Institution: The University of Manchester		
Unit of Assessment: 12 (Engineering)		
Title of case study: System-scale design of water resource systems improves water security and resilience		
Period when the underpinning research was undertaken: 2014 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (*e.g.* job title):**	**Period(s) employed by submitting HEI:**
Julien Harou	Professor, Chair of Water Engineering	2013 – present
Evgenii Matrosov	Research Fellow	2013 – present
James Tomlinson	PhD student, Research Fellow	2015 – present
Anthony Hurford	PDRA, Group Manager	2013 – 2020
Ivana Huskova	PDRA	2016 – 2018
Andrew Slaughter	PDRA	2019 – present
Robel Geressu	PDRA, PhD student (Harou, UCL 2012 – 2016)	2016 – present
Erfani Tohid	PDRA (UoM), then Lecturer (UCL)	2014 – 2014
Kevis Pachos	Erfani PhD student (co-supervised by Harou)	
Period when the claimed impact occurred: 2015 – 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

The University of Manchester's Water Resource Group (UMWRG) has developed design approaches, models and open-source software tools for system-scale multi-criteria assessment and optimisation of water resource interventions.

Partners including water companies (Thames Water, Anglian Water), regulators (Ofwat, the Environment Agency), and international funders (World Bank, World Wildlife Fund) have used these approaches and tools to improve their decision-making.

UMWRG has influenced specific water infrastructure planning processes, system designs and investment decisions, including how national water transfer investments are selected for design by water companies and assessed by regulators in England and Wales. The work has informed **GBP9,000,000,000** of investment in water supply systems in London and the East of England, and England's water industry regulators now recommend UMWRG approaches. Outside of the UK, UMWRG work influenced international funder's assessment of hydropower projects, including contributing to pausing the International Finance Corporation's participation in the Sounda Gorge Dam in the Republic of Congo.

2. Underpinning research

Traditionally water resource infrastructure is assessed *via* cost-benefit analysis, considering each proposed investment individually. In water supply planning, the least-financially-costly package of infrastructure options is typically chosen. Since 2015, UMWRG has published a series of papers demonstrating an alternative approach for infrastructure investment assessment under future uncertainty. This approach tackles the infrastructure investment problem from a systems perspective, seeking to assess and optimise complex engineered-natural-human systems under uncertainty using multiple economic, engineering, ecological and social criteria.

UMWRG were the first to use multi-criteria search-based planning methods for UK water planning, and demonstrated that portfolios of water infrastructure options can be optimised for many stakeholder-selected criteria, such as multi-sector service levels, environmental performance and cost, greatly expanding the range of options available to investment planners **[1]**. Paper **[1]**, published in collaboration with Thames Water (London's water supply provider) analysed the city's infrastructure portfolio and is the first UK example of multi-criteria optimised co-design of a river basin and an urban water supply system.

Paper **[2]** showed for the first time how sophisticated the system-scale multi-objective infrastructure investment problem really is (*i.e.*, each time you suggest an infrastructure investment package you must re-optimise the management rules of the system for that specific combination of assets).

Paper **[3]** considered the case of future uncertainty, *i.e.* how to simultaneously design for multi-criteria analysis and seek 'robust' combinations of assets as well as consider a system's performance over multiple plausible future scenarios simultaneously, rather than only accounting for historical data or a single future prediction. Paper **[3]**'s method also allows trading-off of attributes relating to climate change resilience (*e.g.* robustness to uncertainty, duration of failures) with other conventional benefits (like cost).

In 2019, the Global Commission on Adaptation to Climate Change defined resilience as a combination of robustness in the face of an unknown future, and adaptability to it. UMWRG had been working for some time to develop a model-assisted approach to enable resilience defined in this way. An award-winning paper **[4]** achieved the optimisation of cost-flexibility trade-offs; this approach is referred to as 'real options', and aims to identify the value of seeking flexibility in infrastructure investment strategies. This recognises the economic and social-political value of being able to adapt infrastructure systems as new information on supply and demand progressively becomes available in the future.

Reference **[5]** ('Pywr') is UMWRG's open-source water resource management simulation code, under development since 2015. It has now become the preferred model for UK water companies upgrading their simulation software systems. Traditionally, to simulate many scenarios, each simulation starts at the initial time step and advances until the end of the simulated time-horizon. This is slow because sometimes millions of scenario simulations are run with only small variations. In Pywr the time-steps of each scenario are modelled together, such that only the new elements of any scenario are simulated. This results in a four-fold increase in computational speed when simulating many futures, and has expanded the range of possibilities when analysing water resource systems. Pywr also allows users to develop customised metrics of system performance, so the simulator can be parameterised for any system globally.

