DEPARTMENT OF INTERNATIONAL AND EUROPEAN ECONOMIC STUDIES

ATHENS UNIVERSITY OF ECONOMICS AND BUSINESS

Emerging Challenges and the Future of Water Resources Management

Angelos Alamanos

Phoebe Koundouri

Working Paper Series

22-21

August 2022

EMERGING CHALLENGES AND THE FUTURE OF WATER RESOURCES MANAGEMENT

Angelos ALAMANOS, Phoebe KOUNDOURI

Athens University of Economics and Business; Sustainable Development Unit, ATHENA Research Center, Athens, Greece.

ABSTRACT

Most policy bodies involved with water management issues are facing new challenges: more evident climate change impacts, Covid-19, recession, wars, population movements, increased energy and resources demand. These challenges affect water resources management, as they impact several related sectors such as energy, fuels, industry, agriculture, international relations and trade, economy, resources, including water, human and natural capital. This situation creates an ambiguous context (deep uncertainty) that suggests reconsidering the traditional management approaches, and leaves limited space for management failures and delays. We discuss three research questions/areas of focus for the future: 1) Redefining multi-disciplinary science and innovative collaborations to analyze and solve complex problems; 2) Efficient communication and continuous engagement to create the culture for science-supported policies, and speed up the response of policy-makers to grasp and adopt research and technological advances; 3) Deciding under deep uncertainty.

KEYWORDS: Water Resources Management; Systems analysis; Future research; Inter-disciplinary science.

EMERGING CHALLENGES AND CONNECTION WITH WATER RESOURCES MANAGEMENT

Most policy bodies and stakeholders involved with water management issues have started to face new challenges, increasingly associated with complex problems, that suggest reconsidering the traditional management approaches.

The increasing needs accompanied by resources overexploitation and the intensification of production have created conditions of scarcity, environmental degradation, and increased emissions of Greenhouse Gases (GHGs) that enhanced climate change (Li et al., 2021). The rapid expansion of various human activities that rely on energy also contributed to an increased energy demand. Among the multiple consequences of climate change, there were observed winds of lower intensity that prevailed in regions of north Europe – which have invested a lot in renewable (wind) energy systems, but do not have the respective energy storage capacity (Akhtar et al., 2021; Laurila et al., 2020). The global alterations in energy supply and demand pattern brought us before a big increment of demand, a reduction of supply and available stocks, thus an overall increase of prices (e.g. electricity, natural gas, etc.), and inflation (Cook, 2021). The 'aggressive' macroeconomic policies of the past were further intensified during Covid-19, while the subsequent war in Ukraine made those effects more evident and much more stressed, initially in Europe (Quitzow et al., 2021).

This situation constitutes an unprecedented phenomenon of diverse challenges that interact, are extremely difficult to predict (know their probabilities distributions), so they create a context of deep uncertainty (ambiguity). This affects systems that are interconnected with water resources, and the respective decisions on management, infrastructure, and investments. The water management sector has to cope with these challenges, additionally to any existing issues of infrastructure, water scarcity, water quality deterioration, and mismanagement in human, economic, institutional terms (Loucks, 2022). Table 1 shows some indicative areas within the water management field that are affected from the various challenges mentioned above.

Table 1. Indicative fields of water management facing increasing challenges.

