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Position Paper

A modeller's fingerprint on hydrodynamic decision support modelling

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ABSTRACT

Model results can have far-reaching societal implications, requiring fit-for-purpose models. However, model output is resulting from a particular path chosen with each modelling decision. We interviewed fourteen modellers in the Dutch water management sector in order to study how decision support hydrodynamic modellers make modelling decisions. An inductive-content analysis was performed. We identified eight motivation-categories. Individual and team considerations mostly motivate modelling decisions. We identified patterns between the motivation-categories and their occurrence across modelling steps. Modelling decisions during model implementation were found to be more in the modeller's direct sphere of influence, while decisions concerning model structure and data selection more outside of it. So, even though modellers can leave their fingerprint, their sphere of influence and thus their fingerprint's clarity is bound by institutionalised predefined decisions. Thus, models and their results are shaped within a broader sphere than the modeller's alone, requiring a broader consideration of organisations and standards.

1. Introduction

After flooding in January 2011 that afflicted large areas near the Australian cities of Brisbane and Ipswich, a lawsuit was filed against two dam operating companies and the state of Queensland. The claim was that negligent operation of the dams, and not the rainfall directly, had resulted in widespread property damage. In the lawsuit, the decisions concerning early dam releases, the modelling they were based on, and the handbook that was followed were questioned. It was concluded that the flooding occurred due to a combination of torrential rains in the catchment and a release from the Wivenhoe Dam to prevent it from overtopping. The judge, initially, ruled in favour of the claimants, but the ruling was later overturned during an appeal (Supreme Court of New South Wales, 2021). As this case shows, model results and decisions informed by model results can have real consequences, and the role of the modeller can be scrutinised.

Model results used for decision support can have far-reaching effects and model users, the decision makers, can be held accountable, as the Australian case shows. This means that model users depend on modellers to provide them with accountable model results. However, model results can vary depending on the path taken with every modelling decision that is made (Glynn et al., 2017; Holländer et al., 2009, 2014; Lahtinen et al., 2017; Melsen et al., 2019; Polhill and Edmonds, 2007). A modelling decision is choosing a particular method within a step of the modelling process. Each decision has a reasoning behind it, which is what we call the motivation for this modelling decision. Given that the modeller is in charge of many of these decisions, it is imperative to take the modeller's role in the modelling process into account to understand their role in the modelling process.

Modelling decisions made by a modeller can impact the various stages in the modelling process. Holländer et al. (2009) asked ten modellers to each model the same artificial catchment in Germany. Because the catchment was man-made, the modellers did not have a priori knowledge of it. The modellers received the same data, but the discharge data were not disclosed. The model results from the ten modellers varied widely. Holländer et al. (2009) concluded that the modeller's personal judgement contributed substantially to the variations in the model results. In Holländer et al. (2014), they continued this experiment by organising a field visit and by releasing more information against extra costs. Afterwards, the modellers redid the modelling study individually. Holländer et al. (2014) found that the modeller's process and system understanding were just as important as the model itself or the data, because the modellers made different modelling decisions. due to the modellers having made different modelling decisions. Melsen et al. (2019) conducted a modelling experiment to test how four modelling decisions impact the modelling results. In stead of having other modellers make modelling decisions and execute

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the modelling, they defined the modelling decisions and their options when they conducted the modelling study themselves. The studied modelling decisions significantly affect the simulated flood and drought events. These studies show that model results depend on the modelling decisions made. With these modelling decisions, modellers leave their fingerprint in their models.

Several studies already investigated how social processes steer motivations for modelling decisions, mainly in an academic setting. Melsen (2022) conducted interviews with hydrological modellers to investigate how they made their modelling decisions during a specific modelling study. Her conclusion was that the team in which a modeller works is an important factor in making certain decisions in a particular way. Babel et al. (2019) also conducted interviews, yet across different disciplines and focusing more on the development of the model. Also here, it was found that the modeller's team and collaborators contributed considerably to model development. Addor and Melsen (2019) looked at how model structures are selected. They performed a bibliometric study, in which they found that legacy, represented through the institute of the first author, is the best predictor for model selection. These studies show a wider range of motivations in modelling decisions, beyond the considerations of the individual modellers, and thus the large role of social processes in technical model use.

However, decision support modelling generally has its roots outside of academia, at governmental agencies and consulting companies. There are several studies who have investigated the modeller's influence in such a decision support setting. Padilla et al. (2018) present a survey regarding modellers' perspectives on modelling and simulations. Their survey was fully completed by 151 respondents who were identified as model builders from both academia and industry. They found that conceptualisation and validation of models relied heavily on informal methods, such as the use of pen and paper or visual inspection. This implies that individual modeller's perspectives shape the modelling decisions made. Deitrick et al. (2021) deployed a survey, which had 27 respondents, and conducted four in-depth follow-up interviews, which focused on how modellers make decisions during the watershed modelling process. They reached an audience working in mainly academics and governmental agencies. Their study highlights how the modeller's ethical – related to personal standards – and epistemic – related to knowledge building – values inform the modelling process. Fleming (2009) conducted a small survey about how a watershed model is selected. Their respondents worked in government, the private sector and academia. They found that both individual considerations, such as familiarity with a certain method, and organisational considerations, such as standards in an organisation, are considerable influences in the modelling process. These studies show that the social aspects of modelling are important to consider in different contexts — academia, government, and the private sector.

Here, we explicitly and solely focus on practitioners that use models for every day decision-making practice. Understanding modelling decisions in such a context is extremely relevant, because these models directly interfere with the real world (Lane, 2014), as also demonstrated by the role of models in the Australian flood. We conducted fourteen in-depth interviews with modellers at water authorities and consulting companies, focusing solely on modelling in the governmental and consulting sectors. The analysis consists of an inductive content analysis covering the motivations behind modelling decisions, the variation of motivations across the modelling process and the difference in motivations between the governmental and consulting sectors.

