Environmental Science and Policy 93 (2019) 75–82

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

The role of evidence-based information in regional operational water management in the Netherlands

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ARTICLE INFO

Keywords:
Evidence-based information
Decision-making
Operational water management
Hydrological modelling

ABSTRACT

The integration of evidence-based information in operational water management is essential for robust decision-making. We investigated the current use of experiential and evidence-based information in Dutch regional operational water management. Interviews with operational water managers at regional water authorities in the Netherlands reveal that they use both evidence-based and experiential information for decision-making. While operational water management is shifting towards an evidence-based approach, experiential information is still important for decision-making. To fulfil the current information need, the operational water managers indicate they would like to have access to high-resolution spatial data, value-added products and tools for communication to stakeholders. We argue that hydrological models are suitable tools to support these needs. However, while several evidence-based information types are used by operational water managers, hydrological models are limitedly applied. Hydrological models are regarded as inaccurate for operational water management at desired spatial scales. Also, operational water managers often struggle to correctly interpret hydrological model output. We propose several means to overcome these problems, including educating operational water managers to interpret hydrological model output and selecting suitable indicators for evidence-based decision-making.

1. Introduction

Densely populated regions like the Netherlands need well-designed operational water management for coping with varying water availabilities and demands (Haasnoot and Middelkoop, 2012). Operational water management requires decision-making within limited time intervals and involve multiple criteria related to for example flood risk, water supply, and navigability (Xu and Tung, 2008). These complex settings are characterized by large uncertainties (Ascough et al., 2008). It is challenging to take robust water management decisions as one has to quantify and assess these uncertainties (Walker et al., 2003; Warmink et al., 2017). Also, water managers have to operate under regulatory, institutional, political, resources and other constraints that limit their capacity to use new information (Morss et al., 2005).

Water managers generally use several information types for decision-making (Polanyi, 1966; Raymond et al., 2010), e.g. experiential and evidence-based information. According to Raymond et al. (2010) the classification of information is arbitrary, which means that there are multiple and overlapping ways of defining experiential and evidence-based information. Experiential information is linked to personal perspectives, intuition, emotions, beliefs, know-how, experiences, and values which are not easily articulated and shared (Timmerman, 2015). Evidence-based information can be described, communicated, written down and documented (Nonaka and Takeuchi, 1995). Evidence-based decision-making can help to ensure that untested practices are not widely adopted, because they have been used previously (Sutherland et al., 2004).

Although evidence-based information can significantly contribute to decision-making in operational water management (Timmerman and Langaas, 2005), several studies state that the science-practice gap limits the use of evidence-based information (Brown et al., 2015; Ward et al., 1986). In other words, evidence-based information does not always match the needs of operational water managers. Instead, managers rely on experiential information for decision-making (Pullin et al., 2004). For example, Boogerd et al. (1997) found that decision-making at regional water authorities in the Netherlands is mainly based on personal expertise. Although the amount of available evidence-based information has greatly increased in the Netherlands in recent years, the dissemination of relevant information for decision-making remains a challenge (OECD, 2014). The science-practice gap has to be bridged to improve evidence-based decision-making in operational water management (Cosgrove and Loucks, 2015; Timmerman, 2015). In this

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https://doi.org/10.1016/j.envsci.2018.12.025
Received 30 May 2018; Received in revised form 14 December 2018; Accepted 19 December 2018

study, we investigated the present application of experiential and evidence-based information in the Netherlands and its impact on decision-making in operational water management.

Brown et al. (2015) show that the adoption of a scientific framework by operational water managers will improve the credibility of evidence-based decision-making. Decision support systems (DSSs) are designed as such supporting frameworks to guide evidence-based decision-making in operational water management. Hydrological simulation models are often an integral part of DSSs (Kersten and Mikolajuk, 1999; Zhang et al., 2013). In this study, when we refer to hydrological models, we refer to the application of such models in a DSS. Several studies have shown the potential of hydrological models for decision-making in operational water management. Hydrological modelling can help in increasing the understanding of a problem and in defining solution objectives (Guswa et al., 2014), in developing and evaluating promising control measures (Beven and Alcock, 2012), and in providing confidence in the solution (Kurtz et al., 2017). Not only can hydrological models be used to manage and optimize water systems, model output can also be used to create understanding among stakeholders (Hanington et al., 2017).

