CEST 2017

15th International Conference on Environmental Science and Technology

Rhodes, Greece, 31 August to 2 September 2017

Bridging Socio-Hydrology with Cyber-Physical Systems: Synergies and Opportunities

Papacharalampou C.[1,*], Kallergis D.[2], Mcmanus M.[1], Newnes L.B.[1] And Douligeris C.[2]

[1]Water Innovation Research Centre, Department of Mechanical Engineering, University of Bath, Claverton Down, BA2 7AY, Bath, United Kingdom

[2]Department of Informatics, University of Piraeus, 80 Karaoli & Dimitriou str., 18534, Piraeus, Greece

*corresponding author: Chrysoula Papacharalampou

e-mail: c.papacharalampou@bath.ac.uk

Abstract

The emerging field of Socio-Hydrology seeks to explore the integrated human-hydrology systems and understand the co-evolving dynamics, feedbacks and behaviours across multiple time and space scales. This paper discusses the ways Socio-Hydrology contributes to the advancements of Cyber-Physical Systems (CPS) for Integrated Water Resources Management mainly focusing on prediction, one of the industry's forecasting pillars. The review of the rationale, methods and applications of Socio-Hydrology is followed by the analysis of an architectural approach of a state-of-the-art CPS. The discussion identifies research gaps and opportunities, especially in regards with the challenging UK water policy landscape, which requires the design of systemic approaches for resilient systems. Further to exploring the potential synergies between Socio-Hydrology and CPS, the paper examines the role that transdisciplinary research and its underpinning methodologies play in the creation of novel approaches.

Keywords: transdisciplinary, cyber-physical systems, socio-hydrology, Industrie 4.0

1. Introduction

In the field of physical resources management, *prediction* and *resource allocation* play a crucial role to accomplish sustainable and economically stable models (Qu *et al*. 2013). To tackle this issue, computing technologies are currently extensively utilised in the energy and water utilities and in the environmental sector. Among others, the deployment of swarms of sensor machinery is a key driver for deploying control and monitoring systems and, thus, for conducting data analysis, which is vital for policy-making processes. In the context of water production and distribution, emerging computing technologies as well as hydrology principles are combined, not only to guarantee a high level of water quality but also to keep track of the infrastructure maintenance. For this kind of applications, the integration and involvement of the society is also required. This can be achieved by raising public awareness and by incorporating multiple feedback processes (Rapousis *et al*. 2015; Giuliani *et al*. 2016). The increasing complexity in the formulation of solutions for the various current and future water challenges, together with the persistent knowledge gaps for socio-ecological issues have triggered the spanning of knowledge boundaries across disciplines or even across sectors and stakeholders (Esler *et al*. 2016). The emergence of "inter-discipline" disciplines in the field of Hydrology, such as Socio-Hydrology, indicates a trend towards the integration of multiple perspectives for tackling water challenges, especially in regard to issues related to equitable and sustainable water resources management (Baveye 2011). As a result, cross-disciplinary research has been boosted, creating novel approaches and enabling the collaboration among experts and stakeholders; thus, enabling "translational science" (Willems 2014) or transdisciplinarity in practice. This paper aims at extending the concept of Cyber-Physical Systems (CPS), which are defined by NIST (n.d.) as "co-engineered interacting networks of physical and computational components". Further, the challenges and potential synergies between CPS and Socio-Hydrology are also discussed. Contributing to the further exploration of cross-disciplinary approaches for tackling water challenges, this paper focuses on one of the pillars which currently drive industrial forecasts; *prediction* (Esterle and Grosu 2016). On this ground, we shed light to a potential synergy space which includes the predictive domain of Socio-Hydrology, and the control and data analysis functions of a typical CPS. The remainder of this work is structured as follows: section 2 illustrates our research approach, while a literature review presenting the state-of-the-art of the field of Socio-Hydrology (SH) and the technological advancements of Cyber-Physical Systems (CPS) is conducted in section 3. Section 4 proposes a novel CPS that highlights complementary challenges and disciplinary synergies, while section 5 discusses the transdisciplinary challenges of our research and section 6 concludes this paper.

