# On the communication of statistical information about uncertainty in flood risk management

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**Highlights:**

-Statistical uncertainty was hard to interpret by water board professionals

-Uncertainty information is underutilized in flood risk decision problems

-During decisions, uncertainty information shifts from quantitative to qualitative

-Well-structured decision problems are essential

-We recommend designing of decision models prior to a project

**Abstract**

Uncertainty analysis is not typically performed in hydrological and hydraulic modelling. This is problematic because this may lead to inefficient decision making in water management. We therefore explored the role of statistical knowledge on uncertainty in decision-making processes in long term flood risk management within the context of regional water boards in the Netherlands. Research questions were: (1) in which parts of flood risk management statistical information about uncertainty is presented to professionals of district water boards, and in which forms?; (2) how is this information interpreted and used by these professionals, and how does this influence decision-making processes in district water boards?; and (3) how can communication about statistically quantified uncertainty be improved? To answer these questions we conducted interviews and surveys among professionals and board members of Dutch district water boards. Results suggest that statistical information on uncertainty is hard to interpret by professionals. The amount of statistical information on uncertainty strongly reduces during the decision making process, during which the information transforms from quantitative to qualitative. As a result the statistical information on uncertainty is not utilized to solve flood risk management decision problems. These decision problems are not formulated within statistical frameworks for decision making, and statistical information on uncertainty is not collected and presented with the purpose to be input of such frameworks. Practical recommendations for long term flood risk management are discussed.

Keywords: Decision analysis; Flood risk management; Risk communication; Uncertainty

# 1. Introduction

## 1.1. Use of statistical information on uncertainty in flood risk management

This study focuses on how professionals in flood risk management process statistical information on uncertainty, which is associated with the outcomes of monitoring and modelling. In particular, we are interested in the psychological aspects related to processing of statistical information and in the various ways uncertainty is coped with. Furthermore, we are interested in how conditions can be created to utilize statistical information on uncertainty optimally in decision making.

Besides expert knowledge and experience, hydrological and hydraulic modelling plays an important role in district water management in the Netherlands. Estimates, predictions and forecasts resulting from hydrological and hydraulic modelling are used to support decision making. Pappenberger and Beven (2006) discussed seven possible reasons why uncertainty analysis is not performed in hydrological and hydraulic modelling by a significant part of the professional community. We cite these seven reasons and briefly expound on them as follows:

1. "Uncertainty analysis is not necessary given physically realistic models". This point of view is typical of researchers who firmly believe in the correctness of their physically based models.
2. "Uncertainty analysis is not useful in understanding hydrological and hydraulic processes". Hypothesis testing can be applied to gain insights in hydrologic systems. Hypothesis tests can be based on model predictions only, without including information on uncertainty. However, the extent to which one can believe in the outcomes of such tests depends on the belief in the correctness of the model.
3. "Uncertainty (probability) distributions cannot be understood by policy makers and the public". A goal of hydrological modelling can be to provide decision makers and other stakeholders with information. Modellers might suppose that policy makers and

public are not capable to correctly interpret information on uncertainty. In the context of this study this reason of ignoring information on uncertainty is interesting, since it is related to effective communication, (lack of) understanding, and the various perceptions of risk and uncertainty.

4. "Uncertainty analysis cannot be incorporated into the decision-making process", because it is supposed that information on uncertainty is useless in decisions that are binary in nature, or that a choice between various scenarios is impossible if uncertainty bounds are large.
5. "Uncertainty analysis is too subjective". In uncertainty analysis it might be needed to make more or less subjective decisions, for example on probability distributions. However, using this as a reason for not considering uncertainty seems to imply that deterministic modelling in which uncertainties are not taken into account can be objective.
6. "Uncertainty analysis is too difficult to perform". As a consequence, uncertainty is not performed because of lack of time, money, and good guidance.
7. "Uncertainty does not really matter in making the final decision". It might be true that the outcomes of decision processes in which uncertainty was not considered nevertheless positively contributed to the civilization. However, it cannot be denied that uncertainty plays an important role in debates on environmental issues such as climate change (Patt & Dessay, 2005).

Pappenberger and Beven (2006) argued that none of these seven reasons are, in the end, tenable. Furthermore, a good reason to utilize statistical information on uncertainty in decision making is that efficiency can be increased, which is a main pursuit for water district managers and board members in the Netherlands. Efficiency means that efforts and expenses actually contribute to the adequate management of flood risks, and that in doing so the costs and benefits are in good balance. To substantiate decision making, decision makers such as water managers and board members need to be informed on the state of water in their district. Raw data are seldom presented to decision makers. Instead, data are usually first processed using statistical techniques, hydrological models, etc., after which estimates, predictions, forecasts, or outcomes of test procedures are presented to decision makers. The degree of accuracy of this information – that is, the degree of resemblance with reality – can be expressed by statistics such as standard errors, confidence intervals, and error rates, which can be seen as measures of *uncertainty* about the true state. Statistical information about the uncertainty is not always provided, however. If uncertainty is presented to decision makers, then this is done by means of statistics. As such, our study deals with the risk that statistical information on uncertainty is not utilized in flood risk management, which may lead to inefficient decision making. This is not trivial, because flood risk management is a very cost-intensive activity performed by regional water boards, which gets funded by public tax money.

Let us define an *efficient* decision as a decision that minimizes loss or maximizes utility, given the available information. The question is now whether or not including an uncertainty analysis using statistical information on uncertainty results in more efficient decisions. Morgan, Henrion, and Small (1990) demonstrated that decisions based on 'best estimates' only, for instance central values such as the mean, are not necessarily the most efficient decisions. They used the Expected Value of Including Uncertainty (EVIU) to measure the value of explicitly accounting for uncertainty in a quantity instead of assuming some fixed, central value. EVIU is the expected difference in loss (or utility) of a decision based on an uncertainty analysis and a decision that ignores uncertainty. Depending on the nature of the decision problem, loss or utility can be expressed by monetary values, lives, crop yields, etc. Similarly, Morgan et al. (1990) used the Expected Value of Perfect Information (EVPI) to measure the value of reducing uncertainty to a zero level. They showed decision problems in which EVIU is positive, or even larger than EVPI. This means that including uncertainty in solving these decision problems is efficient, or even more efficient than reducing uncertainty. Furthermore, this shows that uncertainty analysis can contribute to the efficiency of decisions. Not surprisingly, including uncertainty information is key in risk reduction and designing improved safety decision-making (Pasman, Rogers, & Mannan, 2017; see EFSA, 2018, for an excellent analysis of how uncertainty information is also relevant in the domain of food safety). Nevertheless, uncertainty analysis in which statistical information on uncertainty is applied is not a standard element of decision making in district water management in the Netherlands.

