Power to the programmer: Modeller's perspective on automating the setup of hydrodynamic models for Dutch water authorities

Janneke O.E. Remmers[1], Adriaan J. Teuling[1], Ruben J. Dahm[2], Arthur van Dam[3], and Lieke A. Melsen[1]

[1] Hydrology and Environmental Hydraulics Group, Wageningen University, Wageningen, The Netherlands
[2] Department of Catchment and Urban Hydrology, Deltares, Delft, The Netherlands
[3] Deltares Software Centre, Deltares, Delft, The Netherlands

Abstract

Use of models in decision making, for example in water management, requires confidence in the model and its outputs. Since choices in model setup affect model output, this confidence is affected by the modellers' professional judgement. Computer programmers can use their expertise in coding to standardise some of the tasks associated with computational modelling. Therefore, centralized automation has the potential to ensure quality of modelling decisions. Since it is the modeller that makes the choices in the model set-up, it is important to understand how modellers perceive automation. To explore their perspectives, we conducted fourteen interviews with modellers at water authorities and consulting companies in the Netherlands. The transcripts were analysed through deductive and inductive content analysis. Our study reveals that automated modelling processes can improve efficiency, transparency and consistency, but only if certain requirements are met, such as good documentation, clear ownership, adequate maintenance, and frequent evaluation. Therefore, managing the risks and benefits of automation requires balancing the power between modellers and programmers.

Keywords

Automation, Hydrodynamic Modelling, Modeller's Perspective, Interviews, Standardisation

1. Introduction

Computational models are increasingly used in many diverse disciplines, including climatology (Deser et al., 2012; Eyring et al., 2019; Knutti et al., 2013), epidemiology (Amorim and Cai, 2015; Garner et al., 2011), hydrology (Addor and Melsen, 2019; Mai et al., 2022), and ecology (Schmolke et al., 2010; Yates et al., 2018). Within these disciplines, models are used in a wide range of applications, including forecasting, reanalysis, scenario and sensitivity analysis, and building understanding. Besides their academic use, model results also support decision making about future management plans, or prescribing actions during extreme events, such as bush fires, hurricanes or floods (Bremer et al., 2020; Davies, 2012). The decisions informed by models can have major effects on people, increasing or decreasing the risk of damages or loss of life, for example for residents of bush fire-prone areas (Sharples et al., 2016). Therefore, it is important that people have confidence in the model and the outputs that serve as the basis for decision making.

Modellers (in this paper, defined as the subject-matter experts in representing the system being modelled using numerical relationships) influence the modelling process through the decisions they make in setting up the

Correspondence:
Contact J.O.E. Remmers at janneke.remmers@wur.nl or L.A. Melsen at lieke.melsen@wur.nl

Cite this article as:
Remmers, J.O.E., Teuling, A.J., Dahm, R.J., van Dam, A., & Melsen, L.A.
Power to the programmer: Modeller's perspective on automating the setup of hydrodynamic models for Dutch water authorities
Socio-Environmental Systems Modelling, vol. 6, 18657, 2023, doi:10.18174/sesmo.18657

Socio-Environmental Systems Modelling
An Open-Access Scholarly Journal
http://www.sesmo.org

model. Their influence includes questions of value, matters of fact, ease of use and uncertainty (Babel et al., 2019; Lim et al., 2023; Melsen, 2022; Voinov et al., 2018). We refer to modelling decisions as the choices made throughout the modelling process by the modeller, including: how and which processes are represented, how data are used and how the validation is executed (Figure 1). Examples of specific decisions made are the parameter value of the levee height or model boundary and resolution choices, such as the grid size. With each modelling decision made, a path is created behind each model result (Glynn et al., 2017; Lahtinen et al., 2017; Melsen, 2022; Moallemi et al., 2020; Polhill & Edmonds, 2007), meaning that it is crucial to consider how and in which context the model is used.

Technologies, including models, contribute to shaping the context and modelling decisions made (Verbeek, 2008; Latour, 1990; Melsen et al., 2018). Take this example: a choice in a model was hardcoded by a colleague years ago. Another modeller uses this model later and subsequently relies on the method implemented by their colleague. This influences their future options within the modelling process, for example, by having constraints on the spatial resolution they can choose. Conceptual representations and particularly software suites are created for specific purposes, meaning that care must be exercised when models are use in new domains or for new purposes. (Hamilton et al., 2022; Beven, 2000). As such, which model is chosen and how it is used by the modeller is important.

The responsibility that comes with the use of models consists of setting up models based on several key principles: appropriateness and transferability, reproducibility, and transparency (Crout et al., 2008; Zurell et al., 2020). Appropriateness and transferability refer to the potential of a model to function well in novel situations. This is directly linked to the purpose of the model: often models have better transferability only within a specific purpose for which they were created. Therefore, it is important to delineate and communicate the model's purpose (Werkowska et al., 2017). Reproducibility refers to the capacity for another person, team or organisation to redo the modelling done by someone else (Gundersen, 2021; Schwarz et al., 2020) without leading to unforeseen or unsolvable errors or differences, and ideally, resulting in identical model outputs. Transparency refers to the interpretability and understandability of the modelling process, including but not limited to communication of assumptions, uncertainties, and motivations underlying modelling decisions. Transparent modelling reveals the path behind the modelling results, which involves values and biases. The implementation of these principles in modelling for decision making contribute to justifying model results and their trustworthiness (Wang et al., 2023). For the practical implementation of these principles, different approaches can be used.

Standardisation is one approach to justify the model setup and use (Jakeman et al., 2006). Standardisation, in a general sense, aims to create a process or product of similar quality and with the same features in a similar way. For modelling, this translates to frameworks or guidelines for the execution of repeated steps within the modelling process. Standardisation can streamline the modelling process, increasing efficiency, reproducibility and transparency (Howard & Björk, 2008; Müller et al., 2014; Schmolke et al., 2010). It can also create consistency between modelling studies (Müller et al., 2014; Vrontis, 2003). This facilitates the possibilities for model evaluation through intercomparison. However, standardisation also decreases flexibility, for example, by preventing a model's capacity to capture regional differences. By definition standardisation depends on the acceptance of a single perspective on how a system should be represented, which could lead to path dependence (Wears, 2015). Standardisation can also result in reduced innovation (Mir & Casadesús, 2011). How the standardisation is implemented affects how and which advantages and disadvantages will surface. Furthermore, the standardisation's implementation and the model purpose influence whether the advantages outweigh the disadvantages of standardisation.

The implementation of standardisation can vary widely, ranging from voluntary methods to more prescriptive methods. An example of a voluntary method is the creation and use of guidelines, such as the 'Good Modelling Practice' handbook in the Netherlands (van Waveren et al., 1999), the Australian Groundwater Modelling Guidelines (Barnett et al., 2012) or the Traffic Modelling Guidelines for the UK (Beeston et al., 2021). More restrictive methods include incorporating modelling requirements into law (Fan et al., 2018) or issuing certifications for adhering to certain practices (Balci, 2001; Sampaio et al., 2011). Any of these standardisation methods might include the automation of the modelling procedure.

Automation is a broad term that can be defined in multiple ways. Because we are particularly interested in the execution of computational models, in this study, we define automation of the modelling process as the replacement of manual modelling decisions with a computer programming script that executes those decisions without human intervention. Automation in this sense is frequently used in the pre-processing of data and in calibration procedures. If programmed well, automation decreases the chance of human error. Automation also increases modellers' efficiency, by reducing their cognitive load (Lewis et al., 2018).