2. Research Approach

The research presented in this paper transcends the knowledge boundaries of a single scientific discipline, as a means to create a novel conceptual framework. In order to ensure a robust knowledge synthesis, the paper is built on the principles of transdisciplinarity, as defined by Leavy (2011). Transdisciplinarity refers to the research approach which involves the collaboration between two or more disciplines, which results in high levels of integration and to the development of new conceptual, theoretical or methodological frameworks. As such, a *synergistic research approach* is followed, aimed at creating an *issue-centric* research output, underpinned by conceptual *transcendence*, methodological *emergence*, *innovation* and *flexibility*.

3. Literature Review

3.1 The emergence of Socio-Hydrology

The scientific discipline of *Hydrology* typically focusses on the study and practical implications of the movement, distribution and quality of freshwater in the natural environment (Oxford Dictionary of Earth Sciences), aiming to investigate hydrological processes under pristine conditions (Troy *et al*. 2015). Nevertheless, in the era of the Anthropocene (Crutzen 2002), where mankind represents ‘a global geological force’ (Steffen *et al*. 2007), humans have an immense effect on the water cycle resulting in hydroclimatic shifts (Destouni *et al*. 2012) which may lead in both positive and negative social impacts within the coupled human-natural systems (Wagener *et al*. 2010). In order to capture and account for these impacts, five human variables need to be integrated in hydrological modelling (Carey *et al*. 2014): *(i)* political agendas and economic development, *(ii)* governance, *(iii)* technology and engineering, *(iv)* land resource use, and *(v)* societal responses. As a response to these research challenges, the inter-disciplinary and use-inspired discipline of ‘Socio-Hydrology’ has recently emerged. According to Sivapalan *et al*. (2014; 2012), *Socio-Hydrology* aims at understanding ‘the dynamics and co-evolution of coupled human-water systems’, by uncovering the cross-scale interactions and feedbacks between natural and human processes. Its focus can be categorized in three domains (Joeng and Adamowski 2016): *(i)* historical /predictive, *(ii)* comparative, and *(iii)* process. The latter involves the quantitative science required for modelling coupled human-water systems and for predicting future trends. The former domains involve the historic (e.g. Liu *et al*. 2014) or comparative (e.g. Chang *et al*. 2014) analysis of socio-hydrological systems respectively, along with the identification of their underpinning principles and structures. The research undertaken in the framework of SH includes, but it is not limited to, to the study of the impact of changing social norms and values, the systems’ behaviours across different spatio-temporal scales, and the interpretation of the procedures governing the water cycle within the rapidly changing human systems (Blair and Buytaert 2016; Montanari *et al*. 2013). Some recent case studies include models for wastewater reuse at a catchment scale (Joeng and Adamowski 2016), the simulation of societal behaviours in relation to flood risk assessments (Di Baldassarre *et al*. 2015; Viglione *et al*. 2014), the creation of an approach for incorporating gender into water biophysical modelling (Baker *et al*. 2015), and the modelling of climate change impacts on glacier-fed catchments (Carey *et al*. 2014). Recently, an extensive review article (Blair and Buytaert 2016) on socio-hydrological modelling has shed light on the ‘why, what, and how’ of this emerging field and showed the wide range of techniques which have or could be applied in a SH study. They highlighted areas of future research and the outstanding challenges of the field. Further advancements are required for conducting in-depth socio-hydrological studies, through the integration of modelling across social, economic and hydrological systems and the translation of research outputs into policy applications. On the technical side, the establishment of the appropriate level of complexity of the SD models, the determination of appropriate modelling techniques and the development of new data collection efforts are prioritised.