2. Methodology

In order to investigate how decision support hydrodynamic modellers make modelling decisions, we conducted fourteen interviews. We used the Netherlands as a case study, which will be described in the first subsection. The interviewees worked at local water authorities or consulting companies. The interviewee selection and interviews are detailed in the second subsection. The analysis of the interviews consisted of an inductive content analysis, which is elaborated in the third subsection.

2.1. Case study

Since social processes are highly localised, it is infeasible to further our understanding of the social aspects of modelling at a general level. Therefore, we focus on a defined case: decision support modelling in the Netherlands. Such an approach is also defended by Deitrick et al. (2021), having conducted a survey and interviews in the Chesapeake Bay Watershed (US), indicating that other case studies would improve the general understanding of how decision support modellers make modelling decisions.

In the Netherlands, national and local water authorities and consulting companies are the main parties that execute decision support modelling for water management, assisted by research institutes. At the national level, the governmental agency Rijkswaterstaat has this responsibility (Government of the Netherlands, SA). At the local level, there are 21 water authorities, which carry responsibility for the water management in their region (Government of the Netherlands, SA). Over the past decades, the management structure of Rijkswaterstaat and the water authorities has shifted. Initially, in the 1950s and 60s, they had substantial in-house modelling knowledge, which allowed them to facilitate their own modelling studies. At some point, the structure changed from having in-house knowledge to performing project management. As a result, Rijkswaterstaat and the water authorities had to rely more on consulting companies and research institutes to (partially) carry out the modelling process (Vukovic, 2022; van den Berg and van Lieshout, 2022). Through public biddings, there are several consulting companies that support the water authorities. This support consists of executing of the whole modelling process, setting up the model, or knowledge provision and training for water authorities so that they are able to set up and execute models themselves. Research institutes support the hydrodynamic modelling mainly through developing new model software. The research institutes specifically target the knowledge intensive and technical aspects of the software development. Moreover, the research institutes play a key role in the maintenance and quality assurance of the software suites. Some of the interviewees of this study that work at water authorities indicated that, since a few years, water authorities aim to obtain more in-house knowledge again through human resources and knowledge acquisition.

For decades, most water authorities have worked with the same model software suite: SOBEK (Deltares, 2023; Stelling and Duinmeijer, 2003). The functionalities of this software suite cover among others rainfall-runoff processes, 1D open and closed hydrodynamics and 2D overland flow. Currently, the water authorities are looking into suitable alternatives to SOBEK, as its maintenance is discontinued.

2.2. Interviewee selection and interviews

To study the modeller's motivations for their modelling decisions, we interviewed fourteen modellers at water authorities and consulting companies. The interviewee selection was within a hydrodynamic modelling project and through snowball sampling, which is not an unusual method. Still, it could affect the representativeness of the interviewee sample. We examined this by evaluating the saturation of coding and the differences between the interviewees working at the same organisation.

Nine of the interviewees worked at six different water authorities at the time of the interviews. The other five worked at four different consulting companies. Modellers at water authorities and consulting companies execute other aspects of the modelling process due to the different role of each organisation. The interviewees were all hydrodynamic modellers. Their experience with modelling ranged from one to fifteen years. The interviewees use models for various applications. For flood applications, all interviewees execute real-time forecasting to evaluate if their water system can cope with certain events. Other applications include infrastructure dimension design and scenario testing, which were both mentioned by about half of the interviewees.

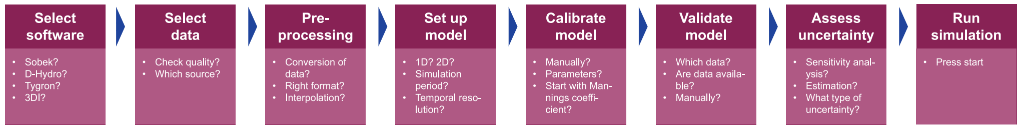

Fig. 1. General overview of the modelling process and examples of decisions that modellers have to make for each step, for Dutch water management modellers.

Additional, though less-frequently mentioned applications are water system design, drought management, and water quality modelling. Fig. 1 provides an example of modelling decision the interviewees encountered during their modelling studies.

All interviews, semi-structured, took place between September and December 2021. All but one were conducted in Dutch, with the other one being held in English. On average, the interviews lasted between 1 h 15 min and 2 h. The interview guide, included in Supplementary Material A, covered questions about motivations behind modelling decisions, i.e. how the interviewee made a certain modelling decision or when they would change their decision. For instance, one of the interviewees considered the aim of the modelling study to determine the simulation period: for one flood event a couple of days or weeks, and for groundwater-related studies at least a year. Each interview was recorded and subsequently transcribed.

2.3. Content analysis

An inductive content analysis of all transcripts was carried out using AtlasTi, version 9 (ATLAS.ti Scientific Software Development GmbH, 2022). This analysis, firstly, entailed inserting topical interview codes to categorise which segments of the transcripts covered the different modelling decisions and which segments covered general questions such as the interviewee's confidence in a model and its simulations, and the interviewees' perceived influence as a modeller. For example, the topical interview code 'Calibration' indicates all quotations in the transcript that were about calibration. This can be in response to a question about calibration, but it can also be that the interviewee mentioned calibration in relation to another question.

The second part of the content analysis produced interview codes, which contain the results of this study — how modellers make modelling decisions. Here, we specifically focused on whether and how modellers make a certain decision, and when they would decide differently. The set obtained from this inductive content analysis contained 96 interview codes (see Supplementary Material B). Each interview code can be applied to multiple quotations — an excerpt of the transcript. A single quotation can also have multiple codes. For example, we assigned two codes ('Tender requirements' and 'Earlier work within organisation') to the following quotation: 'The decision was made based on a proposal that was tendered and awarded before I started at the company'. The code 'Tender requirements' relates to the fact that it was based on a tendered proposal and the code 'Earlier work within organisation' covers that this proposal was tendered before the interviewee started working at the organisation.