Automation introduces a paradox. Initially, because automation requires explicit representation through computer scripting, transparency of the modelling process may be increased—the steps being automated need to be made explicit, and rationales for the automation need to be made clear to programmers. Yet, over time, automation can also obfuscate the underlying processes if certain requirements, such as documentation of the automation procedure, are not met. Also, automation removes decision power from the modellers, shifting this power to the person or group that develops the automation script – i.e. 'the programmer' (note that one person can embody both roles at different moments in time). Even though automation is always a form of standardisation, we refer to standardisation as a way for decision makers to control the quality of modelling studies, and their underlying modelling decisions. Since modellers are subject matter experts that make the modelling decisions and shape the model results, it is important to understand how they perceive the trade-offs between potential efficiency and transparency gains and shifts in power that may be associated with the act of automation. Figure 1 depicts stages of the modelling process that might include automation that we will examine in this paper (all steps except 'Select software').

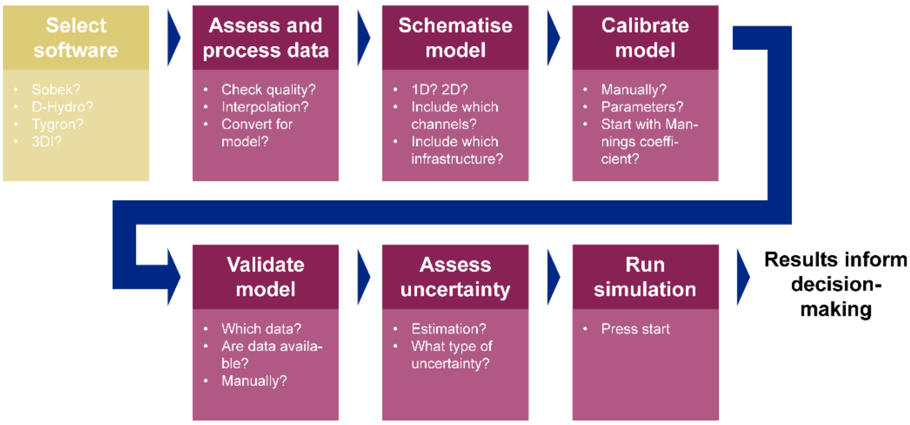

Figure 1: Simplified representation of the modelling process. Each rectangle is a modelling step, in which multiple modelling decisions can be made. Below each step, we mention some examples of modelling decisions that the modellers that we interviewed encounter in their modelling work. Automation of the modelling process refers in our study to all step except 'Select software', because this step was often not in the sphere of influence of the interviewed modellers. After the simulation is run, the results are used to inform decision making by the decision maker, which is often another person than the modellers themselves. This last aspect is not part of this study. This representation of modelling steps is based on Figure 1 in Refsgaard et al. (2007).

In this study, we explore modellers' perceptions on automation with a case study of decision-support hydrodynamic modelling in the Netherlands. We conducted fourteen interviews with modellers working at Dutch water authorities or consulting companies that participated in a project including automation of modelling decisions.

2. Methods

2.1. Case Study

In the Netherlands, decision-support modelling for water management is predominantly executed by the national and local water authorities and consulting companies. Surface water modelling includes: flood and drought simulations, infrastructure design, and water system operation and water quality analyses. The Netherlands has 21 local water authorities, which are responsible for water management in their area (Government of the Netherlands, SA). The government agency Rijkswaterstaat functions at the national level (Government of the Netherlands, SA). In the 1950s and 60s, Rijkswaterstaat and the water authorities had considerable in-house knowledge. They were able to develop model software and execute all modelling steps themselves. However, the structure and focus of Rijkswaterstaat and the water authorities has changed, beginning in the 1970s, shifting from in-house model use and development to greater reliance on external consulting companies and research institutes to conduct more aspects of the modelling process (Vukovic, 2022; van den Berg & van Lieshout, 2022). In recent years, a reversal of this trend is visible: local water authorities are now trying to regain more in-house knowledge.

There are numerous consulting companies that support the water authorities in the Netherlands. This support can range from implementing the whole modelling process for the water authorities, to providing training to water authorities to set-up and execute models themselves. Applied research institutes, such as Deltares, co-develop new model software with other parties. Research institutes focus on the knowledge-intensive components of the software. They also maintain and monitor the quality of these software suites and advance the modelling processes for a variety of physical domains. Figure 2 demonstrates a common distribution of tasks between water authorities and consulting companies based on the interviews for this study. In this study, we focus on automation developed and used by local water authorities and consulting companies.

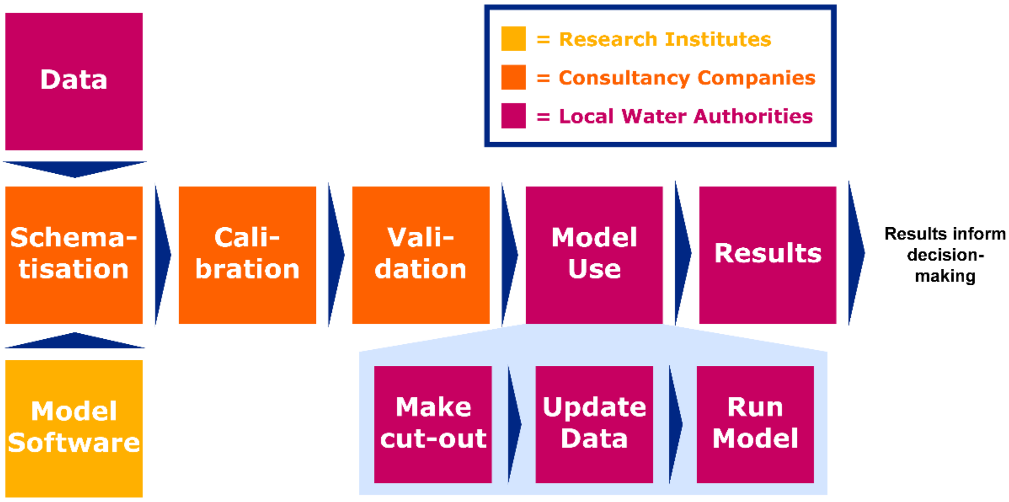

Figure 2: Representation of a general modelling process for decision-support in managing the Dutch river systems. It depicts the frequently observed roles in Dutch water management. Local water authorities, consulting companies and research institutes execute different modelling steps. In this study, we focus on the local water authorities and consulting companies, because our interviewees, at the time, worked at either one of these organisations. The process might look different depending on context and vision of the organisations involved. Furthermore, the process often involves an iterative procedure (not indicated for clarity).

Over the last decades, most water authorities used the same model software for rainfall-runoff processes, 1D open and closed hydrodynamics and 2D overland flow: SOBEK (Deltares, 2023d; Stelling & Duinmeijer, 2003). Automation scripts to set up and use SOBEK already existed locally and were partly incorporated in the model software. A new modelling suite, D-HYDRO Suite 1D2D (Deltares, 2023a), was developed, eventually leading to the discontinuation of updates of SOBEK. This instigated the transition to D-HYDRO for many of the water authorities. An important development in tandem is the HyDAMO dataframework, a shared data structure for the water authorities (Nederlands Hydrologisch Instrumentarium, SA). The switch to D-HYDRO is accompanied with an effort to centralise and uniformise already existing automation scripts scattered around different companies and organisations to facilitate the modelling process and stimulate the transition to D-HYDRO.

Centralising and extending the existing automation scripts was the goal of the HYDROLIB project, led by Deltares (Deltares, 2023b). This project was funded by a public-private partnership, which grants funding to consortia focusing on obtaining knowledge and innovation (a so-called TKI-project). Within this project, automation scripts from participating organisations are adapted for general usage and new scripts are developed and stored in a central public library (see Deltares, 2023c). These automation scripts tackle different aspects of pre- and post-processing in the modelling process. The project also consisted of testing the scripts, mainly done by water authorities, and organising workshops for modellers to familiarise themselves with the automation scripts.

These workshops were co-organised by the organisations that developed the automation scripts (the consulting companies and Deltares). The project ran for two years and finished in 2022.