3.2 Intelligent computing and communication technologies

Furthermore, on the technical side, intelligent computing and networking devices are required to record everything in the physical realm and, thus, to control it and promote its sustainable evolution. Such devices can be sensors and actuators: tiny devices which can first perceive multiple variations of the analogue world, then transform these variations to communication signals and finally transmit them for further processing and analysis by utilising networked infrastructures. These devices communicate with Machine-to-Machine (M2M) enabling technologies, a concept that has been first introduced in the late 1960s by Paraskevakos (Bloomberg 2013), and comprises of a minimum of two machines that lie on computer networking automation. M2M systems take advantage of various sensor networking principles and they are utilised in telemetry, industrial automation, supervisory control and data acquisition (SCADA) systems (Anand 2015). Although the M2M concept drives the economy to 50 billion connected devices by the end of the decade (Barki *et al*. 2016), it is the expansion of the Internet that offers the connecting glue between the digital world and the physical realm. In this context, the *Internet of Things (IoT)* is considered as networks of sensors and smart objects which can intelligently interact with humans (Garofalaki *et al*. 2016). This technological eruption has become the backbone of the so-called *Cyber-Physical Systems (CPS)*, which are ‘co-engineered interacting networks of physical and computational components’ (NIST *n.d.*). Liu *et al*. (2017) discuss on another definition of a CPS, which is the new engineering system that integrates computations and physical processes aiming to control the latter through a feedback loop, in a real-time, reliable and safe manner. Due to a plethora of recent advances in M2M communications which have led to the transcendence from an IoT ecosystem to a CPS, we need to enrich the converged network model with human interaction principles under which people interact with engineered systems and promote sustainability (Wang *et al*. 2015). Nevertheless, contemporary CPS infrastructures do not consider social and economic considerations. In this context, Um *et al*. (2016) propose a future *Social-Cyber-Physical (SCP)* infrastructure which is the adhesive entity of the three distinct worlds (i.e. society, cyber-space, physical world). Their work though did not address a discrete integration path for the three worlds apart from “share information and create knowledge”.

4. The state-of-the art CPS

In the core of the proposed water-CPS framework (Figure 1), the cyber space comprises of a large number of sensors and actuators deployed to allow the collection of data-sets through sensing the water’s behaviour within any environment. This space also includes virtual objects such as software agents and services working over computing, storage, control and networking enabling components. The physical space includes the water in any form and any natural (i.e. sea, river, lake, soil) or technical milieu (i.e. hydroelectric utility, urban or domestic distribution system). Within the core of the proposed CPS, vast volumes of bytes (Big Data) are processed for predictive purposes offering opportunities for the optimal control of the physical realm. While technology and engineering as well as societal responses are integrated in hydrological modelling, Socio-Hydrology erupts in the historical/predictive, the comparative and the process domains. For instance, the quantitative analysis introduces proactivity in problematic circumstances such as actions in pollution incidents in agriculture or utilities and infrastructure breakdowns caused by faulty maintenance. The historical/predictive domain is the connecting glue between the core of the proposed CPS and Socio-Hydrology, as also depicted in Figure 1. Esterle and Grosu (2016) discuss that any industry sector, including telecommunications, manufacturing, utilities, urban planning and environment, drives its forecasts upon four pillars: connectivity, monitoring, prediction, optimisation. The proposed CPS focuses on the prediction pillar as the raison d'etre of the Socio-Hydrology and Cyber-Physical Systems concepts. However, from a technological perspective, it is implied that connectivity and monitoring are also included in the core of our framework. In conclusion, Figure 1 addresses the synergy space between the SH domains, the industry forecasting pillars and the entities of a water-CPS. Built on the principles of a typical CPS, the innovative framework is flexible due to its building blocks (i.e. sensor networking, M2M enabling technologies and IoT) which own a by-default emerging nature. Thus, this framework can be adjusted for the analysis of multiple water systems and challenges, whilst it can also be accommodated to integrate future technological advents.