Although Pappenberger and Beven (2006) did not address psychological reasons explicitly, some of the reasons they mentioned imply that the way people think and decide is an important factor in the way they use statistical information on uncertainty. In particular, the distinction made in the psychological literature between experiential and analytical ways of processing of information might be very relevant to understand the way statistical information is used in water management (Chaiken & Trope, 1999; Epstein, 1994; Marx et al., 2007; Sloman, 1996; Slovic, Finucane, Peters, & MacGregor, 2004), and warrants further scrutiny. In the analytical or 'slow' way information is processed using reason and logic, expressed in algorithms and normative rules, whereas in the experiential or 'fast' way information is processed using intuition and affect (Kahneman, 2011). The distinction between these two ways of processing information is relevant in understanding the way professionals in water management process statistical information in decision making (for an example in which these two systems predict flood risk perception among members of the public, see Botzen, Aerts, & Van den Bergh, 2009). For instance, decisions in operational water management, to be made under time pressure with the outlook to an upcoming hazardous event, will be based more on experience and feeling rather than on analysis, logic and statistical data. However, if decisions with long term impacts can be taken without serious time pressure – such as is typically the case in long term flood risk management – then time will not be a serious limiting factor for an analytical processing of statistical information on uncertainty. Nevertheless, Pappenberger and Beven (2006) indicate that also in these situations professionals in water management might find reasons not to perform uncertainty analyses. Furthermore, they suggested that one reason why uncertainty analysis is not common practice is the lack of guidance on methods and applications.

### 1.2. Aim and scope

In this article, we put forward the notion that insight into the psychological aspects of decision making in long term flood risk management can help in understanding why statistical information on uncertainty is ignored, and to create conditions under which statistical information is optimally utilized to take efficient decisions. In summary, we first want to find out how professionals in flood risk management process statistical information on uncertainty, before developing and implementing new tools and guidelines for uncertainty analysis. This seems to us a more efficient and rewarding approach than first developing new tools and guidelines for uncertainty analysis, and being disappointed afterwards about professionals who make little or no use of it.

The aim of this study is to analyze the presentation, interpretation and utilization of statistical information on uncertainty by professionals and board members of water districts in the Netherlands, in order to develop recommendations for improving the strategic decision making processes in long term flood risk management. Research questions are:

1. In which parts of flood risk management is statistical information about uncertainty presented to professionals of district water boards, and in which forms?
2. How is this information interpreted and used by these professionals, and how does it influence decision-making processes in district water boards?
3. How can communication about statistically quantified uncertainty be improved?

### 1.3. Theoretical framework

In this study on communication of statistical information about uncertainty in flood risk management, two aspects of human behavior need further consideration as a theoretical starting point. The first aspect concerns the ways in which people process statistical information, such as estimates, confidence intervals, outcomes of statistical tests, et cetera. The aforementioned distinction made in the psychological literature between experiential and analytical ways of processing of information (Chaiken & Trope, 1999; Epstein, 1994; Marx et al., 2007; Sloman, 1996; Slovic et al., 2004; Kahneman, 2011) is therefore the first element of the theoretical framework used in this study.

Since we focus on communication of statistical information about *uncertainty*, the second aspect of human behavior to be considered is the way people cope with uncertainty. A useful second element of the theoretical framework might be the 'monster metaphor', applied by Van der Sluijs (2005) "to explore the way in which the scientific community responds to the monstrous uncertainties that they face in the production of the knowledge base of complex environmental problems." The monster metaphor was introduced by the Dutch philosopher Martijntje Smits in a PhD thesis in Dutch (Smits, 2002; see Smits (2006) for an article in English based on this PhD thesis). The monster metaphor is based on the idea that people are accustomed to order the world into binary, mutually categories such as humans versus animals. If a phenomenon fits into two categories that were considered to be mutually excluding, it will grow out to a monster. The mutually excluding categories, determined by Van der Sluijs (2005) in the science-policy interface of environmental problems might also apply to the applied statistics-decision making interface in long term flood risk management: "knowledge versus ignorance, objective versus subjective, facts versus values, prediction versus speculation, and science versus policy".

Therefore, we consider the monster metaphor as a useful theoretical framework in exploring the way professionals and board members of water districts in the Netherlands deal with statistical information on uncertainty in flood risk management. Van der Sluijs (2005) defined four coping strategies with monsters in the science-policy interface. If we apply the monster metaphor to statistical information in flood risk management, we can distinguish the following strategies with which professionals and board members of water districts cope with uncertainty: (1) performing additional research and monitoring to reduce uncertainty (*monster exorcism*); (2) dealing with uncertainties by quantifying them (*monster adaptation*); (3) emphasizing uncertainties, for instance from a holistic or spiritual point of view or to perspective the outcomes of scientific research (*monster embracement*); (4) mentioning uncertainty explicitly, and looking for ways to account for multiple outcomes and to make choices transparent (*monster assimilation*). In contrast to monster adaptation, in monster assimilation there is not a single 'optimum' that can be computed. Transparency of the possible options from various perspectives is strived for, and ambiguity and pluralism are seen as unavoidable aspects of risk assessment. Complementary to the four coping strategies proposed by Van der Sluijs (2005) we add the possibility that executives deny uncertainty and put the responsibility for decision making at the layer of policy makers (*monster denial*).

## 1.4. The present research

To answer the research questions we conducted interviews and surveys among professionals involved in various stages of decision making, and district water board members. In the Netherlands flood risk management is extremely important. The country is situated in the delta of the rivers Rhine and Meuse, large parts are below the North Sea level and the yearly precipitation surplus is positive. Not surprisingly, the Netherlands have a long tradition on 'the fight against water'. Traditionally, water districts are responsible for the protection of inhabitants against floods. Water boards are the oldest democracies in the Netherlands, with elected board members. The board is responsible for all decisions made on flood risk management. The board is supported by a staff, with professionals such hydrologists, civil engineers, legal advisors, and policy officers. They collect and process all information needed to support the board members in decision making. Data are collected in monitoring networks in the water district or derived from national databases, and research is commissioned to research institutes and consultancy offices.

In the current research we present three consecutive studies in which water management professionals were invited to participate. The first and second study focused on hydrologists and policy makers to explore in which phases they encounter information about statistical uncertainty, how this information is presented to them, and how they interpret it. The third study moves further along the decision chain by interviewing board members and this study focuses on the question how communication and interpretation of statistical information play a role in decision-making processes of board members of district water boards. Together, this series of studies aims to provide insights in these communication processes in order to provide recommendations for improving communication about statistically quantified uncertainty so that this information is optimally used by professionals in decision-making processes.

## 2. Study 1

### 2.1. Methods

This study consisted of two complementary phases. The goal of the first – explorative – phase was to gain insight into the concrete and actual way of testing water systems against standards of regional flooding, and into the practices of communicating about uncertainty. Four water board professionals who worked as policy advisors or hydrologists were interviewed. Interviews were semi-structured around relevant themes. Questions were asked about what statistical information means in practice, in what activities statistical information about uncertainty is communicated, how it is made clear that statistical information may include an uncertain element, and how the regional water board in general deals with statistical information about uncertainty. Also, it was asked whether formal training is offered to employees to interpret statistical information, and whether those trainings are obligatory. Finally, it was asked whether the communication about uncertainty is positive of negative for the work at the water board, and to what extent the interviewees felt satisfied regarding the extent of communication about this topic. Furthermore, interviewees were asked to respond to four cases in which statistical information about uncertainty played a role (see Appendix). In the second – in-depth – phase water board professionals from eight water boards were interviewed. The goal of that phase was to gain insight into how statistical information is presented and interpreted among different water boards. Questions were asked about how statistical information about uncertainty is understood, whether in the job-related activities uncertainties are statistically represented (e.g. in scenarios), whether certain presentation formats are asked by the general board, whether data can always be interpreted, what positive and negative effects presentation of uncertainty may have, which constraints exist in communicating uncertainty, and to what extent the interviewees felt satisfied regarding the extent of communication about uncertainty. In the in-depth phase, apart from conducting semi-structured interviews we also analyzed how statistical information about uncertainty was presented within (internal) reports produced by the respective water boards.

