting relevant but often neglected considerations, advances presented in the articles of this Special Issue, and ways forward. Understanding and prediction of how dissolved nutrients and other solutes, suspended sediment and other particulate matter, and thermal pollution are propagated and mixed in natural channels are important for designing effective management and mitigation strategies concerning these scalars.

Complexity stressed in the title of this Special Issue is in fact a philosophical notion, typically not sufficiently well defined. *Complex* or *complexity* is a keyword very often used in environmental hydraulics, in most cases intuitively, sometimes as synonyms of the adjective *complicated*. At the same time, *complexity* has strong scientific connotation and is treated almost as a separate research domain. In contrast to many other scientific disciplines, in environmental hydraulics, it is not well established when the subject of our investigation can be described as complex.

In principle scientists face the double, incredibly intricate problem of unraveling the cause and effect relationships between various phenomena and processes on one hand, and developing mathematical descriptions of the extraordinarily complicated reality on the other (Rowiński and Dębski 2011). Quoting (Heylighen et al. 2007), complexity science emerged in the 1980s, having the following roots:

- “nonlinear dynamics and statistical mechanics—two offshoots from Newtonian mechanics—which noted that the modeling of more complex systems required new mathematical tools that can deal with randomness and chaos;
- computer science, which allowed the simulation of systems too large or too complex to be modeled mathematically;
- biological evolution, which explains the appearances of complex forms through the intrinsically unpredictable mechanism of blind variation and natural selection;
- the application of these methods to describe social systems in the broad sense, such as stock markets, the Internet or insect societies, where there is no predefined order, although there are emergent structures.”

According to Standish (2008), the term *complexity* has two distinct usages, which may be categorized as either a quality or a quantity. It is often stated that complex systems are a particular class of systems that are difficult to study using traditional analytical techniques. Standish (2008) mentions that biological organisms and ecosystems are complex, yet systems like a pendulum or a lever are simple. Complexity as a quality is therefore what makes the systems complex. Complexity maybe also treated as a quantity—with “statements like a human being being more complex than a nematode worm, for example.”

Let us pay the attention of the Reader to a popular book of Johnson (2001) that explains complexity through the notion of emergence. From his fascinating story, one may read that complexity is generally used to characterize something with many parts that interact with each other in multiple ways, culminating in a higher order of emergence than the sum of its parts. In this context, emergence refers to the ability of low-level components of a system or community to self-organize into a higher-level system of sophistication. In other words, emergence occurs when an entity is observed to have properties, its parts do not have on their own. Quoting the description of the series of *Understanding Complex Systems* (Springer): “Such systems are complex in both their composition—typically many different kinds of components

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interacting simultaneously and nonlinearly with each other and their environments on multiple levels—and in the rich diversity of behavior of which they are capable.”

Whichever definition we consider, the papers presented in this Special Issue fall under the category of describing complex systems, i.e., complex open channel transport processes in the present context. The transport of constituents by advection, dispersion, and other processes in streams, rivers, and other channels is dependent on hydrological and hydrodynamic characteristics of the channel which in turn depend on the geometry and morphometry of the reach. Complexity in the physical settings may be related, e.g., to cross-sectional geometries and associated flow distributions that cannot be easily reduced into single characteristic scales, composite roughness, and multiple physical scales that interact with each other. One of the most important factors causing complexity in these categories is vegetation (e.g., Rowiński et al. 2018). The contributions in this issue address different aspects of solute transport in complex natural flows, bridging fundamental research to practical challenges in watercourses. The articles are based on selected talks presented during Special Session FM.2 entitled “Heat and mass transport under complex natural conditions” at the 5th IAHR Europe Congress that took place on 13–15 June, 2018, in Trento, Italy.

Mass transport processes of solutes can be experimentally investigated based on tests performed with soluble tracers. The most common mathematical descriptions of the processes are the one-dimensional advection–dispersion model, and the transient storage model that allows for the reconstruction of the abrupt leading edges and the long upper tails in the distributions of solute concentrations in flows including vegetation or other transient storage zones (e.g., Rowiński et al. 2008). The associated equations are typically solved using various numerical methods, which forms a distinct source of uncertainty for the parameter estimation, e.g., through numerical diffusion and dispersion (e.g., Kalinowska & Rowiński 2007). In this issue, Silavwe et al. (2019) address the reliable estimation of the parameters of the advection–dispersion model by comparing the performance of selected numerical schemes under different transport regimes. Wallis & Manson (2019) describe the sensitivity of the transient storage model parameters on the spatial and temporal resolution of the numerical solution.

In cases when tracer tests are not available, the reliable estimation of the parameters becomes extremely difficult and can be a source of large uncertainty. Dispersion coefficients are usually related to known hydraulic parameters, such as average depth, width and velocity, shear velocity, and channel sinuosity. The derived formulae are of rather limited universality, and thus, more attention should be placed on documenting their ranges of applicability and the methods used in identifying the parameters. Determining some of

the basic hydraulic variables in complex natural situations constitutes a problem per se (e.g., Mrokowska and Rowiński 2017).