Fields	Description
Disaster Management (floods, droughts, pollution, pollution events, peaks)	Forecast, protection, warning, prevention, evaluation, restoration, awareness, under changing conditions and behaviours (Sudmeier-Rieux et al., 2021; Papaioannou et al., 2021; Alamanos and Linnane, 2021a)
Transboundary waters and water rights	Control and fair management of different demands and pressures, under changing conditions and conflicts (Deribe and Berhanu, 2021; Englezos et al., 2021)
Resources Allocation	Covering competitive demands with limited and deteriorating available surface and groundwater resources (Naghdi et al., 2021)
Water Infrastructure (storage, distribution, land reclamation works, hydropower, etc.)	Different strategies considering different objectives and investments for design, operation, performance and efficiency of infrastructure (Mala-Jetmarova et al., 2018; Alamanos, 2021)
Water quality	Planning, decision-making, management, performance, protection, warning, prevention, restoration, control of point and non-point pollution sources from all uses (Baghapour et al., 2020)
Interconnected physical systems with water resources (soil, land, landscape, air, atmosphere, climate, oceans, biodiversity, ecology, etc.)	Monitoring, forecast, protection, warning, prevention, evaluation, restoration etc. management actions considering multiple effects, costs and benefits (Grafton et al., 2019; Huang et al., 2021)
Social and Economic aspects, (behavioural dynamics, environmental economics, investment decisions, etc.)	Different policies, ways, decision strategies, methods and applications to cope with changing objectives of rights and shares, distribution of costs and benefits, social acceptance (Pulido-Velazquez et al., 2016)
Other cross-disciplinary, interconnected dynamic systems (Ecohydrology, Socio-hydrology, Water- Energy-Food Nexus, Water Ethics, etc.)	Identification – implementation of 'best' management practices, optimizing efficiency and performance under specific criteria (Pande et al., 2020; Pastor et al., 2022; Alamanos and Linanne, 2021b)
Policy and Governance	Combining all the above into strategies, education, Public Participation and stakeholder engagement, strong institutional and financing mechanisms and regulations (Lubell and Morrison, 2021)

The danger of complex crises is the creation of conflicts and dichotomies – thus any opportunities for improvements can be missed (Schulte et al., 2022). By seeing the short-term benefits of satisfying certain needs, makes many people, including policymakers see dichotomies, and treat the different systems (water-food-energy-fuel resources-economy) as competitive.

From the perspective of water management, this complex situation must be seen as an opportunity to improve the perception of systems, build inter-disciplinary innovative collaborations, and put more emphasis on the communication of these ideas. Below, we discuss some research areas/ questions for future research.

1. Redefining multi-disciplinary science and innovative collaborations to analyze and solve complex problems

During the last years the transition to a multi-disciplinary world is evident; consolidating scholarship under one umbrella is gathering momentum, and an inter-disciplinary space for water management is now being materialized (Pande et al., 2022). Loucks (2017) raised questions on how water systems analysts and planners can analyze and managing water in a changing world, where sustainable development must be seen as a system science problem, and suggests inter-disciplinary approaches. Redefining multi-disciplinarity should be built on the equal contribution of the different disciplines, their harmonization into modelling and implementation (*coupled* scientific areas rather than just addons to a main body of work based on a single discipline). Such an approach could bring fundamental advances in practice.

The knowledge base has been developing, preparing the ground for this transition, and this is justified by several examples:

Sophisticated integrated models representing system dynamics have been increasingly developed, highlighting the complexity of the interacting factors involved (Purkey et al., 2018). Besides the progress in the relevant fields of socio-hydrology, hydro-economics, and the modelling and conceptual advances they can provide in water management, there have been many more examples and applications. Porse et al. (2018) and Pincetl et al. (2019) presented a holistic representation of coupled hydrologic, social, economic, stakeholder, historical and institutional sub-systems aiming to covert a water-scarce to water self-sufficient system. The provision of open, freely accessible tools is also important for mainstreaming and the reproducibility of those approaches. Lund (2020) described the "*systems engineering knowledge and skills for water and environmental problems"*, illustrating the need for systemic multi-disciplinary approaches, and providing valuable lessons and insights. The technical, social, educational, communicational, diplomatic, problem-solving, analytical, and organizational skills are necessary conditions to successfully address complex challenges, and the failures of the past should be studied as lessons for improvement. The connection with real-life situations makes the above more tangible, and we see social and political aspects having a central role. This last statement is also noted from Pande et al. (2020): Socio-hydrological models are an example of coupling disciplines in integrated assessments, as they represent the hydrological-social-economic-management dynamics; However, culture is seen as a missing and emergent property of such dynamics, with institutions being the substance of that culture. The best way to build this culture for all actors involved is by learning, from their discipline and others' disciplines. Van Mierlo et al. (2020) highlighted the importance of "*learning about learning in sustainability transitions",* as a means to enhance the capacity of water governance to deal with complex management challenges. This is also an important way to overcome the multiple weaknesses accompanying the integration of multiple disciplines.