The project results were picked up further in 2023, when the organisation behind the Netherlands Hydrological Instrument – a collection of data sets, model codes, tools and models to describe and simulate the full hydrological cycle in the Netherlands – organised HYDROLIB community meetings and joint script-developing working days. Additional functionality was added by several of the partners. The Netherlands Hydrological Instrument organisation has also commissioned 'review' training, where colleagues from different organisations will gain the knowledge to review additions or changes to automation scripts. Model code contributions require review before being added to the HYDROLIB code repository with the aim to assure quality standards. Hydrodynamic model generation for international applications is being implemented in 2023, building upon the general framework of HydroMT for automated and reproducible model building and analysis (Eilander et al., 2023).

Even though the results are obtained for a case study within a specific water governance system, we believe the insights are transferable to other contexts where multiple parties are involved with decision-support modelling, e.g. through outsourcing.

2.2 Interviewee selection and interviews

To explore the Dutch modeller's perspective on automation, we conducted interviews with modellers at the water authorities and consulting companies that participated in the HYDROLIB project. The interviewees were selected through convenience and snowball sampling. Although not an uncommon approach, it could influence the representativeness of the sample. We checked this by evaluating the differences between the interviewees working at the same water authority or consulting company and by evaluating the saturation of coding. Saturation of coding is the point at which no new codes are added during the inductive content analysis (Hennink et al., 2017). In our study, we barely added any new codes in the final interviews. Most of the interviewees participated in the HYDROLIB project and might, therefore, be at the forefront of taking up new developments in modelling – or at least they are open to that. Therefore, we expect that they have a more positive outlook on automation than other modellers might have, which might bias our sample.

At the time, nine interviewees worked at six different water authorities and five interviewees at four different consulting companies. All interviewees are hydrodynamic modellers, but their post-graduation work experience level varied between one and fifteen years. All interviewees model for flood applications. Aside from being a modeller, five of the interviewees have an advisory role in their function and four also have a role as programmer.

The fourteen semi-structured interviews were conducted between September and December 2021. All were held in Dutch, except one, which was in English. All interviews lasted between 1 hour 15 minutes and 2 hours. The interviews consisted of questions regarding automation in the modelling process, e.g. its current state, the possibilities, and the modeller's perspective on it. The interview guide is included in Supplementary Material A. The questions relevant to this study are highlighted. The interviews were all recorded and transcribed.

2.3 Theoretical background

Part of our content analysis was based on the issues and best practices of automation derived from literature by Pagano et al. (2016). They described three issues and seven best practices for automation. They obtained their findings from other disciplines, such as meteorology, but apply these to automation in hydrology.

The three issues identified by Pagano et al. (2016) are: changes in the modelling process, in people's behaviour, and in the perception of the model's trustworthiness. First, modelling processes change due to automation, which may require the modeller to assume a different role or execute tasks not part of their expertise. Commonly, the first aspects that are automated are the most-easily automated tasks, such as data preparation. At some point, this leaves tasks that may not suit the modeller's expertise, which were previously done by someone else or not at all. Secondly, automation changes people's behaviour. Automation transfers the source of human error from the modeller to the programmer of the automation script. For example, inconsistent assumptions can be recorded in an automation script by the programmer. This transfer of errors can influence what a modeller communicates. For example, when the automatic system does not indicate that a warning should be issued, but the modeller estimates differently, what should the modeller communicate? If the modeller does issue a warning, they might have less ground to stand on depending on the operational protocol. Thirdly, the perception of the trustworthiness of a model might not be accurate, e.g. due to a persistent first impression that is no longer valid. A modeller can perpetuate this first impression by recommending or dissuading the use of certain automation scripts. The issues with automation that were identified by Pagano et al. (2016) present themselves at different moments in the automation process. Since the case study we explore started recently, some issues cannot yet be observed.

Besides the three issues described by Pagano et al. (2016), they also derived seven best practices from meteorology. We focus on five of the seven best practices, because these centre on the link between modeller and automation. The other two best practices, ‘Use automation to quality-control and ingest data’ and ‘Use well-designed forecasting interfaces’, cover which aspects are most suitable to automate and how the automation should be designed, not the interaction between the modeller and the automation procedure. The five best practices we explore in this study that Pagano et al. (2016) suggest for the modeller are:

- **Have transparent systems** – A modeller should be able to retrace the different steps done by the automation procedure, such as intermediate results.
- **No peeking at the answer** – A modeller should give an estimation of the expected outcome before analysing the automated output. This creates better understanding of the results and makes the modeller more critical of the results from the automation.
- **Evaluate your results** – Evaluation of the automated output is crucial for improving the automation procedure itself. This should be done in a constructive and structured manner.
- **Never stop learning the science** – A modeller must keep learning the underlying science behind the modelling. This expertise will help the modeller in evaluating the automated results. This cannot be learned from modelling itself.
- **Redefine your role** – The role of the modeller might have to be redefined. As the modelling process will become less time consuming for the modeller due to automation, this might give the modeller more time for other tasks. However, this requires a different expertise, which might lead to the modeller being more removed from the modelling itself. This can reduce the modeller’s ability to interpret and understand the results.

2.4 Content Analysis

The transcripts were analysed in ATLAS.ti, version 9 (ATLAS.ti Scientific Software Development GmbH, 2022), through deductive and inductive content analysis.

The deductive content analysis was based on the issues and best practices described by Pagano et al. (2016) (Supplementary Material B.1). Each issue and best practice was subdivided into several interview codes, resulting in 18 predetermined interview codes. This was directly based on the text in Pagano et al. (2016). For example, the best practice ‘Evaluate your results’ was subdivided in the interview codes: ‘Evaluation’, ‘Evaluation decrease’ and ‘Evaluation increase’. ‘Evaluation’ covers anything that is related to evaluation of the scripts. The other two relate to how the evaluation develops over time. ‘Evaluation increase’ meaning more in-depth evaluation over time and ‘Evaluation decrease’ less.

To supplement the predetermined codes of the deductive analysis an additional set of interview codes (see Supplementary Material B.2) were developed through grounded theory in a first round of coding. These interview codes were divided over seven code groups, indicated in the Supplementary Material (column ‘Group’). We were not able to group all codes, so seven codes were added to the ‘Miscellaneous’ group.

3. Results and Discussion

First, we describe the findings related to the different levels of automation development and uniform use (results of inductive analysis). Second, we relate the results to the theoretical framework of Pagano et al. (2016) (results of the deductive content analysis). Finally, we discuss the different roles of water authorities and consulting companies and how this influences automation perception (results of inductive content analysis).

3.1 Social levels of automation practice as standardisation procedure

The HYDROLIB project is about gathering and centralising automation scripts. The uniform application of these scripts contributes to increasing standardisation at the (inter-)organisational automation level. As such, this standardisation not only serves the purpose of increased efficiency for the modeller, but also as a way of quality assurance for decision makers (provided that certain implementation requirements are met - as will be discussed in this section).

The social levels of automation practice, presented in this section, are not necessarily directly related to the quality of the automation, but the scale is relevant to evaluate the usefulness of automation as a standardisation procedure. We will refer to these social levels of automation practice as automation levels. From the interviews it became clear that automation scripts already exist at several 'automation levels'. Based on that, we identified four levels at which automation is uniformly applied: Individual, Team, Organisational and Inter-organisational.

Individual – Any modeller will write an automation script at a given moment to create a more efficient and consistent workflow for themselves. This is often done for repetitive tasks that are cumbersome to execute manually and easy to automate. The scripts are built quickly, often having little to no documentation. For example, one respondent described their process as existing *"only on ad hoc basis at the moment that someone needs data for a part of the area. That would be executed with Excel-files that only the person who worked with it would understand"*. The modeller is responsible for the development and implementation of their own scripts. Different modellers can create similar scripts, resulting in overlapping tools and inefficiency from the organisation's perspective. Another interviewee said it is sometimes more efficient to create your own script than to ask around if someone already has a script and figuring out how that script works. Here, the interviewee showed how a modeller considers the effort both options would take to make the choice to develop their own script. Of course, this would only be possible if a modeller has the capacity and knowledge to develop a new script. Evaluation happens ad hoc. At this level, the generalisable lesson learned is that automation as standardisation creates more efficiency for the individual modeller, but not necessarily more transparency and reproducibility between modellers in the modelling process, nor quality assurance for the decision makers. There is, however, a high level of agency for the individual modeller, flexibility to adapt the procedure, and different approaches to the same task can provide insights in uncertainty introduced by choosing a particular method.