As in the Netherlands two main types of water boards exist – those located in more elevated parts and those in lower areas, each with different implications for water management practices – professionals working at water boards were selected by drawing a stratified random sample from both types of organizations (50% of interviewees worked at a low area or elevate regional water board, respectively). Interviews lasted about one hour, and were conducted at the local office of the respective water board professionals.

**2.2. Results**

**2.2.1. Explorative phase**

The interviews from the explorative phase were held to orient for the subsequent in-depth phase regarding how professionals deal with uncertainty. All four respondents indicated that (a) communication of uncertainty is very relevant, but complex, and takes place thinly, and that (b) communication of uncertainty may lead to unrest and additional uncertainty (also see Nakayachi, Johnson & Koketsu, 2018). One respondent mentioned that by just presenting 'hard numbers' – without including statistical uncertainty – will lead to poor decisions on the long term. However, the same respondent also pointed at the hazard of 'stacking' different kinds of uncertainty in an analysis could also hinder the goal of making decisions. Another respondent gave an example of an area in which a way too high safety level was implemented (i.e. the costs-benefits differed a factor 10). This led too exorbitant costs, which could have been avoided if uncertainty was included in the decision making. Five reasons were mentioned for not communicating uncertainty: (1) lack of knowledge about statistics; (2) the word 'uncertainty' suggests that one does not know or does not have grip on professional matter; (3) a lack of time causes little attention for the communication of uncertainty; (4) the value of information about uncertainty is not acknowledged; and (5) communicating uncertainty is too complex. One respondent said she considered things are fine as they are. Board members need to keep the bigger picture in mind and statistical uncertainty is too detailed and required too much expertise. So, she thought the board must be able to rely on people who know what they are doing and give advice based on this as these matters are just far too technical for the board. All interviewees pointed at the gap between parties who present statistical information about uncertainty, and those who – later on in the chain – interpret it. Presenting parties are consultancy firms, research institutes, and professionals at water boards who work on technical subjects. The interpreting parties are technical water board professionals, policy advisors, and people working in water governance. For people working on this interpreting side no formal statistical training is offered. Solutions to close the gap between the parties that present and interpret information about uncertainty included suggestions that refresher courses in statistics should be taken by people working in interpretation, more knowledge is needed at presenting parties concerning decision problems of water boards, and that research assignments issued by water boards should be reformulated. One interviewee explicitly brought up that some policy makers have insufficient statistical skills, and are therefore unopen to feedback on the subject. Instead that knowledge on statistical uncertainty helps them to make better decisions, it makes these people uncertain themselves.

Finally, the respondents voiced that they preferred presentation of statistical information about uncertainty to technical employees and hydrologists, so that they can implement this information in advising their board members, but that this would require a shift in thinking because it becomes harder to advocate policy measures when a bandwidth is used alongside 'hard' numbers. Although bandwidths are considered to be a sound way of presentation, often this information about uncertainty is not offered because it complicates matters.

The four respondents were also confronted with four cases of statistical decision problems (see Appendix) in order to find out how they interpret these problems. The first case concerned absolute and relative frequencies and single-event probabilities. Respondents indicated that return periods are the most common way to represent crossing a water level. Single-event probabilities were not reported to be common nor appealing, but relative frequencies were considered an attractive alternative. One respondent noted that 'once per fifty years' was often interpreted as 'every fifty years', while another respondent said that 'once per fifty years' would be seen at the water board as an event that would take place at least once in a lifetime.

The second case was about the interpretation of confidence intervals versus error bars. The respondents indicated to be more familiar with 95%-confidence intervals than with error bars (that represent a mean plus or minus the standard error). They mention that error bars are barely used, and found this case hard to respond to. Bandwidth is a much used term in communication in tactical-strategic water management. Apparently, it is intuitively assumed that with bandwidth a 95%-confidence interval is meant. The respondents were not acquainted with the concept of standard error, nor with its relationship with a 95%-confidence interval.

The third case concerned interpreting a risk map that included information about model uncertainty, versus not. Respondents indicated that a map like this is more appealing to them compared to figures or a graph, and that it stimulates them to put more effort in its interpretation. However, correct interpretation of the statistical problem turned out to be difficult.

The last case concerned testing of water systems in the light of null-hypothesis significance testing (NHST). All respondents agreed that this kind of decision problem is rare in water management, and it showed that all respondents had a hard time answering this question. This is remarkable, because in tactical-strategic water management testing for meeting standards is common.

#### 2.2.2. In-depth phase

After the explorative phase, structured interviews were held with professionals from eight water boards. No structural differences in responses emerged between respondents from water boards located in low versus high areas. One of the questions that we sought to answers was in which parts of long term flood risk management statistical information about uncertainty is presented to professionals of district water boards. During the interviews, the picture emerged that different steps in communication can be distinguished:

1. Consultancy firms & research institutes → hydrologists at water boards;
2. Hydrologists at water boards → policy advisors at water boards;
3. Policy advisors at water boards → general board members of water boards.

Along this chain there is a shift from quantitative information about uncertainty to qualitative information (see Figure 1). There is an apparent decrease in communication about statistically quantified uncertainty. As became apparent from the interviews, the strength of decrease differed between water boards. For each of the communication steps the following can be noted:

Ad 1) about half of the water boards have clear arrangements with consultancy firms and research institutes on how to present quantitative information. At some water boards the professionals from consultancy firms and research institutes have in-house office space, which can result in more direct and more frequent communication. At other water boards, there is more freedom regarding the choice in modes of presentation. This may lead to difficulties in interpretations because there is a disconnect between consultancy firms and research institutes on the one side and water board professionals on the other. One respondent indicated that reports from consultancy firms tended to be shallow on information about statistical uncertainty. This respondent voiced the complaint that this was a pity as it impedes a full understanding of the situation.

Ad 2) at this step the transformation from quantitative to qualitative information about uncertainty takes place. However, because of direct communication channels, this communication is not regarded to be problematic. One interviewee said that people working at this stage have highly developed statistical skills, but choose often not to use those because they don't need to be overly precise. Another respondent said that internal communication about uncertainty takes place primarily in conversations or through short emails, but typically not in formal reports.

Ad 3) it was found that at most water boards, statistically quantified uncertainty is only sparingly communicated to the general board. The following reasons for this were mentioned: a lack of knowledge about statistically quantified uncertainty; a lack of insight into the added value of statistically quantified uncertainty; a lack of motivation; a lack of time, because of work pressure. One respondent mentioned that they use qualitative information, i.e. classes or categories, rather than the underlying quantitative estimates – admitting that no precise calculations have been performed to support these recommendations. However, he said that he did communicate bandwidths, to add that those are not solidly founded, and that the bandwidths had a more of a qualitative nature just to indicate uncertainty was involved. Another respondent mentions that some general board members would become uncertain if too much information on statistical uncertainty would be included in advices to the board. Yet another respondent said communication about uncertainty to the general board has predominantly a qualitative character, but when that information about statistical uncertainty is used in the form of bandwidths in case cost estimates are given.