The complexity increases when moving from 1D to 2D or 3D approaches. For the case of depth-averaged 2D mass transport associated with incomplete lateral mixing, the dispersion tensor represents an additional significant transport mechanism, which is not a physical process, but a consequence of depth-averaging of the equation (Kalinowska & Rowiński 2012). It deserves to be stressed that the longitudinal dispersion coefficient of the 2D equation is not the same as that of the 1D equation. Despite this, 1D dispersion coefficients are often adopted to 2D models, unconsciously of the difference or since values for the 2D approach are not available. In the context of complex open channel flows, further work on parameterizing 2D transport processes is warranted.

Mass transport is particularly complicated to describe in vegetated flows since vegetation is known to control the flow and mixing at multiple scales ranging from the leaf to plant, plant stand, patch, patch mosaic, and reach scales (e.g., Marion et al. 2014). Vegetation causes strong mixing between the vegetated and non-vegetated regions, affects turbulence intensity and diffusion and often significantly alters the channel geometry (e.g., Curran & Hession 2013). Despite the fact that the rate of mass transport may notably deviate from the rate of momentum transport in vegetated settings (Ghisalberti & Nepf 2005), experiments on the influence of vegetation on dispersion coefficients and parameters of the transient storage model are limited. In this issue, Sonnenwald (2019) proposes a model to predict the longitudinal dispersion coefficient in vegetated regions based on stem spacing. Such models based on easily measurable, physically based variables are useful tools for the practitioners.

A reliable estimation of the mean and turbulent flow distribution is a prerequisite for mass transport predictions, but significant uncertainty is still present in modeling vegetation hydrodynamics. Herein, the suitable parameterization of the vegetative drag and flow resistance is a key factor (e.g., Västilä & Järvelä 2018). In their contribution, D’Ippolito et al. (2019) present an extensive dataset to investigate how the vegetative drag coefficient of rigid cylinders depends on their solid volume fraction and on flow forcing. The studies with simple plant morphology form the basis for devising investigations on flexible natural plants having multiple length scales and more complicated structures.

Because of its distinct hydrodynamic behavior, natural vegetation commonly exhibits higher complexity than simplified rigid surrogates. This is foremost associated with the strong dependency of the flow-vegetation interactions on the hydrodynamic forcing mainly through the flexibility-induced reconfiguration (e.g., Vogel 1994). Mechanisms such as bending of the stems, changes in the posture and orientation

of the leaves and branches, and dynamic motions at different scales are typically observed for natural vegetation. For instance, the periodical waving of flexible plant stands significantly alters the turbulent momentum transfer between submerged aquatic vegetation and the overflow (e.g., Ghisalberti & Nepf 2006) and has been recently reported to occur at the lateral interfaces between unvegetated regions and foliated shrub-like vegetation (Caroppi et al. 2019). In this issue, Termini (2019) investigates turbulent mixing and dispersion mechanisms in flows with submerged natural herbaceous vegetation. In a highly complex setting, Przyborowski et al. (2019) explore how highly flexible plant patches of naturally occurring structure influence the turbulent flow structure in a river with movable bed. Verification of results from controlled laboratory environments in the yet more complex natural settings is required to enable up-scaling the findings for solving real-life engineering challenges.

The six papers of this issue advance our understanding, but reaching a wide-ranging impact calls for researchers to increasingly engage in science-based advising of the engineering and management of our streams and rivers. A vast challenge lies in developing robust, straightforward-to-use tools with reasonable accuracy and acceptable level of uncertainty to allow application to practical engineering. This requires new experimental data from carefully designed, executed and reported experiments, including a description of how they represent the complex physical reality. Based on the data, modeling can be further developed for different scales and purposes. Finally, coupling understanding of mass transport to the physical, chemical, and biological processes of the investigated scalar may aid in tackling water quality issues ranging from the management of riverine nutrient loads through specific nature-based channel designs (e.g., Västilä et al. 2016; Rowiński et al. 2018) to the prediction of the spreading of industrial pollutants, such as heat (e.g., Kalinowska 2019).