Team – Within a team, automation scripts can be created for common use. At this level, each individual maintains a degree of agency – the capacity to make their own decisions and be responsible for them. The scripts are developed and evaluated organically. Whenever a bug or a potential improvement is encountered, the script is adapted. The script often originates at the individual level, but has been proven to be useful for more than just one individual. Scripts are often used multiple times or as starting point for a specific application. Similarly to the individual level, evaluation happens impromptu and documentation is added only if necessary, but asking colleagues for help or explanation is easy. So in general, on the team level, standardisation in the form of automation results in more efficiency and collaboration between colleagues. However, this standardisation does not automatically result in more transparency as colleagues can easily ask each other for needed explanations instead of writing documentation.

Organisational – At the organisational level, scripts are required to be more generalised for internal use. Documentation is often added. In one example, an organisation established a monthly hackathon, in which an individual or team script was generalised for everyone to use. Such a hackathon or some other (formalised) approach or initiative is necessary to move a script from the Individual to the Organisational level. The organisation benefits because it can streamline its overall modelling and automation efforts. However, organisations can also encounter variation in approaches and the challenge of inter-operability between departments. This raises the question which method should be used and if an organisation-wide script is feasible and desirable. This is dependent on how this process is set up and how everyone is included in it. One approach raised by interviewees was that organisations established new processes for script development, for example the hackathon in the interviewee's organisations. This also raises issues about how evaluation of scripts would be handled. The evaluation of the automation scripts was dependent on how the scripts were developed and the vision and resources of the programmers. If scripts are developed for a commercial purpose, i.e. delivering a paid service to others, the organisation will have a financial incentive to maintain them, at least as long as the service is required. If the scripts are open-source, there is still the incentive to provide a good service, but the evaluation might also be partly the user's responsibility subject to the programmer's vision. For instance, Mer et al. (2020) recognise that in open-source modelling the documentation might become more fragmented due to the user's own responsibility. As such, it will partially depend on how willing and able individual modellers are in contributing to the evaluation and further development of a script. In summary, efficiency does increase in general with automation at the organisational level and there is potential for more transparency and reproducibility on this automation level. If automation is implemented properly with attention to maintenance, evaluation, and documentation, this potential can be realised and contribute to standardisation and to quality assurance for decision makers.

Inter-organisational – Sometimes, different organisations each bring their own modelling culture, methods and scripts to coordinate inter-organisational automation efforts, such as HYDROLIB. In this circumstance, each organisation has to be open to a certain flexibility in their way of working, relinquishing some of their agency. Organisations involved in an inter-organisational initiative have to relay the outcomes of collaboration to their own modellers and programmers. These new or adapted tools might be in contradiction with what modellers are familiar with, meaning that the modellers might need time and incentive to adopt it. Bringing together these different scripts presents distinct challenges. For example, one interviewee stated, *"[when] steering towards automation, ... the Waterschaphuis [Dutch governmental institution assisting all water authorities] [is] run[ing] into these problems, [for example,] within a water authority, [there] are problems of data formatting not align[ing] with what the hydrologist wants"*. The organiser of this effort also has to ensure that the automation is interoperable. This pertains to among others operating systems, programming languages, data sharing, and computer capacity to run the scripts. The generalisable lesson learned is that automation at the inter-organisational level does motivate to uniformise data, enhancing the ease of data implementation and sharing. As such, automation a means of standardisation at this level can contribute to quality assurance for the decision maker through improved transparency, reproducibility and consistency. However, this does require the automation script to have, among others, documentation and an evaluation plan.

Figure 3 summarises the effects of standardisation across the different social levels of automation that emerged from our interviews.

Figure 3: Depiction of change in the effects of standardisation when scripts move between levels at which automation is uniformly applied. Standardisation in this instance refers to ensuring quality assurance. These changes in effects of standardisation are from the (inter-)organisational perspective. On the side the requirements for standardisation are shown in order to achieve the effects.

As automation scripts are developed further, progressing from Individual to Inter-organisational level, the modelling process is slowly standardised to ensure quality for decision makers due to more reproducible and transparent modelling. This does necessitate among others documentation, evaluation, determined ownership and maintenance of the automation scripts. If these requirements are not met, the automation, as a standardisation method for quality assurance, loses its value. For example, centralised scripts from the (Inter-)organisational level can also be further developed at the Individual or Team level without feeding this back to the (Inter-)organisational level. This leads to decreased standardisation from an (inter-)organisational perspective. Additionally, automation at the (Inter-)organisational level may decrease insight into uncertainty because it suppresses different methodological choices, and the freedom of the modeller to make choices. Therefore, modellers should maintain a good understanding of the hydrological system and the automation choices for the interpretation and evaluation of the results (Pagano et al., 2016; Woods & Sarter, 2000).

3.2 Results based on Pagano's theoretical framework

Based on the interview codes informed by Pagano et al. (2016), two common topics were identified when analysing the interviews: 1) what is automated, and 2) appreciated practices by modellers.

What is automated? – At the time of the interviews, mainly less complex components of the modelling process are automated within the Dutch hydrological community, at the individual, team and sometimes organisational level. The execution of modelling decisions (i.e. the choices made throughout the modelling process by the modeller) is automated, not yet the actual choices themselves. For example, the data importation into the model is automated, but which data and how is still determined by the modeller themselves. As such, the transfer of modelling decisions to the automation script does not occur frequently, according to the interviewed modellers. Still, the modellers are aware of giving power to the programmer when modelling decisions are automated beyond the individual level for purposes of standardisation. The modeller loses insight into the modelling decisions made by the programmer, which would also increase the difficulty to question and examine the assumptions behind the modelling results. Because of the loss of insight, modellers are hesitant to adopt automation at the (Inter-)organisational level, because they have to relinquish their own modelling decision power. For example, one interviewee stated, *"I, myself, would like to keep influence on that. But there will undoubtedly also be many people that just say 'Yes, it can be automated'. I want to know to some extent what the consequences are of the modelling decisions."* Programmers, on the other hand, will receive more agency. The trade-off in agency affects how automation is perceived and illustrates the potential reduction in the modeller's responsibility as a consequence of increased automation (Limerick et al., 2014).

Convenience and efficiency are important factors to consider in Organisational or Inter-organisational level automation, even though this might lead to less transparency. For example, an interviewee stated, *"For ease of use, I would say yes, but I do think that you lose insight into certain [modelling] decisions."* Decreased transparency can also result in a lower degree of interoperability of the automation scripts, especially if the effort is not made to understand the metadata. Multiple interviewees indicated that they would not read texts of tens or hundreds of pages long.

Besides a general loss of insight into the process, the loss of insight might vary per modeller, because each modeller has their own expertise with which they can understand and use the automation scripts. The sense of loss of understanding may also depend on the purpose of the modelling study, the resources available and the experience of the modeller themselves.