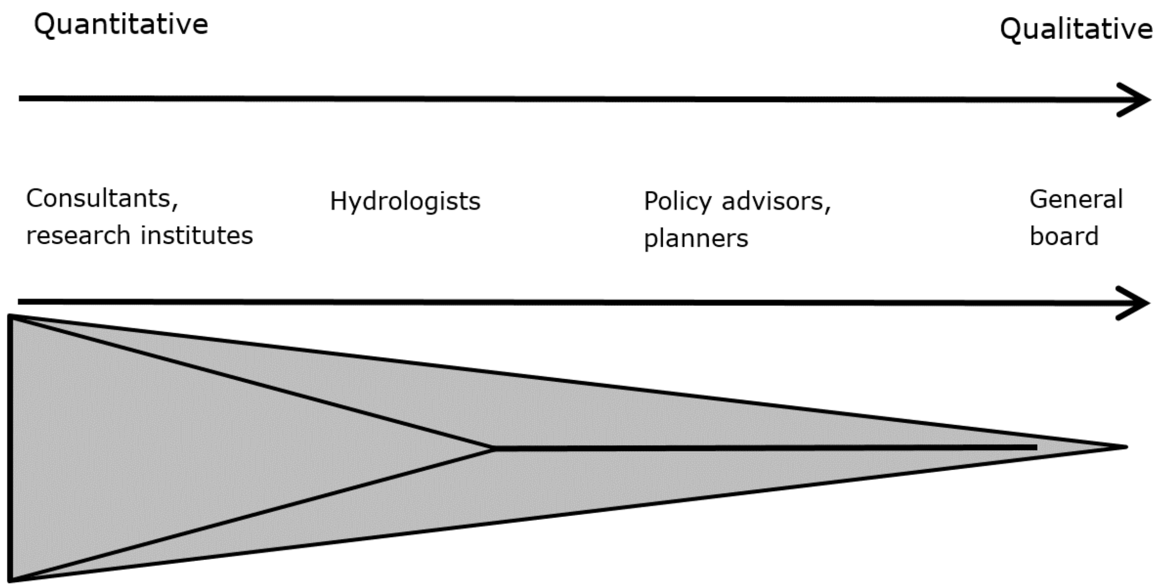


**Figure 1.** Scheme of the reduction in communication of uncertainty at district water boards. During initial stages, quantitative information on uncertainty is amply communicated. Moving towards the phase in which board members make decisions, the amount of information being communicated reduces quickly and changes from quantitative into qualitative (Study 1).

Apart from a shift from quantitative to qualitative information, also a picture emerged that showed a shift from analytical to experiential information processing. This is relevant for answering the second research question. Experts from consultancy firms and research institutes tend to process statistical information in a more analytical way, defined by formal acts, logical rules, abstract symbols, and deliberate decisions. We also observed that policy advisors and water board executives will rely more on cause-consequence relationships, vivid imagery, and heuristics – especially the recency, availability, and affect heuristics (Slovic et al., 2004; Tversky & Kahneman, 1973). For example, one hydrologist indicated that general board members have to take political decisions, so they just want a rough understanding of the bigger picture. The respondent indicated to deal with this by just preparing information for the policy makers that is lean on information about statistical uncertainty.

During the interviews positive and negative aspects of communication of statistical information about uncertainty were expressed. Positive aspects were: (1) it offers transparency; (2) data is handled in a conscientious way and avoids false certainties; (3) it offers bandwidths to the general board – as long as the board can handle that; and (4) it enables more cost-effective decisions, possibility to save money. The following negative aspects were most often mentioned by the interviewees: (1) absence of added value and purpose; and (2) uncertainty instils unrest. Other negative aspects were (3) that uncertainty hinders comprehension; (4) uncertainty costs time and money; and (5) work becomes easier by just omitting uncertainty.

## 3. Study 2

The second study builds on the results of Study 1. Interviews with policy advisors at water boards were conducted to answer the question how quantified information about statistical uncertainty is interpreted and used by these professionals. More specifically, we wanted to explore which way of presentation would be interpreted best by policy advisors.

### 3.1. Methods

Eight water board professionals from eight different water boards were interviewed. As in Study 1, a stratified random sample of professionals who worked as policy advisors from low and high water boards were included (four from each type). The semi-structured interviews included a number of predetermined topics: Statistical information: which forms of presentation of statistical information are used at the water board? What is the personal opinion about the use of statistical information and the way in which it is presented? Target group: does the target group (recipients of uncertainty information) make a difference for its way of presentation? Statistical knowledge: what is the perceived level of knowledge about statistical information of water board co-workers? Research institutions: do these provide (enough) information about uncertainty to policy makers? Communication with the board:

what is the perceived level of knowledge about statistical information of board members? How do policy makers ensure that the right information reaches board members, and how do they present this? Secondly, just like in the explorative phase of Study 1, interviewees were asked to respond to four cases in which statistical information about uncertainty played a role (the same cases were used, see Appendix). Interviews lasted about 45 minutes, and were conducted at the local office of the water board professionals.

### 3.2. Results

Each respondent was asked to study the four cases. The semi-structured interviews were structured along questions related to these cases, the participants' first reactions, and some predefined subjects to discuss the use of statistics. At the end of each interview the interviewees were asked to assess the ease of comprehension, whether it provides a clear overview, the usefulness, and its clarity. The interviews did not yield any noteworthy differences between water boards in low versus high areas in terms of use and communication of statistical information about uncertainty.

**Case 1** was answered most often correctly, because the three statements represent an equal chance on flooding. The respondents indicated to be familiar with return periods. One of the respondents found that the presentation in relative frequencies or in single-event probabilities suggested too much certainty about future events. Return periods scored highest of all ways of presentation in all four cases in terms of ease of comprehension, providing a clear overview, usefulness, and clarity.

In **case 2** standard errors turned out to be difficult to interpret. Ease of comprehension, providing a clear overview, usefulness, and clarity were judged to be low for standard errors, and most respondents reported to not know what a standard error is. 95% confidence intervals received a more positive evaluation.

**Case 3** turned out to be difficult to interpret as only one respondent gave the correct response. One respondent indicated that maps are a popular way of presentation. Ease of comprehension, providing a clear overview, usefulness, and clarity was judged to be relatively positive compared to the other ways of presentation among the cases. The maps were derived from BOWA (Berekenen Onzekerheid van de Wateropgave [Computing the uncertainty in the water task]; Kallen, Botterhuis, & Hakvoort, 2012), an instrument intended to incorporate uncertainty in testing water systems against the national standards (Nationaal Bestuursakkoord Water [National Governance Agreement Water]; NBW). BOWA was actually developed as a response to calls of regional water management professionals to get more insight into the uncertainty of the calculated *water task*, which is the volume of water to be discharged, stored or retained to meet a standard for protection against flooding.

**Case 4** turned out to be the most difficult one to interpret. Respondents indicated that information about null-hypothesis significance testing scored lowest on ease of comprehension, providing a clear overview, usefulness, and clarity. Some respondents indicated that the presentation was too elaborate, and some respondents said they themselves did not perform hypothesis testing. This suggests that testing against standards related to flooding nuisance and water task are not performed in a statistical context, and therefore the chances for drawing wrong conclusions are unknown and the risks that result from that are not controlled. Moreover, this shows that statistical information about uncertainty that can be generated with BOWA (Kallen et al., 2012) is not utilized in testing water systems, which was the intended purpose of BOWA.

