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Why are reservoir operation optimisation methods hardly used in practice? Insights from a survey of water resource managers

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Introduction

The use of mathematical models to guide reservoir operations has a long history. The first reviews of the scientific literature on the topic already appeared in the 1980s (e.g. Yeh 1985), while the number of papers introducing new methods and applications has steadily grown in recent years (see e.g. Fig. 2 in Dobson et al., 2019a). Over time, algorithmic advances have enabled the application of reservoir operation optimization to increasingly complex simulation models and to larger number of objectives (e.g. Reed et al. 2013). Given the renewed interest in dam construction, particularly for hydropower development (Zarfl et al. 2014), and the pressure to expand the range of interests considered in dam operation, particularly towards environment conservation targets (e.g. Poff and Schmidt 2016; Chen and Olden, 2017), (multi-objective) optimisation would be expected to play a growing role in informing reservoir operations.

Despite this potential, however, there is a shared perception among researchers that optimisation methods have seen limited uptake by practitioners. For example, in a state-of-art review of the Water Resource System Analysis (WRSA) field, Brown et al. (2015) concluded that, while simulation models are widely used for what-if analyses and manual appraisal of options, optimisation methods are rarely used outside academia (with the notable exception of hydropower applications, see e.g. Ibanez et al. (2014)). Perhaps surprisingly, attempts at formally surveying practitioners to assess the validity of this perception have been quite limited so far. To our knowledge, the first study of this type dates back to the survey of US practitioners by Rogers and Fiering (1986), who reported a very limited uptake of WRSA methods at the time. More recently, Rosenberg et al. (2017) interviewed some practitioners in the US and Asia and found that “all practitioners mentioned use of simulation modeling” whereas most “indicated that they never implemented formal optimization algorithms”, and “were more inclined to either manually generate scenarios or use simple search algorithms”. The apparent disconnect between research and practice communities is a recurrent theme in commentary papers in the WRSA field, and further efforts have been advocated to provide more stringent evidence of the contribution of WRSA to society (Kasprzyk et al., 2018).

In this paper, we contribute to this ongoing discussion by presenting the results of a survey of practitioners of water companies in England and Wales, aimed at assessing specifically the use of reservoir simulation and optimisation tools. We complement the survey results with interviews of practitioners in consultancy companies and our own experience of interacting with the UK water industry. Finally, we suggest some directions for future research that we think may be interesting for researchers while also helping to make the field more relevant for practice.

Background

Beyond our own links to the region, we think England and Wales are interesting places to measure the uptake of reservoir simulation and optimisation software for several reasons. The region is relatively water stressed, having the 63rd smallest renewable water resources per capita worldwide (FAO, 2008), mainly because of high population density, particularly in the South-East of England. Importantly, water companies are private, so they should seek to maximise efficiency and profitability, but their water management decisions are open to scrutiny by the public and they must be approved by the regulator (the UK Environment Agency). Specifically, every 5 years each company must prepare a "water resource management plan", which appraise options for closing the demand-supply balance over the next 25 years, and a "drought plan", which describes the management measures that will be taken in drought conditions (WaterUK, 2016). Clearly, all these planning activities may benefit from the adoption of state-of-art modelling tools to increase both efficiency and transparency. Furthermore, companies have a certain degree of flexibility in the operation of their reservoirs, which are often part of a wider connected water supply network (around 80% of the population receive their water from treatment works that can be supplied from multiple sources), so they could specifically benefit from using reservoir operation optimisation to design operating rules, or to define the thresholds triggering drought conditions, or even to inform real-time decisions.

Survey design

Before carrying out the survey it was important to determine a set of questions and a terminology appropriate for the target group. Therefore, we first performed two pilot interviews with water resource planners and managers in two companies, scoping the company's operational procedures and understanding the terminology in use. We then prepared a questionnaire that could be meaningfully answered by water resource managers across other companies. We selected the format of self-administered questionnaire via the internet to enable recipients to respond without time pressure and to avoid introducing 'interviewer effects' into the results, i.e. subconsciously guiding the interviewee towards certain responses (Opdenakker, 2006).

The questionnaire covered the following topics:

i) Availability and use of rule curves for the company's reservoirs' operation.

ii) Approaches to decision-making during normal and drought conditions.

iii) Use of software tools for simulation and/or optimisation of reservoir operations.

iv) Outlook on future challenges and opportunities.