However, hydrological model output does not always comply with the needs of decision-makers. Although approaches such as participatory modelling and indicator-based modelling are developed to decrease this science-practice gap, the application of hydrological models by operational water managers is not common practice (Borowski and Hare, 2006; Leskens et al., 2014; Serrat-Capdevila et al., 2011). In contrast, Reinhard and Folmer (2009) state that the use of hydrological models in Dutch water management is widely accepted. It is unknown how hydrological models contribute to decision-making in present-day regional operational water management in the Netherlands.

The aim of this study is to investigate the current role of experiential and evidence-based information, in particular hydrological models, for decision-making in regional operational water management in the Netherlands. Similar to Warmink et al. (2011) and Höllermann and Evers (2017), we used expert interviews to study the perspective of regional water managers. A step-wise approach is applied; first, we studied how experiential and evidence-based decision-making is integrated in Dutch regional operational water management. Secondly, we assessed the integration of hydrological models in evidence-based operational water management.

This paper is organised as follows: Section 2 describes the decision-making framework applied in this study. Section 3 introduces the research methodology for the interviews. Results are presented in Section 4, and are discussed in Section 5. Finally, conclusions are drawn in Section 6.

2. Decision-making framework

We set up a decision-making framework based on Dicks et al. (2014), see Fig. 1. This framework is used to analyse interviews with operational water managers for determining which information they use in the decision-making process. The framework is based on the following assumptions: (1) Water managers have to evaluate a water system condition. (2) Water managers collect both evidence-based and/or experiential information concerning this condition. (3) Water managers will assess the water system condition using all available information. (4) Taking a decision will lead to new water system conditions, which again have to be evaluated in time. Dicks et al. (2014) present two bypass routes that, in this case, operational water managers can take in decision-making. Firstly, water managers who base their decisions on experiential rather than evidence-based information use the opinion-based bypass. Pullin et al. (2004) describes the opinion-based bypass as “relying on the status quo of continuing with an established but unevaluated practice”. Secondly, water managers who do not incorporate all available evidence-based information in decision-making use the limited guidance bypass. Water managers are bound to time and other constraints, limiting the ability to take all available information into account. These bypasses may lead to sub-optimal water management decisions. For example, small-scale solutions, such as locally adapting water levels by raising a weir level, may not have the desired effect on a catchment-wide scale.

We categorize the decisions as defined in the framework using two aspects that characterize operational water management. These aspects are the situation type and the situation urgency. Firstly, decisions are made for dry or wet situations. Secondly, the urgency of a decision is a reflection of the severity of the situation. We identify regular day-to-day decisions and calamity decisions concerning extreme events. This leads to four decision-making situations: Regular-Dry, Regular-Wet, Calamity-Dry, and Calamity-Wet.

Typically, decisions concerning dry periods are considered over a time span of weeks. Dry periods often occur during summer. Operational water managers have to monitor and maintain the supply of both surface water and groundwater resources. In regular situations, operational water managers can deal with droughts by controlling a system of pumps and weirs to optimize water supply. During calamity situations, water managers focus more on limiting water use by prioritizing important functions like drinking water supply above functions like agriculture, which is a general tendency across the European Union (Kampragou et al., 2011).

Decisions concerning wet situations are generally taken over a time span of hours to days. For example, the supply of water regularly exceeds water demand in winter periods. Decreasing evapotranspiration rates lead to wet soils and shallow groundwater levels. Often, soils cannot adequately cope with heavy precipitation events during such periods, which lead to inundations. Operational water managers can control soil storage capacity to a certain extent by adapting water levels in ditches, streams and channels. Calamity situations like the imminent flooding of streams and rivers can cause severe damage. Controlling the discharge capacity of the water infrastructure plays a large role in those events.

3. Methodology

We set up a case study for investigating the use of experiential and evidence-based information for decision-making in regional operational water management. The study area is described in Section 3.1. Furthermore, the approach for expert interviews is given in Section 3.2.