The interviews made clear that legal and policy requirements and societal interests are the most important drivers for water boards; efficiency and sustainability were remarkably enough judged to be less important. Standards are established on a national level as return periods. Water board professionals deal with societal actors that recognize formulations like ‘once every fifty years’. That explains the positive judgement of return periods as a way of presentation.

Although testing against standards was familiar to the interviewees, they had a hard time interpreting the information of null-hypothesis significance testing and they judged ease of comprehension, providing a clear overview, usefulness, and clarity of this information least positively. Most of the times an average is compared to a standard. In case the average does not meet this standard, further research is conducted and, if needed, measures are taken. The risks of wrong conclusions – that is inferring that the standard is met or not met – are not taken into account. The risks of wrongfully investing in additional research or taking measures are not controlled as a result. As a consequence, taking inefficient and suboptimal decision is not unthinkable.

Most interviewees are aware of the usefulness of information about uncertainty. However, communication about this takes often place with actors with little or no statistical skills: governance boards, citizens, farmers. Keeping up knowledge about statistics is therefore often not a priority. It is striking that most interviewees said that their knowledge about statistics used to be better, especially when they were students. However, they expressed that, during their professional work their statistical knowledge deteriorated because they tend to use this knowledge on a rather irregular basis. When asked whether research institutes provide sufficient uncertainty information and accuracy to the policy makers in order to be able to carry out their work properly, a number of interviewees said that they have agreed with research institutes and hydrologists how they would like to receive the information. One respondent indicated that he would like to know more about how figures and results are prepared, for example why sometimes percentages are used in reports, and sometimes not, while another wanted to know why little information about the accuracy of research measurements was used in practice. The statistical knowledge of the board members was generally estimated to be low. In order to prepare reports for the general board, one respondent voiced that he felt better off if one lets expertise speak without being dressed up explicitly with numbers.

## 4. Study 3

While the first two studies focused on presentation for and interpretation by water board professionals who worked as hydrologists or policy makers, the final study focused on board members and executives working at water boards and sought to provide answers to the question to which extent and in which way communication and interpretation of statistical information plays a role in decision-making processes of board members of district water boards.

### 4.1. Methods

Interviews were conducted with nine members of the executive board of the eight different water boards that were selected in Study 2. As in the previous studies, stratified random sampling made sure that executives from low and high water boards were evenly included (four of each type were selected). The interviews each lasted an hour on average, and semi-structured interviews were used. This means that it was established in advance what topics should be discussed with each director, and how these questions would be asked, but also that there was ample room for the respondent's own contribution. Interviews were structured along a number of themes relevant for the research question that this study focused on: (1) perception of uncertainty and risk: how board members define uncertainty in decision making in the context of managing flooding risks; (2) the role of knowledge and information in decision making: what role statistical information about uncertainty plays for board members in their decision making; and (3) communication of uncertainty: in what way uncertainty is communicated with executives, and possible points for improvement therein. Each interview specifically asked for example projects within the relevant water board, in order to make the answers as concrete as possible.

### 4.2. Results

#### 4.2.1. The role of knowledge and uncertainty in decision making

The interviews with board members provides a picture of how they understand uncertainty. The following themes emerged: (1) not everything can be known; (2) having doubts and not being sure about a decision; (3) the system is unpredictable: things can differ between situations, and it is impossible to learn about all characteristics and use this information in decision making; (4) uncertainty in decision making and about implementation of policies: e.g. executing measures is dependent upon finances and people which one cannot predict upfront. As in the previous studies, no substantial differences emerged between the two main types of water boards.

Board members expressed awareness that risks are always involved in decision making. Many board members describe the issues that they must decide upon as policy problems that vary from being well-structured to moderately-structured, and which the accompanying knowledge can support the decision making process. Four board members explicitly stated in the interviews that they are aware that uncertainty plays a role in the statistical information that is provided. However, one board member indicated that doubt about making the right decision was what many other board members understand by uncertainty.

In well-structured policy problems there is certainty about the relevant knowledge, and there is consensus about values. Statistically quantified uncertainty is often communicated in well-structured policy problems, while in moderately-structured policy problems weaknesses in the knowledge and missing information are apparent (Petersen, 2012, p. 83). From the interviews the picture emerges that executives deal with uncertainty in different ways (between parentheses the typologies proposed by Van der Sluijs (2005) that match the uncertainty strategies): (1) they call for (additional) research and monitoring to reduce uncertainty (*monster exorcism*); (2) they try to ask good questions in an effort to understand the decisions they need to make (*monster assimilation*); or (3) they put more effort in the way in which a decision under uncertainty is made (the process of decision making) than in doing more research to reduce uncertainty (*monster embracement*). Complementary to the coping strategies proposed by Van der Sluijs (2005) we also observed that interviewees (4) deny uncertainty and put the responsibility for decision making at the layer of policy makers (*monster denial*).

The strategy of *monster adaptation* (Van der Sluijs, 2005) – dealing with uncertainties by quantifying them – did not emerge as a strategy that was used by executives of water boards. The interviews show that little attention is asked for uncertainty related to the research itself in the decision making process, nor to the underlying values, and bandwidths. Also, a tension is noticed between the different kinds of decision problems and the role that knowledge plays in those. Most decisions are qualified as being structured well or moderately so: there is consensus about the goals, and the accompanying information on uncertainty suggests different possible decisions. However, water board executives also mention the importance of communicating uncertainty in decisions in which no consensus exists about values: in discussions about values there is a risk that uncertainty plays a smaller role, or is completely downplayed.

#### 4.2.2. Communicating uncertainty

Throughout the process of decision making board members acquire knowledge in different ways, during which they have possibilities, at various moments, to ask for explanations and the sharing of information. The information generated by research flows from hydrologists to policy makers, and further through the chain to board members. This is basically a linear process, but possibilities exist for feedback. The reasons given by board members for communicating the results of research are partly in line with the description of situations in which communicating uncertainty is required (Morgan et al., 1990). A few executives indicated that presenting knowledge by means of maps and diagrams has appeal, but that a sound underpinning remains important – stemming from the obvious reason that the executive board needs to be able to explain their decisions to the involved parties, including citizens. Another board member indicated that the use of images in communication to residents can lead to misinterpretations: residents can be frightened by showing expected flooding on their territory.

## 5. General Discussion

### 5.1. Overview of results and theoretical relevance

The results of this study show that the utilization of statistical information on uncertainty in decision making in long term flood risk managements depends on a range of factors, varying from how individuals think to how decision processes go within district water boards. Furthermore, these factors appeared to be interdependent. We summarize these factors and their interdependences as follows, starting at the level of how individuals think.

The distinction made in psychological literature between experiential and analytical processing of information (Kahneman, 2011) appeared to be very helpful in understanding how professionals and board members of district water boards interpret statistical information on uncertainty: nothing human appeared to be alien to them. The way of processing statistical information depends on the stage in the communication chain from professionals of consultancy offices and hydrologists of district water boards via policy advisors to board members: a shift from analytical to experiential processing of information was observed. The board members, at the end of the chain, are not provided with statistical information on uncertainty. Nevertheless, they are aware of the risk of taking inefficient decisions due to uncertainty and they discuss the need and costs of measures in relation to uncertainty. In decision making, board members rely on expert knowledge.