After the inductive content analysis, the interview codes were classified into motivation-categories, which resulted in a general overview of the motivations. This classification was made through discussion within our team. In our analysis, we have also looked at overarching themes. These themes appear in several of the previously determined categories. Furthermore, combining the categorised codes with the topical codes (i.e., topics) allowed for exploration of different motivations for different modelling steps. For example, the motivations in the category 'Organisational' appear on average most frequently in the quotations related to the topical code 'Model structure', which implies that decisions related to model structure generally occur at the organisational level. Moreover, we analysed the average occurrence of codes, compared between modellers at water authorities and consulting companies. Since water authorities and consulting companies have a different role in the Dutch water management, i.e. water authorities are responsible for producing model results for decision support, while the consulting companies support the water authorities in executing the modelling process, we hypothesise that this leads to different motivations in making modelling decisions.

3. Results and interpretation

3.1. Motivation classification

Across all interviews, 1699 quotations that contained a motivation were identified in total. These quotations could be classified into 96 different motivations (Supplementary Material B), which were again grouped in eight different motivation-categories (Fig. 2). A modelling decision is the choice for a certain method within one step of the modelling process. The reasoning to choose this method is the motivation for this decision. A decision can have multiple motivations, also from different categories. The eight identified categories are: Individual, Team, Organisational, External, Commissioner, National, International and Consequential. These are discussed below. Although we identified these eight categories, some interview codes could not be classified in one category, therefore we classified them in two. For example, 'Testing' is in both the Individual and Team category, because this is sometimes executed by the individual modeller, and other times it is executed within the team.

Individual — This category refers to all motivations made at the discretion of the modeller themselves. This category is the biggest category of all eight in terms of both codes and quotations, even when not taking into account the shared codes with the 'Team' category. The most prevalent codes in this category are 'Personal insight' and 'Personal experience' with 152 and 115 codes, respectively. Quote 1 gives an example of personal experience influencing a modelling decision. This interviewee chooses to not use certain data because in their experience the approach of statistics-based cross sections is not reliable enough. Another frequently-occurring interview code is 'Personal preference' with 62 quotations. Other codes included in this category are among others 'I don't know', 'It doesn't make a difference', and 'Logic'.

> I know from experience that they [statistics-based cross sections, red.] are not always reliable. – Quote 1 (Interviewee at Water Authority)

Team — The motivations in this category relate to the modeller and their direct colleagues. For example, a decisions is made by discussing it within the team or with their superior. The most-frequently occurring code in this category is 'Experience colleagues', of which Quote 2 is an example. This modeller adopted a certain method, because their colleagues used it and had experience with it. There is considerate overlap with the Individual category, in total 261 distinct quotations, divided over twelve interview codes. Among others, the interview codes 'Testing', 'Model run time' and 'Hydrological knowledge' are the main codes that overlap, respectively accounting for 77, 59 and 42 interview quotations. For example, 'Testing' can be executed by an individual modeller or a team.

> I think it is more because my colleagues also do it in that way, so that is kind of easy. But I get what you mean, you could also retrieve the roughness values in a different way. For me, it is actually because it was done in this way here, so I have adopted that method. – Quote 2 (Interviewee at Water Authority)

Organisational — The organisation a modeller works at can also influence the decision they make, for instance through the vision the organisation has or through the infrastructure it provides. Another motivation in this category is 'Earlier work done in organisation', of which an example is given in Quote 3. Here, an organisation developed a certain tool for other organisations. Because of this work done, they also use it frequently themselves. This category shares two codes with other categories. One of them is 'Best available' with the 'Team' category. This refers to what is perceived to be the best available method or data within either a team or an organisation.

> Well, we provide a certain tool to other organisations. (...) We also use this tool a lot. – Quote 3 (Interviewee at Consulting Company)

External — Within the modelling process, tasks can be outsourced to an external partner. If this external partner is responsible for making the modelling decision, the motivation has been classified in the External category. This might mean that the interviewed modeller is unaware of the full reasoning for certain decisions made by the external partner, which is generally the case when an external partner executes these modelling decisions without in-between consultation. We captured this in the code 'Executed by an external partner'. This motivation was assigned to 37 distinct quotations. This happens regularly for data pre-processing, which is often already performed by the research institute providing the data. For instance, a modeller uses meteorological data for flooding assessments. These generally-available statistical data or time series have been derived by the Royal Netherlands Meteorological Institute, and it is in this instance not necessary for the modeller to do any additional pre-processing (Quote 4). Another task that is commonly executed by an external partner is the 'Model set-up', calibration and validation for the main model of a region. A consulting company supports a water authority in this way. Still, the water authority can and will adapt this main model when deemed necessary. Of course, the execution of any modelling step can also be an iterative process between two organisations, including discussions between the parties. This is reflected in the code 'In discussion with external partner', occurring 23 times.

> No, we don't do that [pre-processing of meteorological statistical data or time series, red.]. No, that is actually already validated by KNMI [the Royal Netherlands Meteorological Institute, red.]. – Quote 4 (Interviewee at Water Authority)

Commissioner — This category includes the motivations that are influenced by the commissioner of the modeller. The modeller would often be the external colleague or partner of the commissioner. In this sense, External and Commissioner are the other sides of the same coin. In total, this category comprises seven codes, including for instance 'Commissioner determines' (37 quotations) and 'Requirements for model study' (13 quotations). One of the important motivations in this category is 'Time available in project', which Quote 5 highlights. In this quote, they choose to finish the calibration and continue with the modelling process and accept that this will be the best achievable calibration in light of financial and time resources. This category share one code with the 'Organisational' category: 'Limits costs'.