3.1. Study area

We selected six regional water authorities out of a total of twenty-two to incorporate various water management approaches in the Netherlands. Table 1 shows their main characteristics and Fig. 2 shows their management areas within the Netherlands. Aa en Maas and Vechtstromen represent areas within the Netherlands situated above sea level. These areas mainly consist of sandy soils and are generally free-draining, which limits the ability to take control measures. Delfland and Zuiderzeeland represent the low-lying areas within the Netherlands. Most of their management areas lies below sea level and soils are mainly clayey and peaty. Since the water systems of the latter authorities are well regulated, water managers have a number of options for control measures. De Stichtse Rijnlanden and Drents Overijsselse Delta have sandy, clayey as well as peaty soils.

3.2. Expert interviews

We interviewed operational water managers at the selected regional water authorities. The daily tasks of these water managers, in this paper also referred to as experts, mainly focus on surface water quantity management. Generally, the regional operational water managers are responsible for a sub-catchment of the water authorities’ management area. The limited size of these sub-catchments enables them to develop

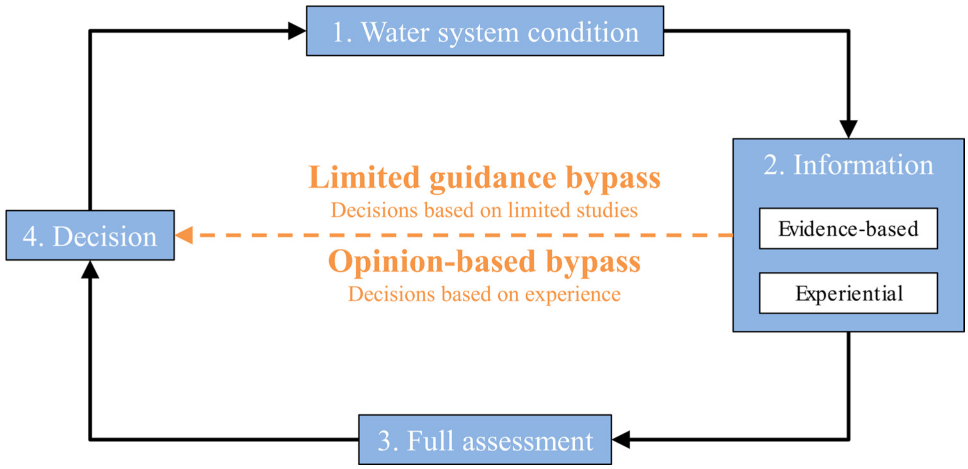

Fig. 1. Decision-making framework and typical bypasses, adapted from Dicks et al. (2014).

Table 1
Selected regional water authorities. Statistics are obtained from Unie van Waterschappen (2014).

Water authority	Inhabitants [capita]	Surface area [ha]	Characteristics
Aa en Maas	743,842	161,007	Elevated sandy soils
Delfland	1,200,000	40,547	Clayey polders
De Stichtse Rijnlanden	750,000	83,021	Elevated sandy soils and peaty polders
Drents Overijsselse Delta	600,000	255,500	Elevated sandy soils and clayey polders
Vechtstromen	800,000	227,045	Elevated sandy soils
Zuiderzeeland	400,000	150,000	Clayey polders

a good understanding of catchment dynamics and possible measures. At least one experienced and one inexperienced operational water manager was interviewed at each authority. We assume that operational water managers are experienced if they have more than 10 years of work experience, similar to Warmink et al. (2011). In total 14 experts were individually interviewed, see Table 2. To limit researcher bias, supervisors at the regional water authorities selected the experts. The interviews were set-up using a semi-structured approach. The interview questions were developed using a literature review and a test interview at regional water authority Vechtstromen. Appendix A contains a full overview of the interview questions. The interview length was approximately one hour.