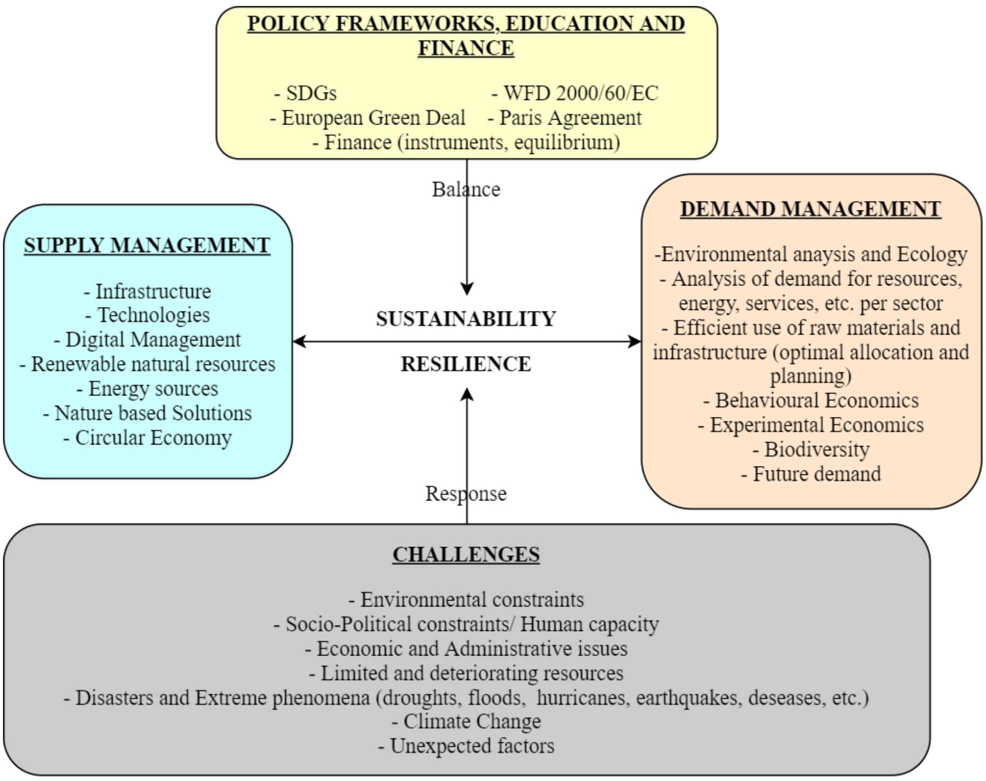

Figure 1: Sustainability and resilience through balancing supply and demand and addressing various challenges in integrated systems (Alamanos et al., 2022).

Analyzing the natural, human (social and behavioural), and economic sub-systems requires the consideration of all their supply and demand components, in order to develop and/or modify the institutional /policy-regulatory sub-system appropriately and proactively. A high-level example is presented in Figure 1: The **supply side** includes environmental, social, and economic factors that need to be analysed, and assessed as assets, either to the degree that we can control or better manage. Supply can be increased sustainably through more efficient and smarter use of our assets. The **demand side** includes also multiple parameters and disciplines (environmental, social, economic) that can be optimized and used efficiently. The **institutional /policy-regulatory** sub-system aims to (and is required to) balance supply and demand in order to make systems operate sustainably (both environmentally and economically). Thus, the ground is prepared and more solutions can be provided to address the various **challenges**, and thus achieve resilience.

2. Efficient communication and continuous engagement to create the culture for science-supported policies

The whole process described cannot operate in a healthy and integrated way without the necessary involvement from policy-makers. Like the other actors, they should be part of a two-way informational process towards the development and the implementation of solutions.

By informing researchers and being informed, the policy-makers could develop the necessary culture for seeing tangible actions and steps towards an improved management of human-environmental systems. This culture is often a missing element of the current management (Pande et al., 2020).

The pace of the technological and scientific advance is much faster than the pace managers need to grasp that information, adopt the appropriate advances and solutions, and develop flexible regulatory frameworks to support them.

A simple example of this pace-difference phenomenon is Digital Water Management, where the policy-makers' response has been slow compared to the private sector, and still, the solutions provided have not been fully exploited (e.g. remote sensing, inexpensive sensors, monitoring networks, smart devices, machine learning, artificial intelligence, virtual reality, etc.) (Doorn, 2021). Such solutions can be highly valuable for real-time water quantity and quality monitoring, improved management of infrastructure assets, direct public engagement and facilitation of localized management, improved and transparent water services, etc. (Li et al., 2014).