> Yes, that [calibration requirements, red.] is very much in consultation, so it depends a bit on the effort you've put in, so the total amount of hours versus the timeframe that is there. Often we say: 'Guys, we have put in this much effort, everyone has looked at it, the money has run out' and at that moment it [the calibration, red.] is simply cut off. – Quote 5 (Interviewee at Consulting Company)

National — Modelling decisions can also be bound by national considerations. This could be national laws that modellers have to adhere to, or the origin of a tool or method that modellers use. The origin of a tool might ease the use of it, because the documentation or support might be provided in the modeller's first language. Additionally, another motivation example is 'Generally used', which means that a particular method is used across multiple or all organisations in the Netherlands (Quote 6). This might have grown organically, as it is easier to compare model studies when using similar methods, or the various organisations came to an agreement on what to use.

> I think also because it is the most used model software within the Dutch hydrological community. – Quote 6 (Interviewee at Water Authority)

International — This category indicates motivations that are based on international factors, such as international agreements. This category is the smallest of all, as most modellers were focused on regional hydrological support modelling. We identified two types of international aspects that modellers used in their modelling decisions: firstly, data sharing, and secondly, agreements regarding rules for environmental protection. The first aspect entails water authorities using data from neighbouring countries (i.e. Belgium or Germany) to obtain more data that is potentially of a higher quality. This most often applied to forcing data. The second aspect relates to constrictions imposed by especially the European Union. Quote 7 mentions European environmental goals that need to be taken into account in the design of the water system. This in turn impacts what needs to be modelled.

> And also the goals you want to achieve. So, there are all kinds of environmental objectives that are imposed from Europe. And how should I say it, extreme is not the right word... The more ambitious they are, that of course also influences your scenario. So when they say 'Oh no you can just have some boring grass', then you don't have to heavily wet that area or anything. But when they say 'There must be a swamp here and this and that', then of course you have to make all kinds of adjustments to raise those groundwater levels. Those kind of things. – Quote 7 (Interviewee at Water Authority)

Consequential — Consequential refers to a choice being (partially) predetermined because of an earlier choice made, demonstrating path dependency. For example, within particular modelling software only certain model settings are available. Then the choice for that software package limits the choices for the settings. Quote 8 provides another example regarding the choice of the simulation time step. In this case, the interviewee needed to select a maximum temporal resolution that the model cannot exceed. For this maximum, the interviewee used the default value provided by the model. Another aspect important in this category is that parts of the modelling process are executed automatically: the modeller chooses a tool to automatically perform certain tasks in the modelling procedure, but then the choices in the automation tool are a consequence of the choice to use that tool.

> I think the default value. – Quote 8 (Interviewee at Water Authority)

Some of the interview codes could not be classified in any of these eight categories. These interview codes pertain to the availability of data or software or technologies, attributes of certain methods or data or model software, and specifics of the model study itself. Because the interviews were set up in a generic manner, the interviewees specified often that their decisions depended on the goal of the model study, the model structure used, the project, the study area and the circumstances. The interview codes 'Based on theory', 'Maintenance stops', and 'Model stability' are stand-alone codes.

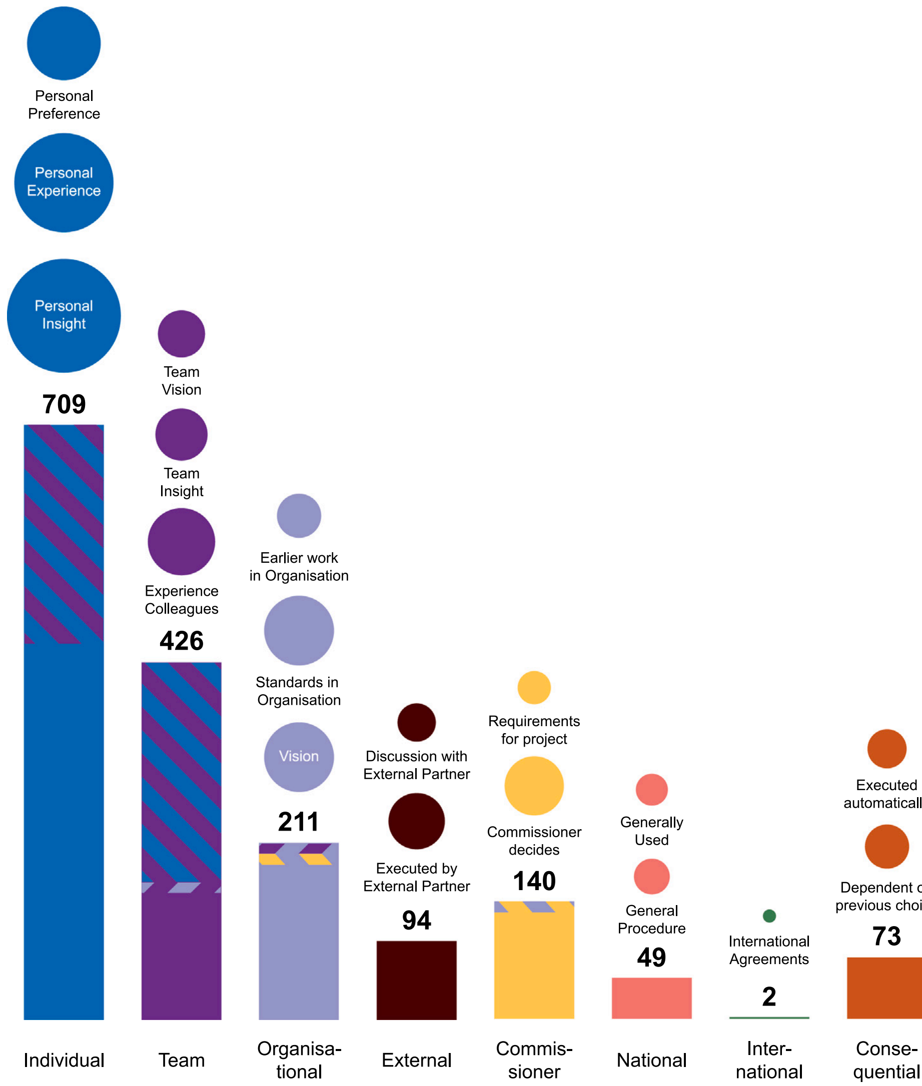

Fig. 2. Classification of motivations behind modelling decisions in hydrodynamic modelling for water management. For each motivation-category, one or more examples of specific codes are given. The number of quotations of the example codes is indicated with circles, which are area-proportional.