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

- Caroppi G, Västilä K, Järvelä J, Rowiński PM, Giugni M (2019) Turbulence at water-vegetation interface in open channel flow: experiments with natural-like plants. *Adv Water Res* 127:180–191. <https://doi.org/10.1016/j.advwatres.2019.03.013>
- Curran JC, Hession WC (2013) Vegetative impacts on hydraulics and sediment processes across the fluvial system. *J Hydrol* 505:364–376. <https://doi.org/10.1016/j.jhydrol.2013.10.013>
- D’Ippolito A, Lauria A, Alfonsi G et al (2019) Investigation of flow resistance exerted by rigid emergent vegetation in open channel. *Acta Geophys*. <https://doi.org/10.1007/s11600-019-00280-8>
- Ghisalberti M, Nepf HM (2005) Mass transport in vegetated shear flows. *Environ Fluid Mech* 5:527–551. <https://doi.org/10.1007/s10652-005-0419-1>
- Ghisalberti M, Nepf HM (2006) The structure of the shear layer in flows over rigid and flexible canopies. *Environ Fluid Mech* 6:277–301. <https://doi.org/10.1007/s10652-006-0002-4>
- Heylighen F, Cilliers P, Gershenson C (2007) Complexity and Philosophy. In: Bogg J, Geyer R (eds) Complexity, science and society. Radcliffe Publishing, Oxford, pp 117–138
- Johnson S (2001) Emergence: the connected lives of ants, brains, cities. Scribner, New York
- Kalinowska MB (2019) Effect of water–air heat transfer on the spread of thermal pollution in rivers. *Acta Geophys* 67:597–619. <https://doi.org/10.1007/s11600-019-00252-y>
- Kalinowska MB, Rowiński PM (2007) Truncation errors of selected finite difference methods for two-dimensional advection–diffusion equation with mixed derivatives. *Acta Geophys* 55:104–118. <https://doi.org/10.2478/s11600-006-0046-3>
- Kalinowska MB, Rowiński PM (2012) Uncertainty in computations of the spread of warm water in a river—lessons from environmental impact assessment case study. *Hydrol Earth Syst Sci* 16:4177–4190. <https://doi.org/10.5194/hess-16-4177-2012>
- Marion A, Nikora V, Puijalon S, Bouma T, Koll K, Ballio F, Tait S, Zaramella M, Sukhodolov A, O’Hare M, Wharton G, Aberle J, Tregnaighi M, Davies P, Nepf H, Parker G, Statzner B (2014) Aquatic interfaces: a hydrodynamic and ecological perspective. *J Hydraul Res* 52:744–758. <https://doi.org/10.1080/00221686.2014.968887>
- Mrokowska MM, Rowiński PM (2017) Bed shear stresses and bed shear velocities – ubiquitous variables in river hydraulics. In: Radecki-Pawlik A, Hradecky J, Pagliara S, Hendrickson E (eds) Open channel hydraulics, river hydraulics structures and fluvial geomorphology: for engineers, geomorphologists and physical geographers, 1st edn. CRC Press, Boca Raton, pp 180–195
- Przyborowski Ł, Łoboda AM, Bialik RJ (2019) Effect of two distinct patches of *Myriophyllum* species on downstream turbulence in a natural river. *Acta Geophys*. <https://doi.org/10.1007/s11600-019-00292-4>
- Rowiński PM, Dębski W (2011) Mathematical modeling of inanimate natural phenomena. The living earth, ACADEMIA, The magazine of the Polish Academy of Sciences. Complexity 29(1):4–7
- Rowiński PM, Guymer I, Kwiatkowski K (2008) Response to the slug injection of a tracer—large scale experiment in a natural river. *Hydrol Sci J* 53:1300–1309. <https://doi.org/10.1623/hysj.53.6.1300>
- Rowiński PM, Västilä K, Aberle J, Järvelä J, Kalinowska MB (2018) How vegetation can aid in coping with river management challenges: a brief review. *Ecohydrol Hydrobiol* 18:345–354. <https://doi.org/10.1016/j.ecohyd.2018.07.003>
- Silavwe DD, Brink IC, Wallis SG (2019) Assessment of some numerical methods for estimating the parameters of the one-dimensional advection–dispersion model. *Acta Geophys*. <https://doi.org/10.1007/s11600-019-00293-3>
- Sonnenwald F, Stovin V, Guymer I (2018) A stem spacing-based non-dimensional model for predicting longitudinal dispersion in low-density emergent vegetation. *Acta Geophys*. <https://doi.org/10.1007/s11600-018-0217-z>

- Standish R (2008) Concept and definition of complexity. In: Ang Yang A, Shan Y (eds) *Intelligent complex adaptive systems*. IGI Global, Hershey, pp 105–124. <https://doi.org/10.4018/978-1-59904-717-1.ch004>
- Termini D (2019) Turbulent mixing and dispersion mechanisms over flexible and dense vegetation. *Acta Geophys*. <https://doi.org/10.1007/s11600-019-00272-8>
- Västilä K, Järvelä J (2018) Characterizing natural riparian vegetation for modeling of flow and suspended sediment transport. *J Soils Sediments* 18:3114–3130. <https://doi.org/10.1007/s11368-017-1848-4>
- Västilä K, Järvelä J, Koivusalo H (2016) Flow–vegetation–sediment interaction in a cohesive compound channel. *J Hydraul Eng* 142:04015034. [https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0001058](https://doi.org/10.1061/(ASCE)HY.1943-7900.0001058)
- Vogel S (1994) *Life in moving fluids—the physical biology of flow*, 2nd edn. Princeton University Press, Princeton
- Wallis S, Manson R (2019) Sensitivity of optimized transient storage model parameters to spatial and temporal resolution. *Acta Geophys*. <https://doi.org/10.1007/s11600-019-00253-x>