Efficient communication by both researchers and policy-makers would be key to create that culture, ensure the proper interpretation of the new technological and scientific advances, and use them properly. As researchers are making efforts to provide scientific results, similarly, policy-makers should make respective efforts to efficiently exploit those outcomes, and overcome any socio-political barriers. Their response to the new challenges, information, and available solutions and technologies should be an area of focus in the future in order to place our societies ahead of the challenges.

3. How to decide under deep uncertainty?

The combination of challenges and crises described from the beginning makes the work of decision-makers more complex, since it is difficult to predict changes, how long they are going to last, how they interact, and successfully explore the trade-offs of many factors in future scenarios. Moreover, there is another factor that adds further uncertainties, and that is the (unknown) way that policy-makers will respond, both to the new challenges and the new information, as mentioned above. Future research could provide more ideas on how to endogenize the reactions to new information, when analyzing complex systems.

As mentioned in the introductory section, such conditions create a context of deep uncertainty – or ambiguity according to the economics terminology (Li et al., 2019). In general, uncertainty can be defined as limited knowledge (inadequate information) about something that has or is going to happen, but its probabilities or an expected range of outcomes is known (Walker et al., 2013). In the case where unexpected situations, the way they interact, or even new information creates more uncertainties, and the probability distributions to represent uncertainty and its key parameters are unknown, then we have a situation of deep uncertainty (van Asselt and Rotmans, 2002). This context of deep uncertainty directly affects water resources decisions (management, investments and policies), because the standard engineering design and the decision-making approaches we follow are built on the assumption of rationality. Rationality in decision-making assumes that actors decide in dispassionate, consistent and purely self-interested ways (Klotz et al., 2018).

The issue of how to decide under deep uncertainty is a topic of broader concern based on the decision theory and economics field, that is related to numerous applications (Koundouri et al., 2022). The roots of this problem can be found in the (already proven) weaknesses of the existing approaches to understand problems and designs where the rationality of the decision-maker cannot be justified. Bossaerts et al. (2019) reflected an increasing number of concerns regarding the use of standard techniques — originally developed to deal with risk — in problems involving uncertainty. The classical framework of expected utility theory by von Neumann, Morgenstern and Savage (typically used to explore *rational decision making*), or Social Cost Benefit Analysis (SCBA - welfare-maximizing sustainable investment allocation decisions), and other optimization approaches are not adequate (Machina and Siniscalchi, 2014; Baillon and Bleichrodt, 2015; Apesteguia and Ballester, 2015). Simply because the complex challenges we are facing can make people perceiving risk and certainty in different ways that deviate from the 'rational' assumptions. Most models of classic decision-theory, economics, and engineering design are based on assumptions of perfect rationality (Friedman, 1953; Simon, 1957; Hazelrigg, 1998; Bromiley and Papenhausen, 2003; Gigerenzer, 2006), which have been characterized as incomplete and flawed (Klotz et al., 2018). This is being observed in real-life applications, where policy-making does not always act as a clear mechanism or process where researchers know in what stage of the process can step in with the scientific evidence to influence decisions. Policy is more complex, and considers more 'hidden' elements, so among other policy-relevant issues, this questions the rationality assumption in decision-making. An idea would be to simulate this as a machine learning problem that would explore possible futures (rather than predict them). The new technologies, such as machine learning can provide some answers also in the way that policy-makers respond to the new information (e.g. as input of the process).

Braun et al. (2021) raises a general concern that such questions cannot be solved only by relying on new technologies and computing advances (Editorial, 2018), but we must achieve a *human-technological efficient cooperative intelligence*. The same applies for water management issues, with governance and policy extents. Yung et al. (2019) explains how this concern affects significant issues of water management (e.g. Water-Energy-Food nexus) or climate (Roelich and Giesekam, 2019). The authors analyze approaches to nexus research and how they manage uncertainty. They find that the current approaches are still inadequate to address deep uncertainty (decision-makers with unclear objectives), it is difficult to identify short-term actions that connect to future benefits, and underline the need for complementary use of current approaches and critical thinking for policy flexibility and adaptiveness to uncertain paths. In the same context, the research of Pot (2019) presents another example on water research (investment decisions and long-term strategic visions on urban water supply and treatment services), that indicates the need of having clearer answers on how to decide under deep uncertainty, and incorporating it in the future planning (Trindade et al., 2019).