3.2. Overarching themes

Aside from the eight categories, we have identified two overarching themes within the interview codes: 'Vision' and 'Standards'. These themes are recurring with distinct interview codes across several categories. An example are the codes 'Team vision' and 'Vision organisation', which are respectively classified in categories 'Team' and 'Organisational'. Both codes relate to vision. Some codes that were not classified in any of the eight previously introduced categories do relate to either of the themes and are discussed in this section.

Vision — Vision, as defined by the Cambridge Dictionary, means 'the ability to imagine how a country, society, industry, etc. could develop in the future and to plan for this' (Cambridge Dictionary, 2024b). In our study, we look at vision related to how the modelling process is shaped and how modelling decisions are made. This vision is informed by the values an individual modeller, team or organisation holds, and can also be created in each of these categories. A certain vision can lead to a preference for a method, however, preferences are not necessarily visionary. An overview of all codes related to vision and the frequency with which they occur is visualised in Fig. 3. Codes related to vision occur in three different categories: 'Individual', 'Team', and 'Organisational'. In the 'Individual' category, the vision relates to a single modeller's perception on how the modelling process should be executed. In our study, this is only visible in three quotations within the code 'Personal preference'. Only these three quotations have been visualised in Fig. 3. In a team, vision is visible by the team vision they set out. For example, Quote 9 shows that the team a modeller works in created a certain vision on which modelling software they wanted to use. They created this vision because it would be easier to work together and fill in for each other. Within this vision, the modellers, including the interviewees, work as much as possible with the model software they determined.

> The underlying idea was that, because we would also have a whole new team of modellers, we wanted to work with one package as much as possible. We did not want to work with six different packages, because then you can no longer communicate with each other or replace each other. And it will then work a little less well.
> – Quote 9 (Interviewee at Water Authority)

At the organisational level, the organisation creates and prescribes their vision. This vision can relate to which model software is used, how the model is set up (e.g. 1D or 2D schematisation), or what data is used. For instance, Quote 10 shows how the vision of a water authority determines which model software is used. The interviewee follows this vision too, among others because it works well. This vision was initially

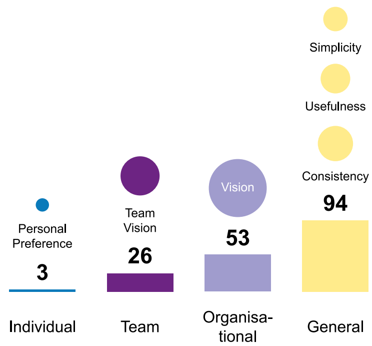

Fig. 3. Different categories, and examples of codes per category, that all relate to the overarching theme 'Vision'. This theme indicates that certain modelling decisions are made because they fit a certain modelling vision. The circles, which are area-proportional, represent the number of quotations for a code. The quotations in the 'Individual' category are a subset of the code 'Personal preference'.

formulated by the hydrological modellers and approved by the board. Afterwards, everyone at the water authority carries out this vision.

> That [model software used, red.] is a choice, which is mainly created generally within the water authority, so we have a whole vision [formulated by the modellers and approved by the board, red.]. Within that vision, they decided to switch from SOBEK to D-HYDRO before I started working here. So, that is a general choice, so to say. – Quote 10 (Interviewee at Water Authority)

On top of that, some codes related to vision could not fit in one of the previously defined categories and are labelled as general vision. These codes include among others 'Simplicity', 'Consistency', 'Usefulness', and 'Efficiency'. Simplicity, for instance, can mean that a modeller wants to keep the modelling process 'as simple as possible, but as complex as necessary'. One of the interviewees described that they as an organisation require consistency in the results, even when different parties have generated the results. Some of these general aspects of vision can be ascribed to one of the eight different categories dependent on the context. For example, a modelling team can strive for simplicity in its modelling process, because that aligns with their vision of the modelling process — fitting the 'Team' category. Also, a modeller can value efficiency and tailor their decisions to that — fitting the 'Individual' category.

Standards — Standards are either a generally accepted method or a level of quality (Cambridge Dictionary, 2024a). In our study, we refer to standards as: a standard is a generally-accepted (informal) or prescribed (formal) method or way of working. The interviews showed that standards are implemented in three different categories: 'Organisational', 'National', and 'International'. Most standards that were mentioned were formally documented. An organisation can have internal standards or generally used procedures, exemplified in Quote 11. This interviewee uses (parts of) the general model to execute their specific modelling study, which is an informal standard. This quote also highlights a disadvantage of a generally-accepted approach or standard procedures: evaluation and updates might not happen regularly once accepted and trusted.

> There are standard models from which I cut out a part. Those models have been created once, I do not know how long ago. – Quote 11 (Interviewee at Water Authority)

In the National category, there are several ways in which standards are implemented, for example based on a national handbook or on national laws. Quote 12 gives another example: the different organisations agreed on using particular data. They recorded this agreement in a guideline.

> And for the flooding part, there is no discussion, because the LGN [National Land use Netherlands, red.] data set is prescribed from that national guidance. – Quote 12 (Interviewee at Water Authority)

Organisations have to adhere to some international laws as well (e.g. Quote 7 above), which have to be taken into account in how the modelling process is executed.

The codes in these three categories – 'Organisational', 'National', and 'International' – are the visible aspects of standards, that is the modeller is executing (part of) the modelling process is aware of them. There are probably also standards in the categories 'External' and 'Commissioner'. However, this is not visible to the modeller, since the modeller is an outside party in both cases. Standards could also exist at the team level, but were not encountered as such in the interviews. Possibly because these standards have grown more organically or are easier internalised.