Appreciated practices by modellers – The interviewees mentioned several practices they would appreciate and which would enhance the use and acceptance of centralised automation. Firstly, transparency of the automation system is key, just as Pagano et al. (2016) mention in their best practices. This would also increase the ability to gain insight into the assumptions behind the automation. Transparency could be facilitated in many ways. One possibility mentioned by an interviewee would be to create an automatic log file of all the modelling decisions made with the automation. However, the log file is created at the end, which might not be used or read by the modeller. This renders the log file to be a silent form of communication between automation and modeller. Another option provided by an interviewee was creating pop-ups of characteristics of the automation when a modeller is using the automation. For instance, a pop-up might provide the limitations of a part of the model software if it is used or not. Carver and Turoff (2007) argue that an automation system should not be silent. This is also mentioned by Woods and Sarter (2000), who stress that people and technology are dependent on each other. This reinforces the idea of creating pop-ups or an equivalent. Yet, pop-ups would disrupt the modeller's work they do simultaneously to the automation, which affects their behaviour, for instance experiencing stress or impacting their performance (McFarlane & Latorella, 2002). Though McFarlane and Latorella (2002) do recognise human's ability to handle these interruptions, this depends on the extent to which the interruptions divert, distract, disturb and disrupt the current task. Besides, with pop-ups, modellers might just click *'OK'* without actually reading or considering the message. Another suggestion was that a slow build-up of the automation system would improve the automation's acceptance. First one aspect is automated, once modellers are familiar with this, a next aspect is automated. The slow build-up ensures that modellers can familiarise themselves with the whole system, leading to better understanding and acceptance of the automation. For the modellers, this will enhance their understanding of the system, which Pagano et al. (2016) recommends. The slow build-up also applies to getting their superiors on board, for example, an interviewee stated, *"How much time will you invest [in the script] the first time? And how certain is it that we will use it again? So, even though* *as a modeller you think you truly need this, often you have to convince your director that it is truly necessary despite the initial high costs."*

Translating this to the inter-organisational level requires clear communication to the potential users of the automation script regarding the features of the automation, also recognised by Calder et al. (2018). During and after the script development, this means having good documentation, even though it might be time-consuming (Polhill & Edmonds, 2007) and the documentation has to be fit for purpose (Müller et al., 2014). However, it is not taken into account whether the documentation is read and used or not. Aside from the documentation, a central point for questions or comments can be implemented to enhance communication. Also, including users in the design or testing process will enhance their acceptance and use of the script, as they can familiarise themselves while it is being developed. Afterwards, they can take their gained knowledge to their own organisation. Lastly, the interviewees prefer to use automation as a method to advise or inform them. For example, an automation script can indicate if an issue occurs between your spatial and temporal resolution. After this, the modeller can make a modelling decision about what to change. Or, as an interviewee indicated, a modeller can be given advise by the automation tool as to what the best temporal resolution is.

Because the efforts to centralise automation scripts at the inter-organisational level are still ongoing, not all interview codes based on the theoretical concepts were applicable in the content analysis. Some interview codes, such as 'Redefining the modellers role' or 'Different skills / knowledge obtained by the modeller', were not used because not enough time has passed to observe these changes. The same is the case for the interview codes related to the accuracy of the automation's perceived trustworthiness. For these interview codes, it might also matter that some modellers were involved in the development or testing of automation scripts, which results in a different first impression.

3.3 Interaction between Water Authorities and Consulting Companies

The interviews showed that the roles of the water authorities, consulting companies and research institutes propagate into the modeller's perceptions on automation, resulting in differences between the water authorities and consulting companies. A modeller at a water authority more easily accepts automation in any of the steps executed by a consulting company since they already transferred this modelling decision to an external partner. For example, if a water authority used data provided by a research institute, the pre-processing of these data is already done by the research institute. Then, as an interviewee stated, *"I just assume that this [automation of pre-processing] already happens at the research institute. Again another assumption, I don't know what exactly happens there."* Even though the modelling step is executed by an external partner, it is still desirable to have transparency and reproducibility. Automation at an (Inter-)organisational level can accommodate this.

Often, similar organisations execute specific parts of the modelling process, e.g. consulting companies tend to execute the calibration and model schematisation steps. Because each organisation is responsible for different modelling steps, it is generally expected that automating certain steps is the responsibility of the organisation that executes it. For instance, automating data pre-processing is the perceived responsibility of the water authorities or research organisations, according to an interviewee at a consulting company.

The general division of these modelling steps between water authority, consulting company and research institute is due to the availability of resources, such as computational power, expertise, staff and funding. Consulting companies generally have more resources than water authorities, especially computational power, but also experience and expertise, to execute calibration, model set-up and validation. Because of the resources needed to automate, water authorities, consulting companies and research institutes need to consider if automation is worthwhile.

4. Reflections and implications

The expectation is that standardisation will result in higher consistency between modelling studies and more transparency. But, achieving these outcomes depends on its documentation, evaluation and maintenance. Consistency and transparency in the modelling process are considered important for model results to be useful in a decision-making context (Watson, 2005). If transparency and consistency are achieved, then decision makers have an improved foundation for their decisions, even though the model results are only one part of their considerations (Calder et al., 2018; Watson, 2005). However, our results indicate that the interaction between automation and its usage might affect the transparency and consistency achieved through standardisation for quality assurance.

There are also other approaches to achieve more transparency, for instance through creating records of engagement and decision making (Cockerill et al., 2019) or audits. All these procedures are meant to achieve quality assurance for decision makers – the persons making decisions informed by model results (in this case study, for example the local water manager).

Automation, like other technologies, shapes its use, and vice versa (Melsen et al., 2018). The usage of automation can change over time, and the distance between programmer and modeller can increase. This increased distance can produce barriers to communication and examination or questioning of the assumptions in the automation, making the need for the development process and final script to be documented essential (Calder et al., 2018; Wang et al., 2023). While modellers familiarise themselves with any automation script, they might become less critical of the automation and its capabilities and limitations (Parasuraman et al., 2000). This can result in the modellers blindly accepting the automation, of which an interviewee gave an example, *"So basically, it is automated: as a modeller you can change the table and put in other values. However, in reality, that rarely happens, I think. So, at some point, someone came up with these numbers and over time we become a bit blind to this, sometimes too blind."* The blindness can affect the transparency, because the modellers no longer understand and evaluate what the results are based on. In general, the loss of understanding in the automation can lead to surprising results (Carver & Turoff, 2007; Parasuraman et al., 2000), leaving the modeller the difficult task to figure out what these results mean.

How automation developed at Organisational and Inter-organisational level is used, will determine if it can actually serve as a standardisation method for quality assurance – its usage shapes the automation. Calder et al. (2018) mention that *'models might be used for purposes beyond those for which they were originally designed'* and this also applies to automation. Furthermore, automation scripts can be taken locally. Here, they can be developed further, while no feedback is supplied to the central automation. This practice could potentially create many versions of a similar automation script again, transferring the automation back to Individual or Team automation level (see Figure 3). Also, automation scripts can be used in such a way that the modeller adapts it to get the hydrological response they would expect. This was mentioned by some interviewees, with for example an interviewee stating, *"Sometimes, you are fumbling about, misusing certain features in order to get the system response that you want"*, raising the question: 'Who is making the modelling decision, the programmer of the script or the modeller?'

The (mis)usage of the automation can potentially negate its intended transparency and consistency at an organisational or inter-organisational automation level, affecting the standardisation potential of automation. For maintaining the quality in models or technologies, Calder et al. (2018) suggest that a proper review system should be set up. At some point, this review might result in needing to retire some of the technology developed. Part of a review system is appointing long-term ownership to give someone the responsibility to keep up the review. While for models the owner is usually quite clear, this is more difficult for automation scripts beyond the individual or team level. To determine ownership is especially important for automation because automation potentially impedes the questioning of assumptions more. The power relations between auditor and client is another aspect influencing the questioning of automation scripts (McCracken et al., 2008; Carlisle et al., 2023). Multiple quality assurance and control procedures exist each with their own (dis)advantages: e.g. code review (Bacchelli & Bird, 2013; Pascarella et al., 2018), documentation (Kajko-Mattsson, 2005; Parnas, 2010), and automated testing (Bartram & Bayliss, 1984; Winkler et al., 2010). Besides improved quality, additional benefits can occur such as knowledge transfer or increasing team awareness (Bacchelli & Bird, 2013).