We did not ask which specific optimisation algorithm was in use or under consideration (a question we originally aimed to ask) because the pilot interviews suggested that water managers did not have in-depth knowledge of different algorithms or were not clear about the use and purpose of optimisation in the first place. This led us to introduce a question in our survey to specifically investigate the respondents' view of the purposes of reservoir operation optimisation, and to formulate the other questions about optimisation tools in hypothetical terms (i.e. make them answerable even if respondents do not actually use these tools).

The questionnaire was sent to the 11 water supply companies in England and Wales that operate more than one large reservoir, and which (together with the 2 companies of the pilot interviews) collectively cover 96% of the total storage for water supply. Given that the relatively small size of the target group would not have allowed a statistical analysis of the responses, we allowed respondents to both select from multiple answers for each question or write their own answer, in order to maximise the amount of information gained through the questionnaire. We complement the survey results with further insights gained through our own experience of working with the UK water industry, and with interviews we held with consultants (3 based in the UK and 6 from other countries - Australia, South Africa, South Korea – with whom we have ongoing collaborations).

Survey results

Figures 1 and 2 report the survey results. Each column corresponds to one company (in total we received responses from 8 companies via the questionnaire, plus 2 companies via the pilot interviews, for a total coverage of 88% of England and Wales's total supply storage capacity). All respondents declare that their reservoirs have rule curves (Q1) but these rules are mostly used informally (Q2). The decision-making process in both normal (Q3) and drought (Q4) conditions uses a variety of information sources and mechanisms. It heavily relies on expert judgement (Q3b), often involving an increased number of staff during drought conditions (Q4b). Yet most respondents are also familiar with simulation software and use it for what-if analyses in normal and/or drought conditions (Q3c,Q4e). Only two respondents declared using real-time optimisation software (Q3d), however, based on their responses to a later question on the purposes of reservoir operation optimisation (Q8), we suspect these respondents may be referring here to optimisation of source-supply allocation, rather than reservoir operation optimisation as typically defined in the scientific literature (more on this later). It should also be noted that in many companies, particularly large ones, the planning department is separate from operations teams, hence our survey respondents may not have full knowledge of software used in real-time. Reasons for concern about current decision-making approaches (Q5) and perceptions of main challenges ahead are also varied (Q6), with about half of all respondents concerned about very system-specific problems such as the inadequacy of ageing infrastructure (Q6b and Q6c) and the introduction of more stringent regulations (Q6d and Q6e).

When it comes to assessing tools in support of decision-making, we find that respondents' reservations regarding simulation software are mainly about its realism (Q7). Also, as anticipated in the pilot interviews, there seems to be a certain confusion about the scope and purpose of "reservoir operation optimisation software" (Q8). Most respondents would put under this name almost any optimisation activity, instead of the more focused definition used by researchers: essentially all respondents think of reservoir optimisation as a spatial optimisation problem (i.e. optimal allocation of water volumes across a network of source-demand nodes, answer Q8b) whereas the scientific literature typically refers to the temporal optimisation problem (optimal allocation of water volumes over time, answer Q8a). A possible reason for this emphasis on the spatial allocation problem is that the software simulation tools currently in use in the UK industry, such as Aquator (Oxcisoft, 2020) and Miser (Servelec, 2020), represent simulation as a source-supply solving problem. No particular reason for the limited use of optimisation tools emerges from the survey (Q9) but about half of the respondents declared that they are evaluating it or have started to use it (Q9f).

Looking ahead, the feature of optimisation software that respondents would value most (Q10) is the ability to interact with the software and manipulate and visualize outputs (Q10d,e) – a response which is expected given the high degree of informality of the decision-making process. Last, most respondents expect reservoir operation optimisation software will be much more extensively used in the future (Q11).

Discussion and implications

Our survey results are consistent with previous studies (Brown et al. 2015; Rosenberg et al. 2017) in confirming a widespread use of simulation software but very little use of optimisation tools. This main conclusion was also confirmed by the interviewed consultants. Interestingly, the consultant who mentioned applying reservoir operation optimisation in the way most similar to the scientific literature (i.e. using a genetic algorithm to optimise rule curves) did so within a simulation experiment, where they had to mimic the behaviour of the water company (their client) under out-of-record inflow scenarios. Indeed, it was the simulation outputs, in the form of an assessment of the system's sensitivity to droughts, and not the optimised rule curves that were provided to the client.

Whereas the answers to the specific question on the applicability of operation optimisation tools (Q10) do not shed much light on the reasons for its limited use, we think some interesting points indirectly emerge from the results. In the remainder of the paper, we discuss these points, complement them with comments found in the literature or made by the interviewed consultants, and we suggest possible ways forward.