3.3. Distribution of categories across different modelling steps

While being cautious in quantifying qualitative data, we identified some patterns between the eight identified motivation-categories and how often they occurred across the different steps of the modelling process (Fig. 4). We analysed how one category is divided over all modelling steps (Fig. 4a) and how all categories are represented within each modelling step (Fig. 4b). We have left out the category 'International' from this part of the analysis, because it only comprised two quotations.

Fig. 4a shows that, in general, the modeller makes decisions based on their individual and team motivations during each step of the modelling process. However, the personal and team motivations are more strongly featured in the modelling steps related to model implementation — i.e. from modelling step 'Model set-up' to 'Validation'. These are the modelling decisions in the modeller's direct sphere of influence — the aspects a modeller can directly change. The categories 'Organisational', 'External', 'Commissioner' and 'National', outside the modeller's direct sphere of influence, feature more frequently for motivations behind decisions about 'Model software and Data selection'. These modelling steps are often formalised in the organisation's vision or available infrastructure. The category 'Consequential' is used as motivation across all modelling steps. Since most modelling steps are related to each other, it is unsurprising that this category is a motivation in all modelling steps. However, this category occurs considerably more in the modelling steps 'Pre-processing' and 'Model set-up'. For the 'Model set-up', this is because this modelling step is partially dependent on the default settings in the model software. This thus implies that some decisions in the 'Model set-up' are not explicitly made, but a consequence of other decisions made earlier.

Fig. 4b depicts the division of the categories within each modelling step, which can indicate what type of motivation tends to inform a decision in each modelling step. Fig. 4b shows a similar general pattern as Fig. 4a — Individual and Team motivations inform the modelling steps concerning model implementation, while the other motivation categories inform the 'Model software and Data selection' more. Still, Fig. 4b highlights some other details too. For instance, the category 'External' accounts for about a quarter of the motivations in the modelling step 'Pre-processing'. This is in line with how forcing data are retrieved by the modellers: they retrieve them already pre-processed from the Royal Netherlands Meteorological Institute. This institute is considered an external partner that executed the pre-processing. It is also shown that the external partner and commissioner influence the modelling decisions 'Sensitivity analysis', 'Calibration', 'Uncertainty analysis', and 'Validation'. This can be explained by the general outsourcing of these steps from water authorities to the consulting companies due to a higher computational capacity and experience with these modelling steps available at the latter. In summary, both figures clearly depict that certain modelling decisions are more likely to be in the modeller's sphere of influence than others. The modeller makes decisions in model implementation, but is often confined in using a particular model or particular data by the organisation or at the national level.

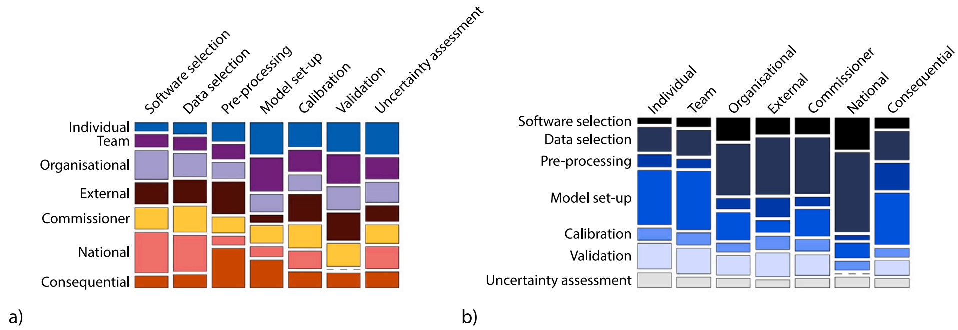

Fig. 4. Distribution of motivation-categories across different modelling decisions. (a) How the motivation-categories are divided within each modelling step. (b) How one motivation-category is spread across the modelling steps. The motivation-category 'International' was excluded, because it only contains two quotations.

3.4. Differences in motivations between water authorities and consulting companies

Another way to divide the motivations is based on where the interviewee worked, a water authority or a consulting company. The difference in responses between these two organisations is compared for each category we identified. We perceived no considerable difference for six of the categories: 'Individual', 'Team', 'External', 'National', 'International' and 'Consequential'. For the two overarching themes, there was only a substantial difference for the theme 'Standards'. In Fig. 5, the average number of quotations per interview are shown for the categories 'Organisational', 'External' and 'Commissioner' and the theme 'Standards'.

The interaction between water authorities and consulting companies can explain the differences in the average quotations per interview. Water authorities are often the commissioner of modelling studies, while consulting companies generally execute (parts of) of the modelling process for a client, in this case the water authorities. In line with this, the interviewees at the consulting companies more often mentioned motivations within the Commissioner category. An interviewee at a consulting company mentioned that the commissioner (i.e. a water authority) would provide the data in order to ensure consistency between modelling studies within the water authority. Interviewees from water authorities mention some codes classified in the 'Commissioner' category, because these relate to project management (e.g. 'Limit costs' and 'Time available in the project'). Where the consulting companies adhere to the vision and requirements of their commissioner, the water authorities define their own vision and requirements within their organisation. Hence, the water authorities have a higher average number of quotations in the category 'Organisational'. Still, modellers at consulting companies are influenced by the organisation they work in, for example through the organisational infrastructure or internal standards. For the difference in the category 'Standards', this has to do with the visibility of the standards. Modellers at water authorities see the standards their organisation imposes. Modellers at consulting companies generally see the standards that a water authority asks for as, for example, 'Determined by commissioner'. We saw this in the individual codes of the 'Standards' category: the interviewees at water authorities mentioned 'Standard in organisation' substantially more than interviewees at consulting companies. The other codes were more evenly distributed, because modellers at consulting companies also adhere to the national standards or have a similar perception that an option is not a choice (anymore).