The monster metaphor, described by Van der Sluijs (2005), was useful in understanding how board members of district water boards cope with statistical information on uncertainty as a group or organization with a certain culture, tradition, policy, and status. *Monster assimilation* occurs if uncertainty is mentioned explicitly, and ways are looked for to account for multiple outcomes and to make choices transparent. According to Van der Sluijs (2005) the strategy of monster assimilation gains ground in policy making, which implies a more prominent role of communication of uncertainties.

The strategy of *monster adaptation* – dealing with uncertainties by quantifying them – did not emerge as a strategy that was used by board members. The interviews show that little attention is asked for uncertainty related to the research itself in the decision making process, nor to the underlying values, and bandwidths. Also, a tension is noticed between the different kinds of decision problems and the role that knowledge plays in those. Most decisions are qualified as being structured well or moderately, so: there is consensus about the goals, and the accompanying information suggests different possible decisions. However, water board executives also mention the importance of communicating uncertainty in decisions in which no consensus exists about values: in discussions about values there is a risk that uncertainty plays a smaller role, or is completely downplayed. The strategy of monster adaptation will flourish if decision problems are well structured, cost-effectiveness is aimed for, and the conditions for analytical processing of statistical information are optimal. Despite the fact that board members classified most decisions to be structured (relatively) well, and their aim for taking cost-effective decisions, the strategy of monster adaptation has not rooted yet in long term flood risk management.  A first possible reason is that the conditions for analytical processing of statistical information are not optimal: decisions are taken under time pressure, statistical expertise is lacking, and statistical information is poorly presented. Other possible reasons can be found in culture and tradition (‘we always take decisions this way’), status (because expertise is expected, uncertainties are not communicated), and policy (the reigning regulations and agreements do not ask for communication on uncertainties).

Because the utilization of statistical information on uncertainty depends on a variety of interdependent factors, a coherent set of measures at various stages of communication and levels of decision making is likely to be more effective than a single measure such as offering guidance on uncertainty analysis (cf. Pappenberger & Beven, 2006). As such, on the basis of our psychological analysis in various stages in de decision-making process, this recommendation builds on but analysis goes beyond the original recommendation formulated by Pappenberger and Beven (2006).

**5.2. Recommendations for practice**

On the basis of the results we will now offer four practical recommendations. Statistical information about uncertainty needs to be communicated better and is to be utilized more fully so as to promote more efficient decision making in long term flood risk management.

1: Expertise regarding statistics and decision science needs early implementation.

The first study showed that in the course of the trajectory from hydrologists and consultants to board members the transfer of statistical information is reduced considerably. Statistical information that is available and that can be useful for taking decisions by water boards is not fully utilized and therefore more efficient decisions are not taken. The distance between experts and board members may be bridged by better framing of statistical expertise and by better contextualizing it in the decision problem of the board member. For this, knowledge about statistics and decision science is needed. The third study showed that statistical information about uncertainty is utilized most optimally in well-structured decision problems, and that for board members it needs to be clear which role knowledge plays in decision making. We therefore recommend to review the decision problems regarding water management decisions before a project starts, and in collaboration with an expert in statistics and decision science. We recommend articulating the decision problem in the form of a decision model like an event-decision tree or a null-hypothesis significance test. Subsequently, board members can make choices regarding the maximum acceptable risks and financial conditions. Policy makers and hydrologists – with the help of an expert in statistics and decision science – can on the basis of this articulate research assignments and develop proposals for intervention and measures. Figure 2 offers a graphical representation.

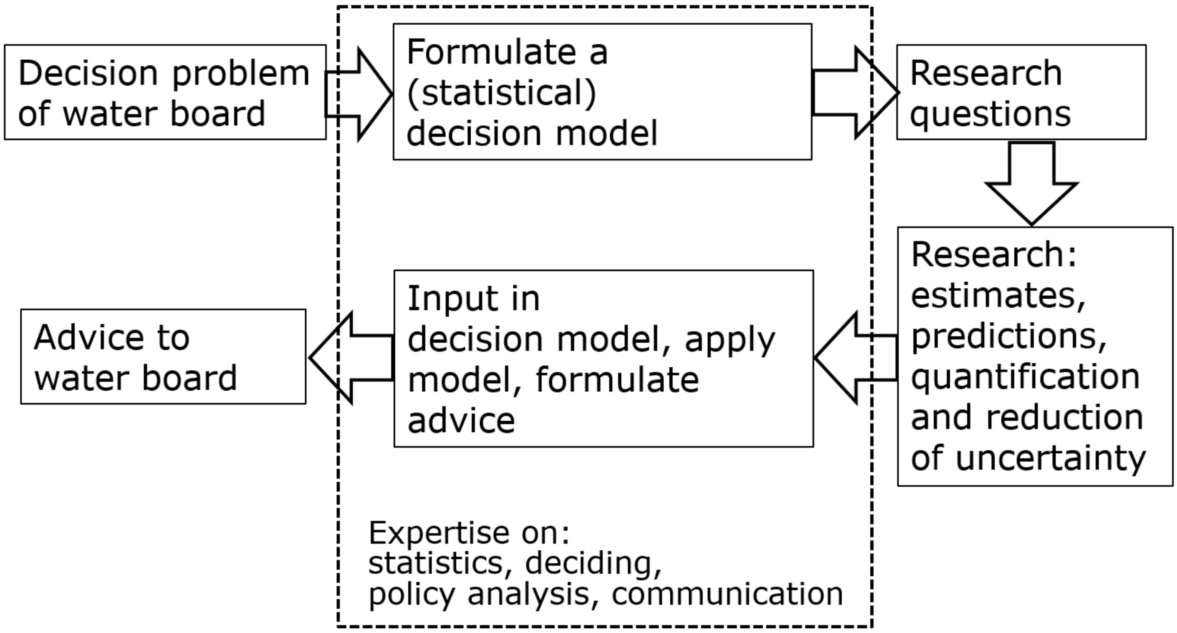


**Figure 2.** Scheme of recommended workflow to utilize statistical information about uncertainty for efficient decision-making in tactical-strategical water management

2: Develop knowledge regarding statistical reasoning and decision making.

The studies showed that a lack of statistical knowledge is one of the reasons for limited communication about and utilization of statistical information about uncertainty. As a cause, various respondents indicated that statistical knowledge they learned during their studies had become ‘rusty’. Although some statistical training modules are available, these are primarily taken by technical water professionals, but not by policy makers, nor board members. During formal education and ‘refresh’-courses there is an emphasis on applying statistical methods, such as hypothesis testing, analysis of variance, regression analysis, time series analysis, geostatistical interpolation and simulation, and sampling. Much less emphasis is put on statistical reasoning and decision making. Psychological research shows that by so-called Bayesian reasoning with absolute frequencies, statistical problems may become more insightful, also for laypersons regarding statistics (Gigerenzer & Edwards, 2003; Gigerenzer & Hoffrage, 1995; Zhu & Gigerenzer, 2006). At courses for water board professionals we recommend to put emphasis on statistical reasoning and decision making: What does statistical information about uncertainty mean for a decision? We also recommend to target such courses not only on hydrologists, but also on policy advisors and board members. It is paramount that an emphasis is put on decision making and not on the execution of statistical analyses so as to ensure that courses like these are not only followed by individuals with an interest and background in statistics. To prevent self-selection, we recommend to convince the entire target population of the importance of this knowledge.