Reconciling optimization with users' expertise

As highlighted by our survey, the decision-making process in reservoir operation does not rigidly follow automatic rules but involves considerations that are difficult to code into a computer model. Mathematical formulations of the decision-making problem are perceived by practitioners as too simplistic to capture the complex nuances of the real processes. As summarized by one of the interviewed consultants:

"*The human elements of our system are so enormously complex that anything as formal as optimisation is unlikely to be of benefit*".

This may help explaining the preference for simulation over optimisation tools. Answering 'what-if?' questions through simulation allows users to complement the model responses with their own system-specific knowledge, whereas answering 'what's best?' questions through optimisation leaves little space for further adjustments. Formulating the reservoir operation problem in purely quantitative (mathematical) terms, as required by optimisation tools, is particularly difficult when the system is highly integrated into a wider infrastructural and socio-economic context. As affirmed by one of the interviewed consultants:

"*We find that the rule curves we produce* [for our clients at water companies] *are either followed rigidly or not at all; we would prefer that they are incorporated with a wider understanding of the water resources system in question*"

The emphasis here is on the inability of the computer algorithm to account for complex, possibly intangible, aspects that humans would be able to consider in their decision-making. Indeed, a feature that most survey respondents identified as very important for reservoir operation optimisation software is the ability to interact with other software and allow effective visualisation and manipulation of results (Q10); presumably to facilitate the integration of model-generated information with human thinking.

Conversely, a criticism sometimes raised in the optimisation literature is that the working mechanisms of optimisation algorithms are too complex to be understood by humans, who are then reluctant to accept their results. Hence the increasing interest in developing new approaches to 'open the black-box' of optimisation and to deliver optimal operating rules in forms that are easier to understand by users (e.g. Herman and Giuliani, 2018). We believe there is an overarching issue here, that is, if optimisation is ever to be accepted and used by practitioners, it needs to be better integrated with user knowledge and expertise of the system to be optimised. This applies to both the formulation of the optimisation problem (see for example discussion in Smith et al., 2017) as well as its solution. Interestingly, new approaches for linking automatic optimisation algorithms and human knowledge, i.e. for 'putting humans in the loop', are an active area of research in machine learning (e.g. Holzinger et al., 2019). Researchers in reservoir operation optimisation may look in this direction of hybrid strategies to find new interesting avenues for future research.

Promoting a value-for-decisions approach to model evaluation

One result we found particularly interesting is the rather widespread concern about the lack of realism of current simulation models (Q7). This also resonates with comments from previous studies, e.g. Asefa (2015): "A key challenge that the applied research community needs to address is how to avoid the use of simplifying assumptions that may limit the usefulness of models/methods in a practical setting". The criticism has some merit. Research studies typically do not include detailed representations of regulations that constrain system operations, or contingent system properties (for example, recurrent misfunctioning of an ageing infrastructure) that may be known to operators – and that are often of big concern to them, according to the responses to our questions about challenges ahead (Q6). Again, this may contribute to explain practitioners' preference for simulation over optimisation tools, as the former enables users to complement model responses with their domain-specific knowledge. As pointed out by one of the interviewed consultants:

"*Optimised results are inherently optimistic due to the assumption that the system is working perfectly; this results in decisions that are overly risky*".

On the other hand, accommodating detailed aspects of system functioning could lead to developing extremely case-specific tools, which would conflict with the researchers' ambition to find general methods and principles that can be transferred across systems. Furthermore, the very idea that increasing the level of detail embedded in the model guarantees, per se, higher accuracy or value for decision-making, is debatable.

Several authors across environmental modelling domains have shown that more detailed representation of processes within a model does not necessarily imply it will provide more accurate predictions (e.g. Young et al., 1996, Beven et al., 2015). Moreover, analyses of the input-output relationship in environmental models consistently shows that spatially and/or temporally aggregated output metrics are typically controlled by a very small number of inputs (Wagener and Pianosi, 2019). This finding implies that, if practitioners only focus on few summary metrics (or "performance indicators", e.g. Groves et al. 2015) to inform their decisions (as they often must do, in search for synthesis), then the model components or parameters that actually control those metrics may be quite limited. Hence, most enhancements or additions to the model might actually make little difference to their decisions. The case for using simple models has been repeatedly made over time, also in the WRSA context, e.g. by Ford (2006) and Doherty (2011), who nicely summarised: "Unfortunately our industry fosters a culture that makes it too easy to discredit a model that does not resemble a picture from a geological textbook, and too hard to accept one that entails incisive abstraction". Clearly the discussion is still ongoing and far from being settled. Last, in a decision-making oriented context, one should remember that prediction accuracy and value for decision-making do not necessarily coincide. The fact that model predictions are erroneous does not necessarily imply that they carry no value for informing decisions, particularly if the possible extent of those errors, i.e. the 'output uncertainty', is explicitly recognised. Several studies have indeed shown that when optimization takes into account uncertainty in model predictions, it can largely compensate for their inaccuracy (e.g. Ficchì et al. (2016)).