We expected that motivations from the External category would be considerably more frequent for the water authorities, since they outsource some of their modelling. As said before, the 'External' category represents in some way the other side of 'Commissioner'. However, there is no substantial difference between the water authorities and the consulting companies in this category. We do see that within this category there is a difference that aligns with our expectation: the

Fig. 5. Comparison of motivations between water authorities and consulting companies.

code 'Executed by external partner' occurs more frequently for the water authorities than the consulting companies. Water authorities use consulting companies (their external partner) to execute parts of the modelling process in the Dutch water governance system. Consulting companies also use external partners, mainly in data pre-processing. This is why they scored equally with water authorities in this category.

4. Discussion

4.1. Modeller's sphere of influence

With this study we investigated how hydrodynamic modellers in Dutch water management make modelling decisions. Other studies have conducted similar work regarding the social aspects surrounding modelling, but focused on different aspects. Our results indicate that most modelling decisions are made at the individual level (the category 'Individual' had the highest number of quotes). This contrasts the findings of Melsen (2022), who found that most modelling-decisions are made at the team level. We hypothesise that this can be explained by how the interviewees conduct their modelling work. Whereas the interviewees from Melsen (2022) worked mainly in large research teams and concerned themselves more with model development and scientific publications, our interviewees worked in smaller modelling teams and were more involved in model application. This difference in context can explain why the individual category is larger in our study compared to the study of Melsen (2022) and can also explain why different classifications emerged from the data compared to Melsen (2022). Babel et al. (2019) – an interview study about how models are constructed in various disciplines – also recognised that the team and collaborators are key actors in model development, which was seen across the different disciplines. These studies Babel et al. (2019), Melsen (2022) highlight team considerations as a main influence on modelling decisions and within model development.

Other studies, that also include perspectives from government and industry, recognised that individual, team and organisational considerations play a considerable role in modelling decisions. Fleming (2009) found that non-technical issues – issues related to the context in which a modelling study is executed – account for 27% of the reasonings in model selection. Within this 27%, the organisation, costs and standards within the industry were the top three motivations. This aligns with our results, in which the national level and the organisation were influential in model selection. Deitrick et al. (2021) show that ethical values, alongside epistemic ones, are used in making modelling decisions. Generally, more epistemic values were mentioned. However, Deitrick et al. (2021) recognise that their respondents related ‘that values are not something that they typically reflected upon’. One of our interviewees brought this up as well: at the end of the interview they expressed that the interview had been insightful for them too, since they do not have a lot of time for reflection during their day-to-day tasks. Another interviewee reflected that it used to be possible to trace back a certain model to an organisation or sometimes even a particular modeller based on its model structure and settings (Quote 13 below). This clearly reflects that modellers leave a fingerprint on their models. Other studies have also shown the modeller’s fingerprint on the model results (e.g. Holländer et al., 2009, 2014; Krueger et al., 2012; Lahtinen et al., 2017; Saltelli et al., 2020). All studies show that modelling decisions are within the modeller’s sphere of influence, meaning that a modeller leaves their fingerprint on the results.

> A few years ago, I mainly worked on a secondment basis, during which you see the models of other consulting companies as well. At a certain moment, I could just see which company made the model based on its schematisation. Sometimes you could even derive which person created a model. As a modeller, you just have a lot of influence on your model. (...) I think that a water authority can also make this distinction – which consulting company made a model when they see it. – Quote 13 (Interviewee at Consulting Company)

4.2. Institutionalisation and internalisation

Even though a modeller leaves a fingerprint on the model result, other factors impact the modelling decisions too. Melsen (2022) introduces the concepts of institutionalisation and internalisation. Institutionalisation occurs when a team or organisation takes up an individual modeller’s method as a general method. Babel et al. (2019) recognise that ‘methods can be actants in shaping organisations’, which reinforces the concept of institutionalisation. This shaping is due to the development of certain infrastructure. Internalisation means that an individual modeller makes the methods used in their team or organisation their own. Babel et al. (2019) use the concepts incorporation and anchoring. Incorporation means that a choice of a certain method is transferred from one person to another, including the process of making this method your own. Addor and Melsen (2019) have alluded institutionalisation and internalisation, as well. They highlight that continuous use of the same model creates a particular ‘modelling ecosystem’, i.e. institutionalisation. Organisations might be more prescriptive about model structure and data selection to ensure a baseline for modelling quality. The modelling outcomes have to be accountable and reliable when used in decision support.

Internationalisation was not explicitly observed in the interviews of this study but was hidden in the answers of the interviewees. For example, in Quote 2 above, the interviewee states that they adopted the common method in their organisation with regards to the retrieval of roughness values. This interviewee was aware of other alternatives, but found it easiest to adopt this particular method. Quote 14 below highlights internalisation by knowledge being passed down from one modeller to the next. Babel et al. (2019) refers to this as embedded social knowledge — knowledge is passed down and adopted. Both quotes (Quote 2 and Quote 14) show that internalisation occurs.

> On the one hand, that [sensitivity analysis, red.] is passed down so to say, from hydrologist to hydrologist. And what works is just shared. – Quote 14 (Interviewee at Consulting Company)

Institutionalisation was more visible in our interviews. The creation of standards within an organisation is a form of institutionalisation. An organisation can formulate a certain workflow or prescribe the use of certain data. Moreover, the code ‘No longer a choice’ encompasses the result of institutionalisation: a modeller no longer feels as if they have a choice because a standard is present in the organisation (Quote 15). The interviewee indicates that at one point a choice was made and this is now copied by them. This standard in the institute can be perceived as if there is no longer a choice. Similar to our code ‘No longer a choice’, Babel et al. (2019) highlighted that for the modellers they interviewed some decision seemed ‘evident’, either because of popularity, standards, typical or common use. Internalisation, institutionalisation and modelling decisions seeming evident imply that motivations are generally applicable to various modellers or within a discipline.