Using the decision-making framework (Fig. 1), we wanted to identify three key aspects in the interviews: the conditions, problems and decisions that regional operational water managers have to cope with, which information water managers use for these decisions, and how the various types of information are used for decision-making. The experts were asked to indicate what type of information they use for decision-making. Since the operational water managers did not use the same terminology, we categorized their answers in information type groups. These information types are split in experiential and evidence-based types according to the decision-making framework defined in Section 2. Furthermore, we asked the experts to indicate the importance of each information type in the four decision-making situations defined in Section 2. The experts had to fill in this information in a Microsoft Excel spreadsheet. A pie chart was updated to directly show the experts the results of their input. The experts were allowed to adapt their input until the results visualized in the pie chart fitted their opinion. This method enabled the experts to reflect on their input. The results were used to study to what extent the experts apply evidence-based and/or experiential information for decision-making. Also, these results indicate whether the experts use all available information for decision-making, or if they use the limited guidance bypass or opinion-based bypass as defined in the decision-making framework. Next, the experts were asked to elaborate on their opinion of the current application of hydrological models for decision-making in regional operational water management. They were encouraged to comment on both positive and negative aspects of hydrological model application. This resulted in the identification of improvement points for both model developers and operational water managers. Last, the interview ended with an open question about the information that operational water managers are currently missing for decision-making. We tried to activate experts to not only talk about possible technological developments, but also about social, institutional, and other developments.

4. Results

4.1. Information types

Operational water managers use a broad spectrum of information types. Based on the interviews, we identified six information types typically applied by operational water managers. These types are listed in Table 3. Firstly, water managers typically use measurement data like precipitation, runoff in streams, groundwater level in wells, etc. Next, water managers can use system knowledge like surface elevation, land use, and soil type. Furthermore, meteorological forecasts of precipitation and temperature are valuable to make predictions about future states of water systems. Also, operational water managers use their expertise and experience to take decisions. For example, a water manager can take a decision based on prior experiences with the encountered problem. Such a decision can lead to the opinion-based bypass as defined in the decision-making framework (Fig. 1). In addition, hydrological models are used for decision-making. While in general the experts do not directly operate models, they often have access to hydrological model output in a DSS. Hydrological models typically provide forecasts of hydrological variables for a specific spatial domain, based on meteorological forecasts and other input data. Last, operational water managers are bound to legislation and institutional policies. For free-draining areas such as the more elevated sandy areas of Aa en Maas, De Stichtse Rijnlanden, Drents Overijsselse Delta and Vechtstromen, water managers have to take into account water level bounds that are pre-described in policy documents. However, water managers are allowed to diverge from this pre-defined set in extreme situations. Polder areas in the management area of De Stichtse Rijnlanden, Drents Overijsselse Delta and Zuiderzeeland have much stricter defined water level rules which are described in water level decrees. Water managers are not allowed to diverge from these decrees. The bounds and decrees are defined in cooperation with local stakeholders.