Organisations internally apply a mixture of these quality assurance and control procedures to a certain extent already, as some of the interviewees indicated. Still, as long as no errors occur, the script, data or technology are often accepted as is. If errors do occur, automation requires that the whole process is evaluated more carefully. According to our interviewees, in some organisations, automation scripts were developed relatively recently and the evaluation has not been set up (yet) at the time of the interviews. The allocation of time and resources are important intervening factors, just as the perceived long-term usefulness of the script or tool in question. Inter-organisationally, setting up these procedures takes even more effort. The HYDROLIB project currently has determined ownership for each component of their project and has set up a review system.

Generally, regular reviews of automation at the inter-organisational automation level would ensure it is fit for purpose and has clear documentation, which Hamilton et al. (2022) and Calder et al. (2018) have, respectively, emphasised. Regular reviews could potentially also help decrease unintended blind spots in the model adaptation. Only when these requirements are met will automation at the inter-organisational level contribute to standardisation as a means to achieve quality assurance, and with that, to consistency, transparency and reproducibility.

5. Conclusion

In this study, we explored the modeller's perspective on automation of the model setup using a case study of hydrodynamic modelling in the Netherlands. We conducted fourteen interviews with modellers at water authorities and consulting companies. Subsequently, we carried out a deductive (based on Pagano et al. (2016)) and inductive content analysis on the transcripts. The analysis resulted in an overview of the different social levels of automation practice at which automation is applied uniformly (Individual, Team, Organisational and Inter-organisational); insights into the current extent of automation and the preferred practices in automation by the modeller; and the interaction between third-parties that conduct part of the modelling work in light of automation. The automation levels cover who created and used the automation script: for the individual, team, organisational and inter-organisational level, this is, respectively, one modeller, within a team of modellers, within one organisation and between different organisations.

Automation of parts of the modelling process has numerous advantages: efficiency, reduction of human error, transparency, reproducibility, and consistency between different modellers. These advantages appear at different social levels of automation practice. Efficiency and reduction of human error show at all automation levels, while transparency, consistency and quality assurance for decision makers can be achieved when automation is implemented at Organisational and Inter-organisational automation level. Automation has to be implemented carefully at these (Inter-)organisational automation levels, as modellers might not be inclined to use it if they do not trust it or have a different view on how modelling should be done. Furthermore, automation as a standardisation procedure requires among others documentation, evaluation, and maintenance in order for the advantages of standardisation to surface.

Even if the automation is used and has all the requirements for a standardisation procedure, it is crucial to keep testing one's own understanding and understanding the automation (at any automation level). Automation at organisational and inter-organisational levels might include the risk of decreasing transparency, i.e. not being aware of underlying modelling assumptions, or (mis)using the automation in a such a manner that it still aligns with the modeller's perception of the hydrological system. Any project targeting automation at the (Inter-)organisational automation level has to find a balance between creating transparency and consistency with their automation tools and safeguarding the modeller's trust and proper use of their automation tools. This requires setting up a review system and determining who has long-term ownership of the automation tool. Automating the modelling procedure is a fine line between giving and taking power to modellers and programmers, managing the risks and benefits of automation.

Acknowledgements

First and foremost, we thank our fourteen interviewees for their time and insights provided in the interviews. Secondly, we appreciate the HYDROLIB consortium in welcoming our research team to participate. LM received financial support from the Dutch Research Council through a personal Veni grant (nr. 17297, entitled What about the modeler? The human-factor in constructing Earth and environmental predictions).

Supplementary Material

The Supplementary Material can be found online at: https://sesmo.org/article/view/18657/18205

References

Addor, N., Melsen, L., 2019. Legacy, rather than adequacy, drives the selection of hydrological models. Water Resources Research 55, 378–390. doi:10.1029/2018WR022958.

Amorim, L.D., Cai, J., 2015. Modelling recurrent events: a tutorial for analysis in epidemiology. International Journal of Epidemiology 44, 324–333. doi:10.1093/ije/dyu222.

ATLAS.ti Scientific Software Development GmbH, 2022. ATLAS.ti Version 9.1.7.0, Retrieved from https://atlasti.com.

Babel, L., Vinck, D., Karssenberg, D., 2019. Decision-making in model construction: unveiling habits. Environmental Modelling & Software doi:10.1016/j.envsoft.2019.07.015.

Bacchelli, A., Bird, C., 2013. Expectations, outcomes, and challenges of modern code review, in: 2013 35th International Conference on Software Engineering (ICSE), IEEE. pp. 712–721.

Balci, O., 2001. A methodology for certification of modeling and simulation applications. ACM Transactions on Modeling and Computer Simulation (TOMACS) 11, 352–377. doi:10.1145/508366.508369.

Barnett, B., Townley, L., Post, V., Evans, R., Hunt, R., Peeters, L., Richardson, S., Werner, A., Knapton, A., Boronkay, A., 2012. Australian Groundwater Modelling Guidelines.

Bartram, D., Bayliss, R., 1984. Automated testing: Past, present and future. Journal of Occupational Psychology 57, 221–237. doi:10.1111/j.2044-8325.1984.tb00164.x.

Beeston, L., Blewitt, R., Bulmer, S., Wilson, J., 2021. Traffic modelling guidelines v4. Transport for London: London, UK.

Beven, K.J., 2000. Uniqueness of place and process representations in hydrological modelling. Hydrology & Earth System Sciences 4, 203–213. doi:10.5194/hess-4-203-2000.

Bremer, L.L., Hamel, P., Ponette-González, A.G., Pompeu, P.V., Saad, S.I., Brauman, K.A., 2020. Who are we measuring and modeling for? supporting multilevel decision-making in watershed management. Water Resources Research 56, e2019WR026011. doi:10.1029/2019WR026011.

Calder, M., Craig, C., Culley, D., de Cani, R., Donnelly, C.A., Douglas, R., Edmonds, B., Gascoigne, J., Gilbert, N., Hargrove, C., Hinds, D., Lane, D.C., Mitchell, D., Pavey, G., Robertson, D. Rosewell, B., Sherwin, S., Walport, M., Wilson, A., 2018. Computational modelling for decision-making: where, why, what, who and how. Royal Society Open Science 5, 172096. doi:10.1098/rsos.172096.

Carlisle, M., Gimbar, C., Jenkins, J.G., 2023. Auditor-client interactions—an exploration of power dynamics during audit evidence collection. Auditing: A Journal of Practice & Theory 42, 27–51. doi:10.2308/AJPT-2020-130.

Carver, L., Turoff, M., 2007. Human-computer interaction: the human and computer as a team in emergency management information systems. Communications of the ACM 50, 33–38. doi:10.1145/1226736.1226761.

Cockerill, K., Glynn, P., Chabay, I., Farooque, M., Hämäläinen, R., Miyamoto, B., McKay, P., 2019. Records of engagement and decision making for environmental and socio-ecological challenges. EURO Journal on Decision Processes 7, 243–265. doi:10.1007/s40070-019-00104-6.

Crout, N., Kokkonen, T., Jakeman, A., Norton, J., Newham, L., Anderson, R., Assaf, H., Croke, B., Gaber, N., Gibbons, J., Holzworth, D., Mysiak, J., Reichl, J., Seppelt, R., Wagener, T., Whitfied, P., 2008. Chapter two good modelling practice. Developments in Integrated Environmental Assessment 3, 15–31. doi:10.1016/S1574-101X(08)00602-9.

Davies, P., 2012. The state of evidence-based policy evaluation and its role in policy formation. National Institute Economic Review 219, R41–R52. doi:10.1177/002795011221900105.

Deltares, 2023a. D-HYDRO Suite 1D2D. https://www.deltares.nl/software-en-data/producten/d-hydro-suite-1d2d, Last accessed July 6 2023.

Deltares, 2023b. HYDROLIB. https://deltares.github.io/HYDROLIB/, Last accessed July 6 2023.

Deltares, 2023c. HYDROLIB github. https://github.com/Deltares/HYDROLIB, Last accessed July 6 2023.

Deltares, 2023d. Sobek Suite. https://www.deltares.nl/en/software/sobek/, Last accessed July 6 2023.