Hydra Platform **[6]** is UMWRG's open-source data manager for networked resource models (*e.g.* energy, transport, water, logistics, *etc.*). Traditionally when engineers apply a generalised computer model to a specific system they use a model input file. Whilst simple, this can make maintaining large real-world models unreliable and cumbersome. The Hydra Platform server manages datasets of large models reliably and securely on private servers or online, and can be linked to UMWRG's 'Polyvis' multi-criteria visualisation suite. UMWRG has used Hydra Platform and Polyvis internally and with partners for projects since 2015.

3. References to the research

[1] Matrosov, E. S., Huskova, I., Kasprzyk, J. R., **Harou, J. J.**, Lambert, C., Reed, P. M., (**2015**). "Many-objective optimization and visual analytics reveal key trade-offs for London's water supply." *Journal of Hydrology*, *531*, Part 3: 1040-1053. DOI: 10.1016/j.jhydrol.2015.11.003

[2] Geressu, R. T., **Harou, J. J.** (**2015**). "Screening reservoir systems by considering the efficient trade-offs-informing infrastructure investment decisions on the Blue Nile." *Environ. Res. Lett.*, *10*, 125008. DOI: 10.1088/1748-9326/10/12/125008

[3] Huskova, I., **Matrosov, E. S.**, **Harou, J. J.**, Kasprzyk, J. R., Lambert, C., (**2016**) "Screening robust water infrastructure investments and their trade-offs under global change: A London example" *Global Environmental Change*, *41*, 216-227. DOI: 10.1016/j.gloenvcha.2016.10.007

[4]* Erfani, T., Pachos, K., **J. J. Harou** (**2018**) "Real-Options Water Supply Planning: Multistage Scenario Trees for Adaptive and Flexible Capacity Expansion Under Probabilistic Climate Change Uncertainty" *Water Resources Research*, *54*, 5069-5087. DOI: 10.1029/2017WR021803

[5] Tomlinson, J. E., **Arnott, J. H.**, **Harou, J. J.**, (**2020**). "A Water Resource simulator in Python", *Environmental Modelling & Software*, *126*, 104635. DOI: 10.1016/j.envsoft.2020.104635

[6] Knox, S., **Tomlinson, J.**, **Harou, J. J.**, Meier, P., Rosenberg, D. E., Lund, J. R., Rheinheimer, D. E., (**2019**) "An open-source data manager for network models" *Environmental Modelling & Software*, *122*, 104538. DOI: 10.1016/j.envsoft.2019.104538

* Paper **[4]** won an American Geophysical Union (AGU) Water Resources Research 'Editor's Choice Award'

The research described in this case has been funded by many grants, totalling over GBP4,200,000, from organisations such as The World Bank, The Nature Conservancy, The International Finance Corporation, Thames Water, Anglian Water, UK Water Industry Research, the Technology Strategy Board, the Department for International Development, the NERC, the

EPSRC, and the ESRC. Specific grants include: EPSRC **EP/G060460/1**, "Living with Environmental Change – Adaptation and Resilience to Climate Change (ARCC-WATER)", Julien Harou (PI), December 2009 – May 2013, GBP79,232; ESRC **ES/P011373/1**, "GCRF: DAMS 2.0: Design and assessment of resilient and sustainable interventions in water-energy-food-environment Mega-Systems", David Hulme (PI), Julien Harou (Co-I and Director of Research), October 2017 – December 2021, GBP8,162,095 total (GBP1,800,000 to UMWRG).

4. Details of the impact

Impacts arising from the research described above fall into two categories. The first is influencing the water resource planning decisions made by water companies and regulators in England and Wales through new tools and approaches. The second is influencing major hydropower investment decisions by international development organisations.

Water supply planning and regulation in England and Wales

Combined water resources and supply infrastructure networks at water company, regional or national scale are complex, often involving multiple stakeholders, region-specific infrastructure, and competing priorities. Consequently, computer model-based infrastructure for investment decision-making has been the industry norm since 2002. Companies traditionally used a statutory least-cost planning approach called the 'Economics of Balancing Supply and Demand' (EBSD), which optimises the schedule of cost-effective supply or demand schemes.

In the last decade, UMWRG has worked with various stakeholders in the UK water industry, such as Thames Water, Anglian Water, the Environment Agency (EA), Ofwat (the financial regulator), regional groups such as Water Resources East (WRE) and Water Resources South East (WRSE), and industry bodies such as UK Water Industry Research (UKWIR). Based on research into resource modelling and decision making in water resources **[1-4, A]**, UMWRG recommended three extensions to least-cost EBSD modelling: to apply the 'multi-criteria paradigm' (multi-criteria visualisation methods to explore how nearly-least-cost investment options perform on other non-financial measures) **[A]**; to use simulation-based multi-criteria optimisation **[1, 3]**; and to explicitly value flexibility and adaptability in infrastructure option optimisation **[4, A]**.