3: Improve the structure of decision problems by formulating them within frameworks for decision making, e.g., hypothesis testing and event-decision trees. The third study indicated that statistical information about uncertainty is utilized most optimally in well-structured decision problems. Although in water management standards are used, our results show that the well-structured framework of statistical testing is not or only seldom used. As a result, risks of faulty decisions are unknown and not controlled, which can lead to inefficient decisions, such as wrong investments or measures that may lead to financial claims. By putting a test against standards in the framework of hypothesis testing, and converting the probability of faulty decisions into financial risks, the risks of wrong decisions can be controlled. As demonstrated by Morgan et al. (1990), utilization of statistical information about uncertainty can contribute to more efficient decisions. We recommend to use an event-decision tree and express different options in monetary values, or other values that are appealing to water management professionals.

4: Do not only present return periods, but also flood risks within a plan period.

Study 1 showed that in communicating statistical information about uncertainty so-called return periods are frequently used. At the same time, many respondents indicated that return periods are susceptible for misinterpretation. An example is the confusion that emerges when an event with a return period of a hundred years occurs twice within a short interval. The extant literature also points at this misinterpretation of return periods (Bell & Tobin, 2007; Serinaldi, 2015). Both studies disagree on an alternative for return periods. Serinaldi (2015) proposes the use of risks of failure (flood risks) within a plan period, while Bell and Tobin (2007) expect that this will lead to problems of interpretation. We recommend to use return periods, but also flood risks within a plan period. These can be very well integrated within a decision model in which statistical chances are multiplied by costs into risks, expressed in monetary values.

### 5.3. Limitations

A number of caveats of the present research deserve discussion. First, in our research we decided to use a stratified random sample of professionals at low and high water boards. We considered this to be important, because the two types of water boards are exposed to different kinds of water management issues, so this stratification procedure allowed us to draw conclusion of general Dutch water boards (and for instance not just the ones that are located in area below sea levels). Although we did not aim to compare the two types of water boards, our results did not indicate systematic differences in the responses gathered by the interviewed water management professionals. However, we cannot rule out that no differences exist between low and high water boards, and this could be an interesting future research avenue. A second limitation is also related to the sampling strategy. We conducted a series of qualitative studies and drew a random sample out of the 23 available water boards. The number of interviewees was limited, and the data we obtained were analyzed in view of variability of responses – which different kinds of view were expressed in relation to the research questions and to the statistical cases presented. A higher number of respondents would possibly have led to a higher level of variance in responses, but at the same time we noted a satisfactory level of saturation in our data (i.e. not much extra variation was observed when conducting the later interviews). A final limitation concerns the qualitative nature of data analysis. We were unable to quantify relations between theoretical concepts or test causal relations, but our goal was to do a more in-depth analysis of how water board professional deal with statistical information about uncertainty in decision-making processes. For future research it would be relevant to develop scenarios and experimentally test how water board professionals or other people involved in hydrological and hydraulic modelling make decisions based on different kinds of information.

**5.4. Conclusions**

A series of three studies was set out to investigate the presentation, interpretation, and utilization of statistical information about uncertainty by professionals and board members of district water boards in the Netherlands. The results allow us to draw to the following conclusions:

1. Statistical information about uncertainty, such as confidence intervals, standard errors, or error rates of hypothesis tests are hard to interpret and therefore not usable to many board members and policy makers in tactical-strategical water management.

2. The current practice in which decisions are underbuilt with expert advice and experience could lead to inefficient decisions, because the risks of faulty decisions like inadequate investments are not quantified and cannot be controlled.

3. The current practice of testing against standards in which a mean value is compared to a standard without taking into account the accuracy of the estimated mean and the risks of faulty conclusions, may lead to inefficient decisions such as unnecessary measures, superfluous extra research, omitting to undertake extra research, or financial claims.

4. In the current practice, statistical information is not optimally used when taking decisions, because the decision problems of regional water board members are not translated into a statistical decision model. Therefore decision problems are not optimally structured. Statistical information about uncertainty is often offered apart from a defined decision problem, and not as input for modelling to solve that problem. In the current practice decisions are substantiated with *best estimates*, expert judgement, and experience. This may cause the risk of inefficient decisions, because best estimates do not necessarily lead to effective decisions (Morgan et al., 1990), expert judgement can lead to biases (Sjöberg, 2009; Tversky & Kahneman, 1974), and decisions on the basis of heuristics that originate from experience do not need to be optimal (Kahneman, 2011).

5. Regional water board policy makers and board members voice that the current practice of statistical information about uncertainty may cause unrest. However, they also view statistical information about uncertainty as a useful addition to experiences and insights from experts, and they agree that communication about uncertainty related to long-term decision making are, in the end, more efficient compared to when uncertainties are not taken into account. We therefore conclude that support exists among water board policy makers and board members to utilize statistical information about uncertainty during decision making.

Of course, care should be taken to extrapolate conclusions beyond the context of regional Dutch water boards, but our study adds to understanding of how (water management) organizational bodies could structure improved ways to approach decision problems. Expectedly, also in other organizational settings of tactical-strategical water management optimal utilization of statistical information about uncertainty might suffer because of a lack of skills, time pressure, or organizational culture, to just name a few reasons. Also, in those contexts the experiential and analytical processing of information will likely play a role in dealing with statistical information relevant for water management (e.g., Chaiken & Trope, 1999; Epstein, 1994; Marx et al., 2007; Sloman, 1996). Therefore, we call for research to follow up and test the current recommendations across different contexts of tactical-strategical water management.

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## Appendix

Four cases presented to professionals of district water boards

**Case 1: Return periods, relative frequencies, single-event probabilities**

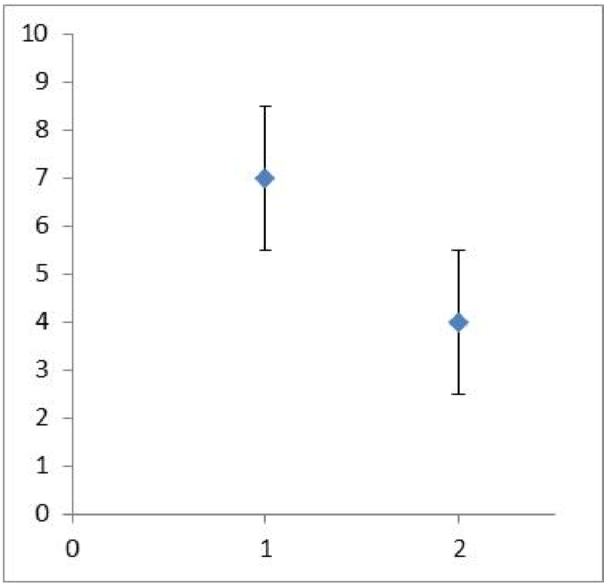
In this case it can be assumed that water levels are uncorrelated in time and climate conditions are constant in time. If a water level of 1.22 m+NAP is exceeded flooding occurs. In which of three situations the flood risk is largest, and in which  smallest?