> Yes, I think that that [temporal resolution, red.] has perhaps just been filled in one time, which you copy so to say. – Quote 15 (Interviewee at Water Authority)

However, generally-applicable motivations are in contrast with modellers leaving a fingerprint on the modelling results. Babel et al. (2019) also saw a pattern that interviewees distanced themselves from generalisations. Initially, their interviewees started with the generalisation ‘Everybody’, which was slowly lessened to their own discipline and to subgroups within their discipline. We distinguished a similar pattern, where our interviewees preluded their answers with ‘It depends on ...’. The aspects it depended on were goal, study area, model structure, situation, and project. Other times, our interviewees referred to a distinct example of when they made a certain modelling decision. This break-away from generalisations supports the idea of a modeller leaving an individual fingerprint. Even though a modeller can leave a fingerprint, their sphere of influence and thus the clarity of their fingerprint is bound by institutionalised predefined decisions.

4.3. Fit-for-purpose models

The tendency to link motivations to specific circumstances implicitly means that according to the interviewees a model should be fit for purpose. A fit-for-purpose framework was developed by Hamilton et al. (2022). They define three requirements for a modelling study to be fit-for-purpose: Usefulness, Reliability and Feasibility. Each requirement covers a different context, respectively end-user and management, problem, and project context. Hamilton et al. (2022) have indicated multiple key considerations per requirement. Taking these into account, the motivations from our interviewees do seem to align with the requirements (as indicated in Supplementary Material B). For example, Usefulness covers among others codes related to ‘Depends on ...’ and the category ‘Commissioner’. Reliability is seen in the codes ‘Hydrological knowledge/processes’, ‘Logic’, and ‘Testing’. The codes ‘Limit costs’, ‘Available time in project’, and ‘Personal experience’ are represented by the requirement Feasibility. This suggests that modelling in the Dutch water governance system seems to align with this fit-for-purpose framework. However, the codes from our interviews mainly fall in the Feasibility requirement (866 quotations, compared to 340 for Usefulness and 283 for Reliability), while in the fit-for-purpose framework it is recommended that the motivations are more balanced across the three requirements (Hamilton et al., 2022).

In the context of model usage for decision support, which require fit-for-purpose models, the interaction between the modeller and the decision maker is relevant. Just as modellers have their own values about, perspectives on and expectations of models, so do decision makers and other stakeholders (Borowski and Hare, 2007; Deitrick et al., 2021; Hamilton et al., 2019; van Voorn et al., 2016). We did not cover this aspect in our interviews, however, our interviewees did address this sometimes. Some interviewees mentioned that they did not perform an uncertainty analysis, partly because they experienced previously that decision makers did not know how to handle uncertainty ranges in their decision making. Yet, addressing model uncertainty is part of the reliability requirement of the fit-for-purpose framework. Therefore, creating fit-for-purpose models should be a joint effort of all stakeholders, in which they will carve their modelling path together.

The interaction between stakeholders is necessary before, during and after the modelling process. However, certain intentions might not be realised. The realisation of a modelling study can be described as a path, on which multiple decisions are made at forks. The interaction between stakeholders can ease the retracing of the modelling steps if necessary (Lahtinen et al., 2017). The retracing is based on checkpoints, peer review and other forms of evaluation. Lahtinen et al. (2017) provide specific recommendations. Still, as one of our interviewees indicated, evaluations are currently not formally executed on a regular basis, especially during crisis situations. They mentioned that during the modelling study not enough time and funding is available to execute evaluations. Also, the time for evaluation is after a crisis, but even then it is not often executed due to other pressing matters. In the Australian example, also a crisis situation, they did adapt the operators manual, so future situations would be handled differently (Supreme Court of New South Wales, 2021). This does show hindsight evaluation. With evaluation in place, a perfect modelling path is not guaranteed, however, following a poor path can be avoided (Lahtinen et al., 2017). Our interviewees seemed to be willing to have a more adaptive modelling approach. To put these evaluations in place requires commitment from modellers to be as transparent as possible, from decision makers to have the conversation about uncertainty, from the commissioner to provide the infrastructure, and from stakeholders to be willing to engage throughout the modelling study.

5. Conclusion

In this study, we explored motivations behind modelling decisions for hydrodynamic decision support modellers in the Netherlands. We conducted fourteen interviews with modellers from water authorities and consulting companies. Afterwards, we executed an inductive content analysis on the transcripts. The analysis lead to a classification of modelling decision motivations with eight categories: motivations based on individual considerations, team considerations, the organisational level, external inputs, the commissioner's requirements, the national level, the international level and consequential effects. Additionally, two overarching themes were identified: Vision and Standards. Furthermore, we evaluated which category of motivations dominated for different modelling steps. On top of that, we looked at differences in modelling motivations between modellers from water authorities and from consulting companies.

Our results indicate that most modelling decisions are made at the individual level (the category 'Individual' had the highest number of quotes). Mainly decisions related to model implementation are within the modeller's sphere of influence — the aspects an individual can (in)directly change. This is where the modeller can leave a fingerprint: one interviewee indicated they were able to recognise which modeller created a certain model schematisation. Most of the model software and data selection is based on motivations in the categories 'Organisational', 'External', 'Commissioner', and 'National'. These aspects tend to be outside the modeller's direct sphere of influence. Still, modellers do see that modelling decisions depend on the context of the modelling study, implying that a model should be fit-for-purpose. The motivations in our case study seem to align with the requirements (Usefulness, Reliability and Feasibility) of fit-for-purpose, but in our case, feasibility seemed to be more of an argument than reliability and usefulness. This means that other factors, such as institutionalised predefined decisions, limit the modeller's sphere of influence and thus the sharpness of their fingerprint

CRediT authorship contribution statement

J.O.E. Remmers: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **A.J. Teuling:** Supervision, Visualization, Writing – review & editing. **L.A. Melsen:** Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

For the protection of privacy sensitive information, the interview data are unavailable for public release. The interview data are stored on the DANS Data Station Social Sciences and Humanities (Remmers, 2024). The interview protocol is included in Supplementary Material A.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.envsoft.2024.106167. The supplementary material contains the interview guides and the inductive content analysis.

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