<u>*Improving water regulators' capabilities in scrutinising and directing water investments*</u>

UMWRG has had strong, ongoing collaborations with the EA to improve their capacity for guiding and scrutinising water resource investments from water companies. The EA's 2017 and 2020 statutory guidance on water company water resource management plans **[B]**, which companies are legally obliged to follow, says that **companies should use the method co-authored by UMWRG [A, B]**. For example, the 2017 guidance on technical methods to use states "*You should identify your solution(s) using the most appropriate method for your company. You should refer to UKWIR (2016) WRMP 2019 Methods – decision making process guidance"*, which is the UoM-authored guidance that includes UMWRG methods and tools **[A]**. UMWRG's emphasis on using adaptive planning methods continues to influence the EA, which has recommended the use of such methods for the first time in their July 2020 water company planning guidance document **[B]**. The EA's regulatory power extends across England, and thus their guidance to water companies impacts upon all residents of England.

In 2018, UMWRG was approached by the EA to build a first national water supply-demand planning model, designed to identify cost savings and resilience benefits achievable *via* an optimised mix of inter-regional water transfers. This model was built with UMWRG's Pywr model **[5]**, and is hosted online using our Hydra Platform **[6]**. The model's results influenced the content of the 2020 National Framework EA-led report **[C, D]**, leading the EA and Ofwat to increase their scrutiny of proposed water transfer plans by water companies. Using UMWRG models empowers the regulators by giving them the ability to perform their own optimisation of the national mix of water transfers, providing "*crucial evidence*" **[D]** in scrutinising water companies' proposals using their own preferred criteria. The EA characterises the tools provided by UMWRG thus: *"…a tool that provides regulators with a systematic national-scale view of how different solutions can meet future water needs, is in the public interest*" **[D]**.

In March 2020 UMWRG was awarded the tender to build an extension of the National Framework supply-demand model to allow the three water regulators (Ofwat, the EA, and the Drinking Water Inspectorate) to optimise and assess 'baskets' of water resource investment planning options **[E]**.

This project finished in November 2020, and incorporates UMWRG's multi-criteria assessment methods into models for assessing water resource investment, built with the Pywr simulation software **[E]**. The value of our models was summarised by Ofwat: "*In the 2020-2025 period water companies in England and Wales will be investing **over £51 billion**. The tool being built with UMWRG provides regulators with a simple, systematic, country-scale view, enabling the partnership to simulate and compare different combinations of water supply options. The output supports exploration of which solutions offer the best value in the public interest*" **[E]**.

Changing investment planning practice at two major regional water company groups

The biggest change in English water planning in the last decade has been the growing influence of regional groupings of water companies (in lieu of each company only making decisions on assets within its borders). Two major English groups are WRE (comprising Anglian Water, Affinity Water, Essex and Suffolk Water, Severn Trent, and Cambridge Water Company), and WRSE (comprising Affinity Water, Portsmouth Water, SES Water, South East Water, Southern Water and Thames Water). UMWRG began working with WRSE in 2010, and WRE in 2011.

WRSE uses an EBSD model built by UMWRG in collaboration with the EA, which WRSE described as "*...key to our 2018 strategy for the South East*" **[F]**. WRSE commissioned a Pywr **[5]** model (built by Atkins) in 2018, and this was used in a 2019 UMWRG study of WRSE decision-making robustness – WRSE described UMWRG as having made "*a significant contribution to the planning of water resources and water supply provision in the populous South-East of England*" **[F]**. The total value of asset investment that was considered in WRSE's region of responsibility between August 2013 and July 2020 is **GBP7,000,000,000 [F]**. These investment decisions affected some **19 million people's water supply** in this region, as well as supplying industry and commerce which represent some 40% of the UK's GDP **[F]**. WRSE's Director described UMWRG's contribution to their planning processes as "*...instrumental in supporting strategic water infrastructure investment for the benefit of water security and resilience for both people and environment now and for future generations*" **[F]**.

WRE uses Pywr and, since 2019, uses an EBSD model designed by UMWRG, as well as analytical decision-making approaches designed by UMWRG **[1, 3, A, G]**. These tools have greatly enhanced the ability of WRE to model planned infrastructure investments, accounting for important criteria that were previously absent **[G]**. WRE confirms, "*Without UMWRG assistance* […] *WRE would likely not have been as effective, transformational and influential as it has been in the 2014-2020 period* […] *we have been able to consider more decision factors than our previous models including environmental sustainability, water availability for the agri-food sector and supply system performance including vulnerability to drought and climate change, reliability and resilience*" **[G]**. These UMWRG tools and methods have been used to inform **GBP1,300,000,000** of investment as part of Anglian Water's statutory Water Resource Management Plan for 2019 (WRMP19), affecting the potable water supply of **6 million people** in England **[G]**. UMWRG tools are also being used by WRE to help its member companies plan for WRMP24 **[G]**. WRE is planning to develop two new public water supply reservoirs with an associated cost of **GBP1,700,000,000**, and have chosen to develop UMWRG tool applications to optimise multi-sector value in these projects **[G]**.