CONCUSIONS

In this research, we tried to point out the situation of the complex challenges that societies are facing and will be facing in the near future, and explain how these can affect water resources management. Our role is to understand the ways they function and interact, and adapt our approach to analyze and address them. Just knowing our future challenges does not tell us how to meet them in ways that will change for the better how we plan, manage, and model.

It is difficult to have these answers, and it is naïve to believe that they are simple and can work for every case. Maybe we will always have such challenges and as science and technology evolve to help us meet them, we (perhaps in response to world events or other externalities) will be introducing and facing new sets of challenges.

In an attempt to shed light on the future pathways of research areas that could help finding more answers, we discussed: a) the role of multi-disciplinary science and innovative collaborations, b) the importance of communication and continuous engagement to create the culture for science-supported policies, and c) the need to further explore how we decide under deep uncertainty conditions. All these three areas are complementary, and their future findings would be useful for each one of them to proceed and further grow.

ACKNOWLEDGEMENTS

We would like to thank Prof. Daniel Peter Loucks, from Cornell University, for kindly providing his thoughts, insights, and encouragement for writing and improving this paper.

REFERENCES

Akhtar, N., Geyer, B., Rockel, B., Sommer, P. S., & Schrum, C. (2021). Accelerating deployment of offshore wind energy alter wind climate and reduce future power generation potentials. *Scientific Reports*, *11*(1), 11826. https://doi.org/10.1038/s41598-021-91283-3

Alamanos, A., Koundouri, P., Papadaki, L., & Pliakou, T. (2022). A System Innovation Approach for Science-Stakeholder Interface: Theory and Application to Water-Land-Food-Energy Nexus. *Frontiers in Water*, *3*. https://www.frontiersin.org/article/10.3389/frwa.2021.744773

Alamanos, A. & Linnane S. (2021a). Drought monitoring, Precipitation statistics, and water balance with freely available remote sensing data: examples, advances, and limitations. Irish National Hydrology Conference 2021. Athlone, Co.Roscommon, Ireland. November 16, 2021. https://hydrologyireland.ie/wp-content/uploads/2021/11/03-A.-Alamanos-Drought-monitoring.pdf

Alamanos, A. & Linnane, S. (2021b). Estimating SDG indicators in data-scarce areas: The transition to the use of new technologies and multi-disciplinary studies. *Earth mdpi 2021*; 2(3):635-652. https://doi.org/10.3390/earth2030037

Alamanos, A. (2021). Water resources planning under climate and economic changes in Skiathos island, Aegean. *Journal of Water Supply: Research and Technology-Aqua 2021*; jws2021061. https://doi.org/10.2166/aqua.2021.061.

Apesteguia, J., & Ballester, M. A. (2015). A Measure of Rationality and Welfare. *Journal of Political Economy*, *123*(6), 1278–1310. https://doi.org/10.1086/683838

Baghapour, MA., Shooshtarian, MR., & Zarghami, M. (2020). Process Mining Approach of a New Water Quality Index for Long-Term Assessment under Uncertainty Using Consensus-Based Fuzzy Decision Support System. *Water Resources Management*, *34*(3), 1155–1172. https://doi.org/10.1007/s11269-020-02489-5

Baillon, A., & Bleichrodt, H. (2015). Testing Ambiguity Models through the Measurement of Probabilities for Gains and Losses. *American Economic Journal: Microeconomics*, *7*(2), 77–100. https://doi.org/10.1257/mic.20130196

Bossaerts, P., Yadav, N., & Murawski, C. (2019). Uncertainty and computational complexity. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *374*(1766), 20180138. https://doi.org/10.1098/rstb.2018.0138

Braun, M., Bleher, H., & Hummel, P. (2021). A Leap of Faith: Is There a Formula for "Trustworthy" AI? *Hastings Center Report*, *51*(3), 17–22. https://doi.org/10.1002/hast.1207

Bromiley, P., & Papenhausen, C. (2003). Assumptions of Rationality and Equilibrium in Strategy Research: The Limits of Traditional Economic Analysis. *Strategic Organization*, *1*(4), 413–437. https://doi.org/10.1177/14761270030014003