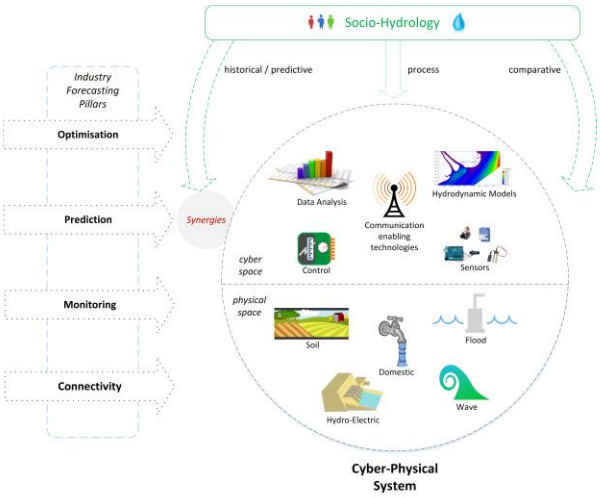

Figure 1. A state-of-the-art CPS

5. Discussion

The historical and predictive aspect of the proposed water-CPS framework could be employed for evolving asset management practices and strategies. For the UK water sector, the structure and capability of the framework could be used to assist in the improvement of existing conceptual models (e.g. Papacharalampou *et al*. 2016) for complex asset systems, such as *catchments*. Furthermore, it would enable the integration of Big Data gathered from real-time control or crowdsourcing in the asset management decision-making. These advancements would improve the understanding of the complexities involved in asset systems and allow for robust long-term strategic planning. The evolving asset management, through the creation of holistic, transdisciplinary approaches, will assist the water sector to achieve regulatory compliance within a challenging landscape, demanding robust solution for system resilience (e.g. DEFRA 2016). The framework presented in this paper contributes to the discussion on cross-disciplinary and cross-expert integration for tackling complex water challenges. The synthesis of the concepts has created a novel conceptual framework, which lies within transdisciplinary research.

6. Conclusions

This paper demonstrates the synergies between the emerging field of Socio-Hydrology (SH) and Cyber-Physical Systems (CPS) and proposes a cross-disciplinary solution for tackling real-world challenges. The proposed water-CPS is a transdisciplinary framework, which is created within the synergy space identified. As such, it enables the integration of the industry forecasting pillars and the domains of Socio-Hydrology in a novel CPS framework. The application of the water-CPS would provide several benefits and solutions to the current needs of the water sector, as far as improved and resilient asset management is concerned.

Acknowledgments

The authors would like to thank Euripides K. for his unequalled help on this work.

References

Aguado J., Arsuaga J.M., Arencibia A., Lindo M. and Allby, M. (2008). Oxford Dictionary of Earth Science, 3rd edition, Oxford University Press, ISSN 978-0-19-921194-4.

Anand, P. (2015). *Towards evolution of M2M into Internet of Things for analytics*. IEEE Conference on Recent Advances in Intelligent Computational Systems (RAICS), 10-12 Dec., Trivandrum, India, pp.388-393.

Barki, A., Bouabdallah, A., Gharout, S., and Traore, J. (2016). M2M Security: Challenges and Solutions. *IEEE Communications Surveys & Tutorials*, 18(2), pp.1241-1254.

Bavere, P.C. (2011). Hydropedology, biohydrology, and the compartmentalisation of hydrology into sub-disciplines: Necessary evolution or dispersal of efforts? *Journal of Hydrology*, 406, pp.137-140.

Blair P. and Buytaert W. (2016), Socio-hydrological modelling: a review asking “why, what and how?”, *Hydrology and Earth Systems Sciences*, 20, pp.443-478.

Bloomberg Businessweek (2013). *Theodore Paraskevakos: Executive Profile & Biography*. [online] Available at: http://www.bloomberg.com/research/stocks/private/person.asp?personId=99411576&privcapId=84684310&previousCapId=84684310&previousTitle=ICVN,%2520Inc.

Carey, M., Baraer, M., Mark, B.G., French, A., Bury, J., Young, K.R., McKenzie, J.M. (2014). Toward hydro-social modelling: Merging human variables and the social sciences with climate-glacier runoff models (Santa River, Peru). *Journal of Hydrology*, 518, pp.60-70.

Chang, H., Thiers, P., Netusil, N. R., Yeakley, J. A., Rollwagen-Bollens, G., Bollens, S. M., and Singh, S. (2014). Relationships between environmental governance and water quality in a growing metropolitan area of the Pacific Northwest, USA, *Hydrology and Earth Systems Sciences*, 18, pp.1383-1395.

Crutzen, P. J. (2002). Geology of mankind. *Nature*, 415, p.23.

Department for Environment Food & Rural Affairs, DEFRA (2016). *Creating a great place for living: Enabling resilience in the water sector*. Report PB14418. March 2016, London, UK.

Destouni, G., Jaramillo, F., and Prieto, C. (2012). Hydroclimatic shifts driven by human water use for food and energy production. *Nature Climate Change*, 3, pp.213–217.

Di Baldassarre, G., *et al*. (2015). Debates—Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes, *Water Resources Research*, 51, pp.4770–4781.

Esler, K.J., *et al*. (2016). Interdisciplinary and multi-institutional higher learning: reflecting on a South Africa case study investigating complex and dynamic environmental challenges. *Current Opinion in Environmental Sustainability*, 19, pp.76-86.