Increasing the breadth and quality of investment planning by Thames Water

Thames Water used UMWRG models and software **[1, 5, 6]** in their statutory WRMP19 **[H]**. WRMPs are exceptionally important in the water industry, as Thames Water explain: "…*developing an efficient, evidence-based plan that represents best value-for-money investment is crucial to the business and its customers*" **[H]**. Thames Water's plan evaluated and optimised options using eight criteria (instead of cost only), including environmental impact, inter-generational equity, resilience, and carbon emissions **[H]**. This approach was introduced through UMWRG's collaborations with Thames Water since 2012, including two funded PhD studentships, and Harou serving on Thames' Expert Panel. As a result of their WRMP19 planning, Thames Water have committed to making **GBP750,000,000** of investments in infrastructure over the five-year period of the plan, all of which has been shaped by UMWRG's planning tools **[H]**. Thames Water supplies water to **15 million people in London and the Thames Valley** in South-East England. All of these people have been affected by UMWRG's influence on Thames' investment planning.

System-scale design approaches for hydropower systems around the world

National ministries of water and/or energy, energy system regulators and river basin agencies influence how countries invest in hydropower projects. Individual hydropower projects are proposed by such organisations, evaluated by international funders with financial, environmental and social metrics, and their implementation is then decided on. Typically there is limited evaluation of how a proposed project will impact other existing or future hydropower dams, or how it will impact other water-using sectors. Optimising hydropower investments to meet multiple sectoral and regional performance metrics is not common practice. Between 2015 and 2019, UMWRG developed new methods and tools for system-scale optimisation of hydropower infrastructure investments **[2]**, promoted and applied them **[A]** to real hydropower systems internationally.

Influencing policies and proposals from international funding agencies and NGOs

UMWRG has worked with international organisations that advocate for a more strategic approach to hydropower investment. This resulted in international policy documents **[A]** published jointly with organisations like the World Bank, the International Union for the Conservation of Nature (IUCN), the World Wildlife Fund (WWF), The Nature Conservancy (TNC), and the Stimson Centre think-tank. As an example, the WWF has collaborated with UMWRG on several major reports into water-energy system design **[I]**, and has "*integrated the work of UMWRG into our engagement with governments in Myanmar, Nepal, Zambia, among other countries*" **[I]**.

Influencing specific hydropower investments

UMWRG has acted as a consultant to organisations such as the International Finance Corporation (IFC), producing reports on specific hydropower investment projects **[J]**. UMWRG produced a report (in conjunction with TNC) for the IFC on the **USD2,000,000,000** Sounda Gorge hydropower project (Republic of Congo) **[A, J]**. UMWRG recommended other, more strategic investments than those being considered by the IFC at the time, and the report demonstrated that the Sounda Gorge project would be difficult to complete. As the IFC state, "*The study helped IFC refine its preferred concept for Sounda, whose implementation in compliance with IFC's Performance Standards would be challenging, technically complex, and involving major mitigation costs*" **[J]**. Consequently, the project has not gone ahead, and the IFC has paused its participation whilst the Government considers its options. Half of the estimated cost would have been paid for by the people of the Republic of Congo, and so UMWRG involvement has helped to prevent the miss-spending of their money **[J]**.

5. Sources to corroborate the impact

- **[A]** Research-based reports for UK and international stakeholders, co-authored by UMWRG researchers, including: i) "Water Resources Management Plan (WRMP) 2019 Methods – Decision Making Process: Guidance", 2016; ii) "Sounda Landscape Alternatives Analysis – An ERM report delivered to the IFC", 2017; iii) "Connected and flowing: a renewable future for rivers, climate and people", 2017. Available on request.
- **[B]** Environment Agency statutory Water Resource Management Plan guidelines for Price Review 2019 and Price Review 2024
- **[C]** Environment Agency, "National Framework for Water Resources", 16 March 2020
- **[D]** Letter from the Executive Director of Environment and Business, Environment Agency, 21 July 2020
- **[E]** Letter from the Director (Stakeholders and Programme) at RAPID, part of the Water Services Regulatory Authority (Ofwat), 8 October 2020
- **[F]** E-mail from the Director of Water Resources South-East, 1 July 2020
- **[G]** Letter from the Director of Water Resources East, 26 May 2020
- **[H]** E-mail from Thames Water's WRMP Senior Technical Advisor, 18 June 2020
- **[I]** Letter from the World Wildlife Fund's Global Lead Freshwater Scientist, 30 June 2020
- **[J]** E-mail from the International Finance Corporation's Chief Environmental Specialist, 28 May 2020