In summary, we believe that we should promote a culture where prediction accuracy and value-for-decisions of simulation and optimisation models is explicitly assessed and scrutinized, instead of being assumed as a consequence of increasing model fidelity to the system (i.e. model complexity). To this end, researchers should keep developing new tools for quantifying, visualising and communicating output uncertainty and its impact on model-informed decisions. Several studies have started scrutinizing optimization results and their robustness to uncertain assumptions in the problem formulation, such as the stationarity of future hydrological conditions (Herman et al., 2016), the definition of system performance metrics (Quinn et al., 2017) or the delineation of the system boundaries (Dobson et al., 2019b). Making uncertainty quantification approaches easier to use, and demonstrating their benefits in real-world applications, will hopefully help practitioners to evaluate model adequacy more coherently with their goals (i.e. to inform decisions), while also contributing to increase trust in simulation and optimisation models.

Considering implementation as part of methods development

Another issue that somehow runs through our survey responses and interviews is the cost of taking up new and more sophisticate approaches, which requires additional training and expertise. A similar point was raised before by Asefa (2015) ("From a utilities perspective, these tools require a commitment to in-house expertise and computing resources."). The problem is only exacerbated in the context of a highly regulated industry, where new methods need to be understood and accepted not only by their direct users but also by the regulators. As one of the survey respondents commented in responding to question Q9:

[*reservoir operation optimisation tools will be applicable to our system...*] "*if regulators approve of the methods and lots of other water companies use them*"

The point is echoed by one of the interviewed consultants, who said:

"*Changing the way things are done means attracting a lot of attention and scrutiny by regulators*".

These problems are typically overlooked by researchers, who tend to evaluate models and methods only based on the improvements they yield, with little consideration of how difficult these new methods will be to understand and to implement by practitioners. As pointed out by Kasprzyk et al. (2018) "Because WRSA is so focused on problem solving methods, it is easy for researchers especially to get distracted from monitoring results, ignoring how the recipients of information react, or how new techniques compare to the needs and capabilities of practitioners".

Responding to this challenge is not easy. More interaction between higher education and practice in WRSA is certainly key, and was advocated already in this journal e.g. by Rosenberg et al. (2017). While that paper focused on the US and Asia, similar discussion would certainly be useful in other regions, including the UK. On the other hand, researchers may also give more consideration to implementation issues when proposing and evaluating new methods. For example, they could develop evaluation metrics that capture performance improvement – how much does a new method improve the system operation with respect to benchmark approaches – relative to the cost and difficulty of their implementation, instead of focusing on absolute improvements only. Also, researchers could do more towards publishing open source implementations of their methods – something that is still often missing in computational hydrology, hence limiting the transparency and credibility of newly proposed approaches (see e.g. discussion in Hutton et al. (2016)) and their uptake by practitioners. Analysing the challenges of implementation and execution of new approaches (e.g. as done in Turner et al. (2016) for the introduction of 'risk-based approaches' to water resource planning in England and Wales) would not only be helpful to bridge the gap with practice but could also lead to identifying new interesting directions for further method development – as the examples discussed in the previous paragraphs show.

Conclusions

Our survey and interviews of practitioners in England and Wales echo previous findings of the few surveys and commentary papers on the topic, that is, we see a growing uptake of simulation models by water resource managers but a very limited uptake of optimisation tools. The reasons for this difference include a limited understanding of the benefits and scope of optimisation software, including a perception that adopting excessively complex methodologies may generate practical problems that do not compensate for the benefits; a lack of trust into the realism of models that lead to discarding optimisation results; and a prevalence of informal decision-making approaches that do not align well with the very essence of optimisation. Interestingly, our study also revealed many commonalities between problems identified by practitioners and issues that are currently debated by the scientific community – for instance on how we evaluate model adequacy, on how to increase the transparency and reproducibility of modelling tools, and how to integrate automatic optimisation with human knowledge. We would thus conclude that 'there is still hope' for reservoir operation optimisation to be used by practitioners: looking at ways to achieve that may not only make our research efforts more relevant for society but also bring interesting new questions for future research.