1. “A water level of 1.22 m+NAP is exceeded once in 50 years.”
2. “A water level of 1.22 m+NAP is exceeded with probability 0.02 in any future year.”
3. “A water level of 1.22 m+NAP is exceeded in 2 % of the future years.”

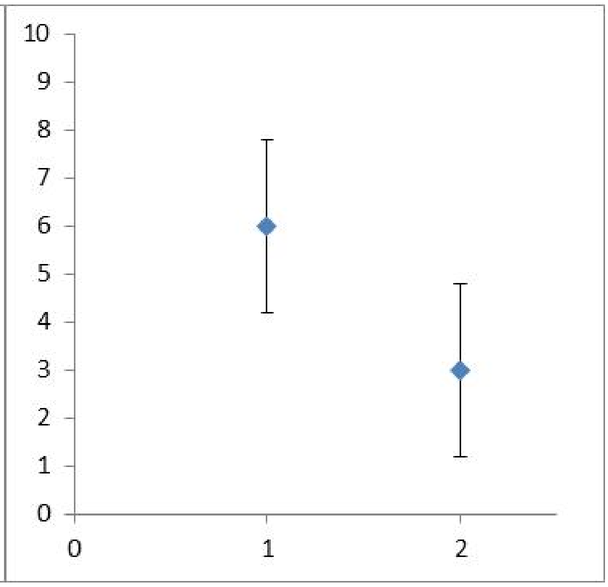
A probability or frequency was expressed by a return period, a single-event probability and a relative frequency. Which of these three expressions is most clear, which less? Why? Do you have experience with presenting return periods, single-event probabilities or relative frequencies to board members?

**Case 2: Error bars, confidence intervals**

**A Error bars (+ an – the standard error)**




**B 95% confidence intervals**

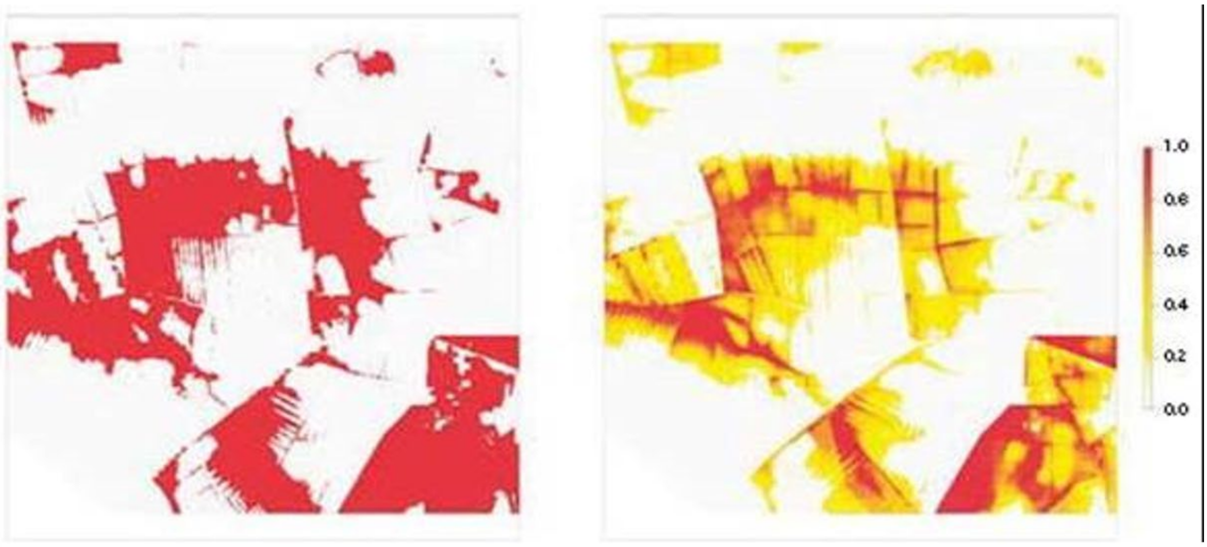


Both graphs show two parameter estimates. The estimates are mutually independent (for example: the mean in area 1, and the mean in area 2). The accuracy of the estimates is indicated with band widths. The left graph (A) indicates the accuracy of the estimates with a bar reflecting the estimate plus or minus its standard error. The right graph (B) indicates the accuracy of the estimates with 95% confidence intervals.

1. Which of the two graphs shows the most accurate estimates?
2. In one of the graphs the estimates differ significantly at a 5% significance level. Is this the case in A or B?

**Case 3: Model uncertainty**

The right map below from Hakvoort et al. (2013) accounts for several sources of uncertainty, but for model uncertainty. Will the right map be more red, yellow or white if model uncertainty would be included?




Without uncertainty With uncertainty

Area in which a standard for flood protection is not met.

**Case 4**

District water boards maintain standards for the area in which inundations occur with a certain frequency. For example, a maximum of 5% of the area of grassland should not inundate more frequently than once in ten years. The areal percentage being inundated more than once in ten years is not exactly known, because return periods are estimated using a model and elevation data have limited accuracy and are incomplete. The uncertainty about return periods of water levels and about elevation has been quantified. A test is performed with the following null and alternative hypothesis:

Null hypothesis H0: the percentage of a grassland area being inundated more than once in ten years is smaller than or equal to 5%;

Alternative hypothesis Ha: the percentage of a grassland area being inundated more than once in ten years is larger than 5%.

The error rates (probabilities of wrong conclusions) are defined as follows:

1. A probability of 0.05 is acceptable for wrongly concluding that the 5% standard is not met (significance level $\alpha=0.05$, probability of type I error = 0.05).

2. It is found to be relevant if the 5% standard is exceeded with at least 1%. This deviation from the standard should be detected with a probability of at least 0.8 (= power of the test). The probability of wrongly not detecting a 1 % exceedance of the standard should not be larger than 0.2 (probability of type II error $\beta=0.2$).

A number of possible test results are listed in the table below. The *p* value is the probability of the test outcome or more extreme outcomes in the direction of the alternative hypothesis, given the null hypothesis.

Give a conclusion, and an advice on taking measures to reduce inundation frequencies or to collect more data. Choose from the following conclusions:

1. The standard is exceeded;

2. The standard in not exceeded;

3. There is not enough statistical evidence that the standard is exceeded.

Choose from the following advices:

1. Take measures to reduce inundation frequencies;

2. Do not take measures to reduce inundation frequencies;

3. Collect more data and test again.

| Estimated areal percentage | *p* value | Power | Conclusion* | Advice* |
|---|---|---|---|---|
| 8.1 % | 0.04 | 0.6 | 1 | 1 |
| 8.1 % | 0.04 | 0.9 | 1 | 1 |
| 8.1 % | 0.08 | 0.6 | 3 | 3 |
| 8.1 % | 0.08 | 0.9 | 3 | 2 |
| 5.2 % | 0.04 | 0.6 | 1 | 1 |
| 5.2 % | 0.04 | 0.9 | 1 | 1 |
| 5.2 % | 0.08 | 0.6 | 3 | 3 |
| 5.2 % | 0.08 | 0.9 | 3 | 2 |
| 4.1 % | 0.1 | 0.6 | 3 | 3 |
| 4.1 % | 0.1 | 0.9 | 3 | 2 |
| 4.1 % | 0.1 | 0.6 | 3 | 3 |
| 4.1 % | 0.1 | 0.9 | 3 | 2 |

*) The answers were not visible for the interviewees.