Esterle, L. and Grosu, R. (2016). Cyber-physical systems: challenge of the 21st century. *e & i Elektrotechnik und Informationstechnik*, 133(7), pp. 299-303.

Garofalaki, Z., Kallergis, D., Katsikogiannis, G., Ellinas, I., and Douligeris, C. (2016). *Transport Services within the IoT Ecosystem using Localisation Parameters*. 16th IEEE Symposium on Signal Processing and Information Technology (ISSPIT2016), 12-14 December, Limassol, Cyprus. pp.87-92.

Giuliani, M., Castelletti, A., Fedorov, R. and Fraternali, P. (2016). Using crowdsourced web content for informing water systems operations in snow-dominated catchments. *Hydrology and Earth System Sciences*, 20(12), pp.5049-5062.

Jeong, H. and Adamowski, J. (2016). A system dynamics based socio-hydrological model for agricultural wastewater reuse at the watershed scale. *Agricultural Water Management*, 171, pp.89-107.

Liu, Y., Peng, Y., Wang, B., Yao, S. and Liu, Z. (2017). Review on cyber-physical systems. *IEEE/CAA Journal of Automatica Sinica*, 4(1), pp.27-40.

Liu, Y., Tian, F., Hu, H., and Sivapalan, M.: Socio-hydrologic perspectives of the co-evolution of humans and water in the Tarim River basin, Western China: the Taiji–Tire model, *Hydrology and Earth System Sciences*, 18, pp.1289-1303.

Montanari, A., *et al* (2013). "Panta Rhei–Everything Flows: Change in hydrology and society–The IAHS Scientific Decade 2013–2022. *Hydrological Sciences Journal*, 58, pp.1256-1275.

National Institute of Standards and Technology - NIST (n.d.). *Cyber-Physical Systems*. [online] Available at: https://www.nist.gov/el/cyber-physical-systems.

Papacharalampou, C., McManus, M., Newnes, L.B., Green, D. (2016). Catchment metabolism: Integrating natural capital in the asset management portfolio of the water sector. *Journal of Cleaner Production*, 142(4), pp.1994-2005.

Qu, S., Gong, M. and Dong, H. (2013). A Water Management Strategy based on Efficient Prediction and Resource Allocation. *IERI Procedia*, 4, pp.224-230.

Rapousis, N., Katsarakis, M. and Papadopouli, M. (2015). *QoWater*. 1st ACM International Workshop on Cyber-Physical Systems for Smart Water Networks (CySWater'15), April 13-16, Seattle, USA, pp.1-6.

Sivapalan, M., Savenije, H. H. G., and Blöschl, G. (2012). Sociohydrology: A new science of people and water, *Hydrological Processes*, 26, pp.1270–1276.

Sivapalan, M., *et al*. (2014). Socio-hydrology: Use-inspired water sustainability science for the Anthropocene. *Earth's Future*, 2, pp.225–230.

Steffen, W., Crutzen, P. J., and McNeill, J. R. (2007). The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature. *AMBIO*, 36, pp.614–621.

Troy, T. J., Pavao-Zuckerman, M. and Evans, T. P. (2015), Debates—Perspectives on socio-hydrology: Socio-hydrologic modelling: Tradeoffs, hypothesis testing, and validation. *Water Resources Research*, 51, pp.4806–4814.

Um T., Lee G. and Choi J. (2016). Strengthening trust in the future social-cyber-physical infrastructure: an ITU-T perspective. *IEEE Communications Magazine*, 54(9), pp.36-42.

Viglione, A., *et al*. (2014). Insights from socio-hydrology modelling on dealing with flood risk—Roles of collective memory, risk-taking attitude and trust, *Journal of. Hydrology*, 518, Part A(0), pp.71–82.

Wagener, T., *et al*. (2010). The future of hydrology: An evolving science for a changing world. *Water Resources. Research*, 46, W05 301.

Wang, Z., Song, H., Watkins, D., Ong, K., Xue, P., Yang, Q. and Shi, X. (2015). Cyber-physical systems for water sustainability: challenges and opportunities. *IEEE Communications Magazine*, 53(5), pp.216-222.

Willems, P., Batelaan, O., Hughes, D.A., Swarzenski, P.W. (2014). Editorial for Journal of Hydrology: Regional Studies. *Journal of Hydrology: Regional Studies* 1, pp.A1-A5.