Cook, M. (2021). Chapter 2—Trends in global energy supply and demand. In M. Cook (Ed.), *Developments in Petroleum Science* (Vol. 71, pp. 15–42). Elsevier. https://doi.org/10.1016/B978-0-12-821190-8.00002-2

Deribe, M., & Berhanu, B. (2021). Conceptualization of Equitable and Reasonable Water Sharing in the Nile Basin with Quantification of International Transboundary Water-Sharing Principles. In A. M. Melesse, W. Abtew, & S. A. Moges (Eds.), *Nile and Grand Ethiopian Renaissance Dam: Past, Present and Future* (pp. 79–106). Springer International Publishing. https://doi.org/10.1007/978-3-030-76437-1_5

Doorn, N. (2021). Artificial intelligence in the water domain: Opportunities for responsible use. *Science of The Total Environment*, *755*, 142561. https://doi.org/10.1016/j.scitotenv.2020.142561

Editorial. (2018). Towards trustable machine learning. *Nature Biomedical Engineering*, *2*(10), 709–710. https://doi.org/10.1038/s41551-018-0315-x

Englezos N., Kartala X., Koundouri P., Tsionas M. & Alamanos, A. (2021). A novel hydro-economic – econometric approach for integrated transboundary water management under uncertainty. *DEOS Working Papers*. http://wpa.deos.aueb.gr/docs/INTEGRATED.TRANSBOUNDARY.WATER.MANAGEMENT.pdf

Friedman, M. (1966). *Essays in Positive Economics*. University of Chicago Press. https://press.uchicago.edu/ucp/books/book/chicago/E/bo25773835.html

Gigerenzer, G. in Contemporary Debates in Cognitive Science (ed. Stainton, R.) 115–133 (Blackwell, Oxford, 2006).

Grafton, R., Doyen, L., Béné, C., Borgomeo, E., Brooks, K., Chu, L., Cumming, G., Dixon, J., Dovers, S., Garrick, D., Helfgott, A., Jiang, Q., Katic, P., Kompas, T., Little, L., Matthews, N., Ringler, C., Squires, D., Steinshamn, S., … Wyrwoll, P. (2019). Realizing resilience for decision-making. *Nature Sustainability*, *2*(10), 907–913. https://doi.org/10.1038/s41893-019-0376-1

Hazelrigg, G. A. (1998). A Framework for Decision-Based Engineering Design. *Journal of Mechanical Design*, *120*(4), 653–658. https://doi.org/10.1115/1.2829328

Huang, J., Zeng, Q. & Alamanos, A. (2021). Modelling the relationship between car ownership, traffic congestion and air quality deterioration in China: Policies for enhancing environmental sustainability, and the potential of Circular Economy approaches. 2nd Symposium on Circular Economy and Sustainability. Alexandroupolis, Greece (online). July 14-16, 2021.

Klotz, L., Weber, E., Johnson, E., Shealy, T., Hernandez, M., & Gordon, B. (2018). Beyond rationality in engineering design for sustainability. *Nature Sustainability*, *1*(5), 225–233. https://doi.org/10.1038/s41893-018-0054-8

Koundouri, P., Pittis, N., Samartzis, P., Englezos, N. & Papandreou A. (2022). Alternative Types of Ambiguity and their Effects on Climate Change Regulation [version 1; peer review: awaiting peer review] Open Research Europe 2022, 2:9 https://doi.org/10.12688/openreseurope.14300.

Laurila, T. K., Sinclair, V. A., & Gregow, H. (2021). Climatology, variability, and trends in near-surface wind speeds over the North Atlantic and Europe during 1979–2018 based on ERA5. *International Journal of Climatology*, *41*(4), 2253–2278. https://doi.org/10.1002/joc.6957

Li, C., Turmunkh, U., & Wakker, P. P. (2019). Trust as a decision under ambiguity. *Experimental Economics*, *22*(1), 51–75. https://doi.org/10.1007/s10683-018-9582-3

Li, R., Huang, H., Xin, K., & Tao, T. (2014). A review of methods for burst/leakage detection and location in water distribution systems. *Water Supply*, *15*(3), 429–441. https://doi.org/10.2166/ws.2014.131