Deser, C., Phillips, A., Bourdette, V., Teng, H., 2012. Uncertainty in climate change projections: the role of internal variability. Climate Dynamics 38, 527–546. doi:10.1007/s00382-010-0977-x.

Eilander, D., Boisgontier, H., e. Bouaziz, L.J., Buitink, J., Couasnon, A., Dalmijn, B., Hegnauer, M., de Jong, T., Loos, S., Marth, I., van Verseveld, W., 2023. HydroMT: Automated and reproducible model building and analysis. Journal of Open Source Software 8, 4897. doi:10.21105/joss.04897.

Eyring, V., Cox, P.M., Flato, G.M., Gleckler, P.J., Abramowitz, G., Caldwell, P., Collins, W.D., Gier, B.K., Hall, A.D., Hoffman, F.M., Hurtt, G.C., Jahn, A., Jones, C.D., Klein, S.A., Krasting, J.P., Kwiatkowski, L., Lorenz, R., Maloney, E., Meehl, G.A., Pendergrass, A.G., Pincus, R., Ruane, A.C., Russel, J.L. Sanderson, B.M., Santer, B.D., Sherwood, S.C., Simpson, I.R., Stouffer, R.J., Williamson, M.S., 2019. Taking climate model evaluation to the next level. Nature Climate Change, 1. doi:10.1038/s41558-018-0355-y.

Fan, S.L., Lee, C.Y., Chong, H.Y., Skibniewski, M.J., 2018. A critical review of legal issues and solutions associated with building information modelling. Technological & Economic Development of Economy 24, 2098–2130. doi:10.3846/tede.2018.5695.

Garner, M., Hamilton, S., 2011. Principles of epidemiological modelling. Revue Scientifique et Technique-OIE 30, 407.

Glynn, P.D., Voinov, A.A., Shapiro, C.D., White, P.A., 2017. From data to decisions: Processing information, biases, and beliefs for improved management of natural resources and environments. Earth's Future 5, 356–378. doi:10.1002/2016EF000487.

Government of the Netherlands, SA. Water management in The Netherlands. https://www.government.nl/topics/water-management/water-management-in-the-netherlands, Last accessed on July 27 2023.
Gundersen, O.E., 2021. The fundamental principles of reproducibility. Philosophical Transactions of the Royal Society A 379, 20200210. doi:10.1098/rsta.2020.0210.
Hamilton, S.H., Pollino, C.A., Stratford, D.S., Fu, B., Jakeman, A.J., 2022. Fit-for-purpose environmental modeling: Targeting the intersection of usability, reliability and feasibility. Environmental Modelling & Software 148, 105278. doi:10.1016/j.envsoft.2021.105278.
Hennink, M.M., Kaiser, B.N., Marconi, V.C., 2017. Code saturation versus meaning saturation: how many interviews are enough? Qualitative Health Research 27, 591–608. doi:10.1177/1049732316665344.
Howard, R., Björk, B.C., 2008. Building information modelling–experts' views on standardization and industry deployment. Advanced Engineering Informatics 22, 271–280. doi:10.1016/j.aei.2007.03.001.
Jakeman, A.J., Letcher, R.A., Norton, J.P., 2006. Ten iterative steps in development and evaluation of environmental models. Environmental Modelling & Software 21, 602–614. doi:10.1016/j. envsoft.2006.01.004.
Kajko-Mattsson, M., 2005. A survey of documentation practice within corrective maintenance. Empirical Software Engineering 10, 31–55. doi:10.1023/B:LIDA.0000048322.42751.ca.
Knutti, R., Masson, D., Gettelman, A., 2013. Climate model genealogy: Generation CMIP5 and how we got there. Geophysical Research Letters 40, 1194–1199. doi:10.1002/grl.50256.
Lahtinen, T.J., Guillaume, J.H., Hämäläinen, R.P., 2017. Why pay attention to paths in the practice of environmental modelling? Environmental Modelling & Software 92, 74–81.
Latour, B., 1990. Technology is society made durable. The Sociological Review 38, 103–131. doi:10.1111/j.1467-954X.1990.tb03350.x.
Lewis, E., Birkinshaw, S., Kilsby, C., Fowler, H.J., 2018. Development of a system for automated setup of a physically-based, spatially-distributed hydrological model for catchments in Great Britain. Environmental Modelling & Software 108, 102–110. doi:10.1016/j.envsoft.2018.07.006.
Lim, T.C., Glynn, P.D., Shenk, G.W., Bitterman, P., Guillaume, J.H., Little, J.C., Webster, D., 2023. Recognizing political influences in participatory social-ecological systems modeling. Socio-Environmental Systems Modelling 5, 18509–18509. doi:10.18174/sesmo.18509.
Limerick, H., Coyle, D., Moore, J.W., 2014. The experience of agency in human-computer interactions: a review. Frontiers in Human Neuroscience 8, 643. doi:10.3389/fnhum.2014.00643.
Mai, J., Shen, H., Tolson, B.A., Gaborit, E´., Arsenault, R., Craig, J.R., Fortin, V., Fry, L.M., Gauch, M., Klotz, D., Kratzert, F., O'Brien, N., Princz, D.G., Rasiya Koya, S., Tirthankar, R., Seglenieks, F., Shrestha, N.K., Temgoua, A.G.T, Vionnet, V., Waddell, J.W., 2022. The Great Lakes runoff intercomparison project phase 4: the Great Lakes (GRIP-GL). Hydrology and Earth System Sciences 26, 3537–3572. doi:10.5194/hess-26-3537-2022.
McCracken, S., Salterio, S.E., Gibbins, M., 2008. Auditor–client management relationships and roles in negotiating financial reporting. Accounting, organizations and society 33, 362–383. doi:10.1016/j.aos.2007.09.002.
McFarlane, D.C., Latorella, K.A., 2002. The scope and importance of human interruption in human-computer interaction design. Human-Computer Interaction 17, 1–61. doi:10.1207/S15327051HCI1701_1.
Melsen, L., 2022. It takes a village to run a model—the social practices of hydrological modeling. Water Resources Research 58, e2021WR030600. doi:10.1029/2021WR030600.
Melsen, L.A., Vos, J., Boelens, R., 2018. What is the role of the model in socio-hydrology? Discussion of "Prediction in a socio-hydrological world". Hydrological Sciences Journal 63, 1435–1443. doi:10.1080/02626667.2018.1499025.
Mer, F., Baethgen, W., Vervoort, R.W., 2020. Building trust in swat model scenarios through a multi-institutional approach in Uruguay. Socio-Environmental Systems Modelling 2, 17892–17892. doi:10.18174/sesmo.2020a17892.
Mir, M., Casadesús, M., 2011. Standardised innovation management systems: A case study of the Spanish standard une 166002: 2006. Innovar 21, 171–188.
Moallemi, E.A., Zare, F., Reed, P.M., Elsawah, S., Ryan, M.J., Bryan, B.A., 2020. Structuring and evaluating decision support processes to enhance the robustness of complex human–natural systems. Environmental Modelling & Software 123, 104551. doi:10.1016/j.envsoft.2019.104551.
Müller, B., Balbi, S., Buchmann, C.M., De Sousa, L., Dressler, G., Groeneveld, J., Klassert, C.J., Le, Q.B., Millington, J.D., Nolzen, H., Parker, D.C., Polhill, J.G., Schlüter, M., Schulze, J., Schwarz, N., Sun, Z., Taillandier, P., Weise, H., 2014. Standardised and transparent model descriptions for agent-based models: Current status and prospects. Environmental Modelling & Software 55, 156–163. doi:10.1016/j.envsoft.2014.01.029.
Nederlands Hydrologisch Instrumentarium, SA. HyDAMO Data Model. https://nhi.nu/ontwikkelingen/hydamo/, Last accessed on July 30 2023.
Pagano, T.C., Pappenberger, F., Wood, A.W., Ramos, M.H., Persson, A., Anderson, B., 2016. Automation and human expertise in operational river forecasting. Wiley Interdisciplinary Reviews: Water 3, 692–705. doi:10.1002/wat2.1163.
Parasuraman, R., Sheridan, T.B., Wickens, C.D., 2000. A model for types and levels of human interaction with automation. IEEE Transactions on systems, man, and cybernetics-Part A: Systems and Humans 30, 286–297. doi:10.1109/3468.844354.
Parnas, D.L., 2010. Precise documentation: The key to better software, in: The Future of Software Engineering. Springer, pp. 125–148. doi:10.1007/978-3-642-15187-3_8.
Pascarella, L., Spadini, D., Palomba, F., Bruntink, M., Bacchelli, A., 2018. Information needs in contemporary code review. Proceedings of the ACM on human-computer interaction 2, 1–27. doi:10.1145/3274404.