Data Availability Statement

All data, models, and code generated or used during the study appear in this article.

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Figure and Tables

Figure 1 – responses to questions 1-6 of our survey from the 10 interviewed water resource managers across England and Wales.

Q1. Do you have **rule curves** for your reservoirs?										
a) Yes	x	x	x	x	x	x	x	x	x	x
b) No										
Q2. How do you follow these rule curves?										
a) We follow them rigidly	x									
b) We informally incorporate them in our decision-making		x	x	x	x	x	x	x	x	x
Q3. **How do you make** abstraction and release **decisions** in normal conditions? (*multiple answers allowed*)										
a) Following rule curves	x	x	x	x	x	x	x	x	x	x
b) Using real-time calculations and experience	x	x	x	x	x	x	x		x	
c) Using software simulation, adjustment and iteration		x	x	x			x	x	x	
d) Using real-time optimisation software			x				x			
Q4. How do you decide which drought measures to enact in drought conditions? (*multiple answers allowed*)										
a) Following drought plan to the best of our ability	x	x	x		x	x	x	x	x	x
b) Involving more staff in the decision-making process			x	x	x		x		x	
c) Following rule curves	x	x	x	x	x		x	x	x	
d) Using real-time calculations and experience	x	x	x	x			x	x	x	
e) Using software simulation, adjustment and iteration	x		x				x	x	x	
f) Using real-time optimisation software										
Q5. What **reservations** do you have about the current decision-making approach? (*multiple answers allowed*)										
a) It leads to decisions that are overly conservative					x					x
b) It leads to decisions that are overly risky				x						
c) It consumes too much time/resources	x									
d) It makes knowledge transfer within the company difficult		x				x				
e) It lacks transparency to those outside of the company										
f) No reservations			x				x	x	x	
Q6. What do you expect to be the **biggest challenge** to continue meeting demand over the next 10 years?										
a) Climate and hydrological change	x				x					
b) Insufficient and ageing infrastructure				x			x			x
c) Extreme events causing simultaneous failures						x			x	
d) Tightening legal requirements on water quality		x	x					x		
e) Tightening legal requirements on abstractions		x	x					x		
f) Lack of staff with required skills										

Figure 2 – responses to questions 7-11 of our survey from the 10 interviewed water resource managers across England and Wales.

Q7. What are your views on water resource systems **simulation software**? (*multiple answers allowed*)										
a) It fits its purpose		x	x				x		x	
b) It is not a sufficiently realistic representation of the system	x	x		x					x	x
c) It takes too long to run										
d) It is not easy to use (e.g. interface is unclear)	x							x		
e) *No views – we currently do not use simulation software*					x	x				
Q8. Regardless of whether you use it or not, how would you describe the **purpose(s) of operation optimisation** tools? (*multiple answers allowed*)										
a) To create rule curves	x	x		x			x	x		
b) To determine the source to abstract from at given moment	x	x	x	x		x	x	x	x	
c) To set trigger levels at which drought measures are taken		x	x	x			x	x	x	x
d) To find the most effective combination of drought measures	x	x	x	x			x	x	x	x
e) Other					÷					
Q9. **How applicable** are operation optimisation tools to your water supply system?										
a) We would use them but do not have the computing resources										
b) We don't need them because our system is not so stressed				x				x		
c) We would use them but lack the expertise to do it										
d) We don't use them because their solutions are not good enough										
e) We use them already!		x	x						x	
f) Other	@	@			@	@				@
Q10. Which **features of operation optimisation software** would be important for you to consider/increase its use in your practice? (*multiple answers allowed*)										
a) Availability and friendliness of the graphical user interface			x	x				x	x	
b) Access to source code			x					x		x
c) Affordable price	x		x							x
d) Ability to interact with other software			x	x		x			x	x
e) Availability of tools for results visualisation and manipulation	x	x	x	x	x			x	x	
Q11. How many UK water companies would you expect to **use operation optimisation software in the next 10 years**?										
a) 0-20%										
b) 21-40%										
c) 41-60%					x			x		
d) 61-80%		x								
e) 81-100%	x		x	x		x	x		x	x

Notes:
(÷) Specification of "Other" response to Q8:
"*Investment planning and development of operational strategies*"

(@) Specification of "Other" response to Q9:
"*We are assessing packages at the moment*" (3 respondents)
"*If regulators approve of the methods and lots of other water companies use them*" (1 respondent)