Loucks, D. P. (2017). Managing Water as a Critical Component of a Changing World. *Water Resources Management*, *31*(10), 2905–2916. https://doi.org/10.1007/s11269-017-1705-7

Loucks, D. P. (2022). Meeting Climate Change Challenges: Searching for More Adaptive and Innovative Decisions. *Water Resources Management*. https://doi.org/10.1007/s11269-022-03227-9

Lubell, M., & Morrison, T. (2021). Institutional navigation for polycentric sustainability governance. *Nature Sustainability*, *4*(8), 664–671. https://doi.org/10.1038/s41893-021-00707-5

Lund, J. (2020). Systems engineering knowledge and skills for water and environmental problems. *Civil Engineering and Environmental Systems*, *37*(4), 183–196. https://doi.org/10.1080/10286608.2020.1850701

Machina, M., & Siniscalchi, M. (2014). Chapter 13—Ambiguity and Ambiguity Aversion. In M. Machina & K. Viscusi (Eds.), *Handbook of the Economics of Risk and Uncertainty* (Vol. 1, pp. 729–807). North-Holland. https://doi.org/10.1016/B978-0-444-53685-3.00013-1

Mala-Jetmarova, H., Sultanova, N., & Savic, D. (2018). Lost in Optimisation of Water Distribution Systems? A Literature Review of System Design. *Water*, *10*(3), 307. https://doi.org/10.3390/w10030307

Naghdi, S., Bozorg-Haddad, O., Khorsandi, M., & Chu, X. (2021). Multi-objective optimization for allocation of surface water and groundwater resources. *Science of The Total Environment*, *776*, 146026. https://doi.org/10.1016/j.scitotenv.2021.146026

Pande, S., Haeffner, M., Blöschl, G., Alam, M., Castro, C., Di Baldassarre, G., Frick-Trzebitzky, F., Hogeboom, R., Kreibich, H., Mukherjee, J., Mukherji, A., Nardi, F., Nüsser, M., Tian, F., van Oel, P., & Sivapalan, M. (2022). Never Ask for a Lighter Rain but a Stronger Umbrella. *Frontiers in Water*, *3*. https://www.frontiersin.org/articles/10.3389/frwa.2021.822334

Pande, S., Roobavannan, M., Kandasamy, J., Sivapalan, M., Hombing, D., Lyu, H., & Rietveld, L. (2020). A Socio-Hydrological Perspective on the Economics of Water Resources Development and Management. In *Oxford Research Encyclopedia of Environmental Science*. https://doi.org/10.1093/acrefore/9780199389414.013.657

Papaioannou, G., Vasiliades, L., Loukas, A., Alamanos, A., Efstratiadis, A., Koukouvinos, A., Tsoukalas, I., & Kossieris, P. (2021). A Flood Inundation Modeling Approach for Urban and Rural Areas in Lake and Large-Scale River Basins. *Water*, *13*(9), 1264. https://doi.org/10.3390/w13091264

Pastor, A., Tzoraki, O., Bruno, D., Kaletová, T., Mendoza-Lera, C., Alamanos, A., Brummer, M., Datry, T., De Girolamo, A. M., Jakubínský, J., Logar, I., Loures, L., Ilhéu, M., Koundouri, P., Nunes, J. P., Quintas-Soriano, C., Sykes, T., Truchy, A., Tsani, S., & Jorda-Capdevila, D. (2022). Rethinking ecosystem service indicators for their application to intermittent rivers. *Ecological Indicators*, *137*, 108693. https://doi.org/10.1016/j.ecolind.2022.108693

Pincetl, S., Porse, E., Mika, K., Litvak, E., Manago, K., Hogue, T., Gillespie, T., Pataki, D., & Gold, M. (2019). Adapting Urban Water Systems to Manage Scarcity in the 21st Century: The Case of Los Angeles. *Environmental Management*, *63*(3), 293–308. https://doi.org/10.1007/s00267-018-1118-2

Porse, E., Mika, K., Litvak, E., Manago, K., Hogue, T., Gold, M., Pataki, D., & Pincetl, S. (2018). The economic value of local water supplies in Los Angeles. *Nature Sustainability*, *1*(6), 289–297. https://doi.org/10.1038/s41893-018-0068-2