Polhill, J.G., Edmonds, B., 2007. Open access for social simulation. Journal of Artificial Societies and Social Simulation 10, 10–10. URL: https://www.jasss.org/10/3/10.html.

Refsgaard, J.C., van der Sluijs, J.P., Højberg, A.L., Vanrolleghem, P.A., 2007. Uncertainty in the environmental modelling process–a framework and guidance. Environmental Modelling & Software 22, 1543–1556. doi:10.1016/j.envsoft.2007.02.004.

Sampaio, P., Saraiva, P., Guimarães Rodrigues, A., 2011. Iso 9001 certification forecasting models. International Journal of Quality & Reliability Management 28, 5–26. doi:10.1108/02656711111097526.

Schmolke, A., Thorbek, P., DeAngelis, D.L., Grimm, V., 2010. Ecological models supporting environmental decision making: a strategy for the future. Trends in Ecology & Evolution 25, 479–486. doi:10.1016/j.tree.2010.05.001.

Schwarz, N., Dressler, G., Frank, K., Jager, W., Janssen, M.A., Müller, B., Schlüter, M., Wijermans, N., Groeneveld, J., 2020. Formalising theories of human decision-making for agent-based modelling of social-ecological systems: practical lessons learned and ways forward. Available at SSRN 4152673 doi:10.18174/sesmo.2020a16340.

Sharples, J.J., Cary, G.J., Fox-Hughes, P., Mooney, S., Evans, J.P., Fletcher, M.S., Fromm, M., Grierson, P.F., McRae, R., Baker, P., 2016. Natural hazards in Australia: extreme bushfire. Climatic Change 139, 85–99.

Stelling, G.S., Duinmeijer, S.A., 2003. A staggered conservative scheme for every froude number in rapidly varied shallow water flows. International Journal for Numerical Methods in Fluids 43, 1329–1354. doi:10.1002/fld.537.

van den Berg, J., van Lieshout, M., 2022. De wraak van de Zuiderzee: renovatie Afsluitdijk kost honderden miljoenen extra door blunder Rijkswaterstaat. Published in the Volkskrant online on May 20 2022, https://www.volkskrant.nl/nieuws-achtergrond/de-wraak-van-de-zuiderzee-renovatie-afsluitdijk-kost-honderden-miljoenen-extra-door-blunder-rijkswaterstaatba836a75/, Last accessed on July 27 2023.

van Waveren, R., Groot, S., Scholten, H., van Geer, F., Wüsten, H., Koeze, R., Noort, J., 1999. Vloeiend modelleren in het waterbeheer: Handboek Good Modelling Practice. Technical Report 99-05/99.036, STOWA/RIZA Wageningen

Verbeek, P.P., 2008. Morality in design: Design ethics and the morality of technological artifacts. In: Philosophy and design: From engineering to architecture (Editors: Vermaas, P.E., Kroes, P., Light, A., Moore, S.A.), 91–103. doi:10.1007/978-1-4020-6591-0_7.

Voinov, A., Jenni, K., Gray, S., Kolagani, N., Glynn, P.D., Bommel, P., Prell, C., Zellner, M., Paolisso, M., Jordan, R., et al., 2018. Tools and methods in participatory modeling: Selecting the right tool for the job. Environmental Modelling & Software 109, 232–255. doi:10.1016/j.envsoft.2018.08.028.

Vrontis, D., 2003. Integrating adaptation and standardisation in international marketing: the AdaptStand Modelling process. Journal of Marketing Management 19, 283–305. doi:10.1080/0267257X.2003.9728212.

Vukovic, R., 2022. From conducting to inspiring: A qualitative research on servant leadership in the corporate service of rijkswaterstaat.

Wang, H.H., Van Voorn, G., Grant, W.E., Zare, F., Giupponi, C., Steinmann, P., Müller, B., Elsawah, S., Van Delden, H., Athanasiadis, I.N., et al., 2023. Scale decisions and good practices in socio-environmental systems modelling: guidance and documentation during problem scoping and model formulation. Socio-Environmental Systems Modelling 5, 18563. doi:10.18174/sesmo.18563.

Watson, R.T., 2005. Turning science into policy: challenges and experiences from the science–policy interface. Philosophical Transactions of the Royal Society B: Biological Sciences 360, 471–477. doi:10.1098/rstb.2004.1601.

Wears, R.L., 2015. Standardisation and its discontents. Cognition, Technology & Work 17, 89–94. doi:10.1007/s10111-014-0299-6.

Werkowska, W., Márquez, A.L., Real, R., Acevedo, P., 2017. A practical overview of transferability in species distribution modeling. Environmental Reviews 25, 127–133. doi:10.1139/er-2016-0045.

Winkler, D., Hametner, R., Östreicher, T., Biffl, S., 2010. A framework for automated testing of automation systems, in: 2010 IEEE 15th Conference on Emerging Technologies Factory Automation (ETFA 2010), pp. 1–4. doi:10.1109/ETFA.2010.5641264.

Woods, D.D., Sarter, N.B., 2000. Learning from automation surprises and going sour accidents. In: N.B. Sarter & R. Amalberti (eds.) Cognitive engineering in the aviation domain. Lawrence Erlbaum Associates Publishers, 327–353.

Yates, K.L., Bouchet, P.J., Caley, M.J., Mengersen, K., Randin, C.F., Parnell, S., Fielding, A.H., Bamford, A.J., Ban, S., Barbosa, A.M., Dormann, C.F., Elith, J., Embling, C.B., Ervin, G.N., Fisher, R., Gould, S., Graf, R.F., Gregr, E.J., Halpin, P.N., Heikkinen, R.K., Heinänen, S., Jones, A.R., Krishnakumar, P.K., Laruia, V., Lozano-Montes, H., Mannocci, L., Mellin, C., Mesgaran, M.B., Moreno-Amat, E., Mormede, S., Novaczek, E., Oppel, S, Ortuño Crespo, G., Townsend Peterson, A., Rapacciuolo, G., Roberts, J.J., Ross, R.E., Scales, K.L., Schoeman, D., Snelgrove, P., Sundblad, G., Thuiller, W., Torres, L.G., Verbruggen, H., Wang, L., Wenger, S., Whittingham, M.J., Zharikov, Y., Zurell, D., Sequeira, A.M.M., 2018. Outstanding challenges in the transferability of ecological models. Trends in Ecology & Evolution 33, 790–802. doi:10.1016/j.tree.2018.08.001.

Zurell, D., Franklin, J., König, C., Bouchet, P.J., Dormann, C.F., Elith, J., Fandos, G., Feng, X., Guillera-Arroita, G., Guisan, A., Lahoz-Monfort, J.J., Leitão, P.J., Park, D.S., Townsend Peterson, A., Rapacciuolo, G., Schmatz, D.R., Schröder, B., Serra-Diaz, J.M., Thuiller, W., Yates, K.L., Zimmermann, N.E., Merow, C., 2020. A standard protocol for reporting species distribution models. Ecography 43, 1261–1277. doi:10.1111/ecog.04960.