Pot, W. (2019). Anticipating the Future in Urban Water Management: An Assessment of Municipal Investment Decisions. *Water Resources Management*, *33*(4), 1297–1313. https://doi.org/10.1007/s11269-019-2198-3

Pulido-Velazquez, M., Marques, G., Harou, J., & Lund, J. (2016). Hydroeconomic Models as Decision Support Tools for Conjunctive Management of Surface and Groundwater. In A. J. Jakeman, O. Barreteau, R. J. Hunt, J.-D. Rinaudo, & A. Ross (Eds.), *Integrated Groundwater Management: Concepts, Approaches and Challenges* (pp. 693–710). Springer International Publishing. https://doi.org/10.1007/978-3-319-23576-9_27

Purkey, D., Escobar Arias, M., Mehta, V., Forni, L., Depsky, N., Yates, D., & Stevenson, W. (2018). A Philosophical Justification for a Novel Analysis-Supported, Stakeholder-Driven Participatory Process for Water Resources Planning and Decision Making. *Water*, *10*(8), 1009. https://doi.org/10.3390/w10081009

Quitzow, R., Bersalli, G., Eicke, L., Jahn, J., Lilliestam, J., Lira, F., Marian, A., Süsser, D., Thapar, S., Weko, S., Williams, S., & Xue, B. (2021). The COVID-19 crisis deepens the gulf between leaders and laggards in the global energy transition. *Energy Research & Social Science*, *74*, 101981. https://doi.org/10.1016/j.erss.2021.101981

Roelich, K., & Giesekam, J. (2019). Decision making under uncertainty in climate change mitigation: Introducing multiple actor motivations, agency and influence. *Climate Policy*, *19*(2), 175–188. https://doi.org/10.1080/14693062.2018.1479238

Schulte, L., Dale, B., Bozzetto, S., Liebman, M., Souza, G., Haddad, N., Richard, T., Basso, B., Brown, R., Hilbert, J., & Arbuckle, J. (2022). Meeting global challenges with regenerative agriculture producing food and energy. *Nature Sustainability*, *5*(5), 384–388. https://doi.org/10.1038/s41893-021-00827-y

Simon, H. (1957). *Models of man: Social and rational; mathematical essays on rational human behavior in society setting.* Wiley.

Sudmeier-Rieux, K., Arce-Mojica, T., Boehmer, H., Doswald, N., Emerton, L., Friess, D., Galvin, S., Hagenlocher, M., James, H., Laban, P., Lacambra, C., Lange, W., McAdoo, B., Moos, C., Mysiak, J., Narvaez, L., Nehren, U., Peduzzi, P., Renaud, F., … Walz, Y. (2021). Scientific evidence for ecosystem-based disaster risk reduction. *Nature Sustainability*, *4*(9), 803–810. https://doi.org/10.1038/s41893-021-00732-4

Trindade, B., Reed, P., & Characklis, G. (2019). Deeply uncertain pathways: Integrated multi-city regional water supply infrastructure investment and portfolio management. *Advances in Water Resources*, *134*, 103442. https://doi.org/10.1016/j.advwatres.2019.103442

van Asselt, M.B.A., & Rotmans, J. (2002). Uncertainty in Integrated Assessment Modelling. *Climatic Change*, *54*(1), 75–105. https://doi.org/10.1023/A:1015783803445

van Mierlo, B., Halbe, J., Beers, P., Scholz, G., & Vinke-de Kruijf, J. (2020). Learning about learning in sustainability transitions. *Environmental Innovation and Societal Transitions*, *34*, 251–254. https://doi.org/10.1016/j.eist.2019.11.001

Walker, W. E., Lempert, R. J., & Kwakkel, J. H. (2013). Deep Uncertainty. In S. I. Gass & M. C. Fu (Eds.), *Encyclopedia of Operations Research and Management Science* (pp. 395–402). Springer US. https://doi.org/10.1007/978-1-4419-1153-7_1140

Yung, L., Louder, E., Gallagher, L., Jones, K., & Wyborn, C. (2019). How Methods for Navigating Uncertainty Connect Science and Policy at the Water-Energy-Food Nexus. *Frontiers in Environmental Science*, *7*. https://www.frontiersin.org/articles/10.3389/fenvs.2019.00037