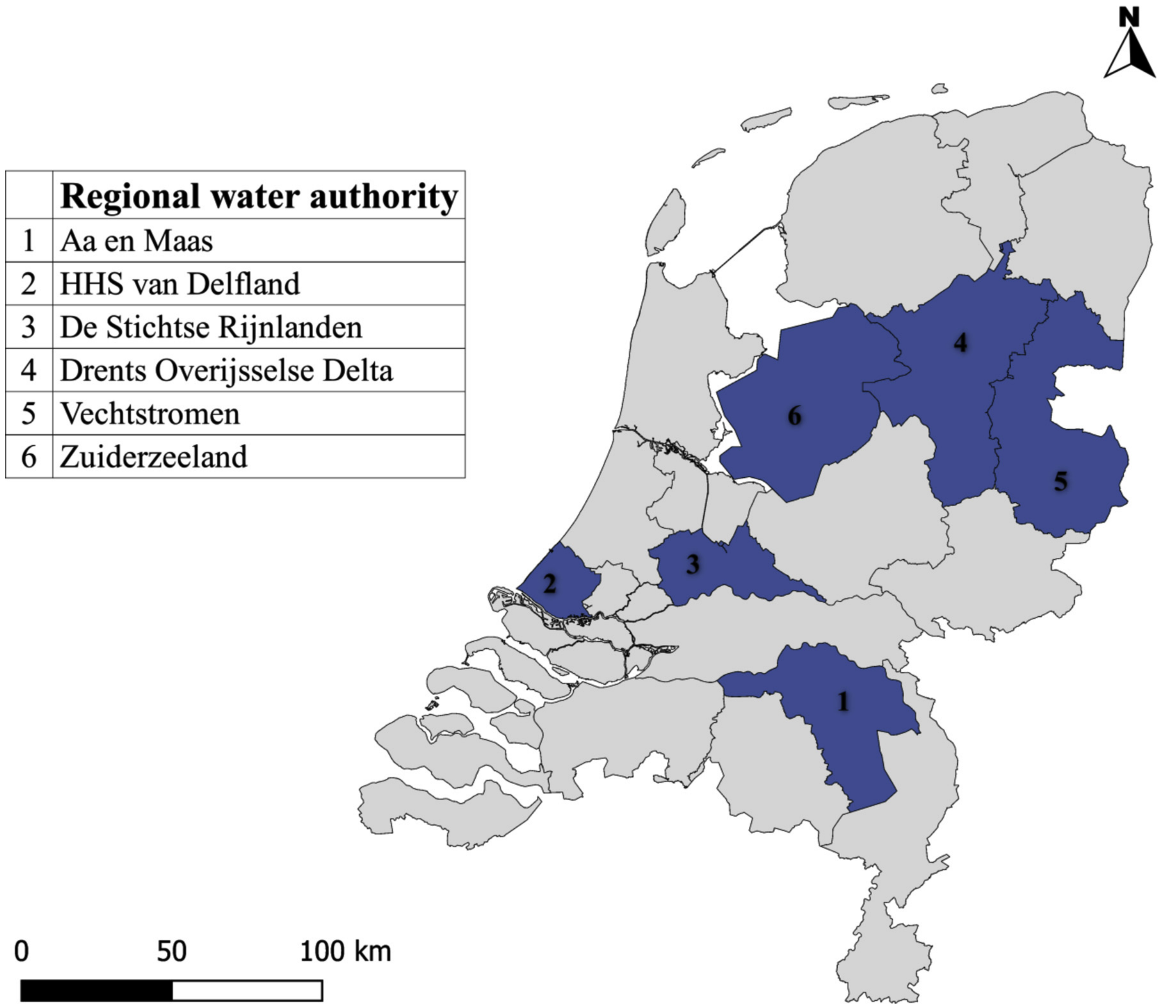

Fig. 2. Management area of selected regional water authorities in the Netherlands.

Table 2
Overview of interview respondents.

Water authority	Work experience		
	< 10 years	> 10 years	Total
Aa en Maas	1	2	3
Delfland	1	1	2
De Stichtse Rijnlanden	1	1	2
Drents Overijsselse Delta	2	1	3
Vechtstromen	1	1	2
Zuiderzeeland	1	1	2
Total experts	**7**	**7**	**14**

Table 3
Identified information types.

Information type	Examples
Measurement data	Monitoring of discharge and groundwater levels
System knowledge	Surface elevation, land use and soil type data
Meteorological forecasts	Precipitation and temperature forecasts
Experience	Prior experiences with an encountered situation, such as lowering a weir during wet conditions based on intuition.
Hydrological model (output)	Assessment of different water management scenarios
Legislation	Water level decrees and other laws

4.2. Importance of information types

Every expert agrees that they take decisions based on at least several information types. Fig. 3 shows the importance of each information type described in Section 4.1 for decision-making in the four decision-making situations (Regular-Dry, Regular-Wet, Calamity-Dry, and Calamity-Wet). The vertical axis represents the importance of an information type in the decision-making situations. The importance is defined as the contribution of an individual information type in a specific decision-making situation expressed in a percentage. The error bars in Fig. 3 represent the sample spread by means of the unbiased standard deviation. The variability between the experts is limited, indicating conformity between expert opinions at different regional water authorities.

Operational water managers depend in all decision-making situations mainly on measurement data, system knowledge, meteorological forecasts, and experience. These information types contribute for more than eighty percent to decision-making. Hydrological models and legislation each account for approximately three to eleven percent in all decision-making situations. Experience is the most important information type in every situation. Hydrological models form the least important information type, except for the Calamity-Wet situation, for which legislation is least important.

The importance of each information type slightly differs per decision-making situation. Experience is most important in all situations, especially in the Regular-Dry situation. The importance of measurement data is similar in the Regular-Dry, Regular-Wet, and Calamity-Dry

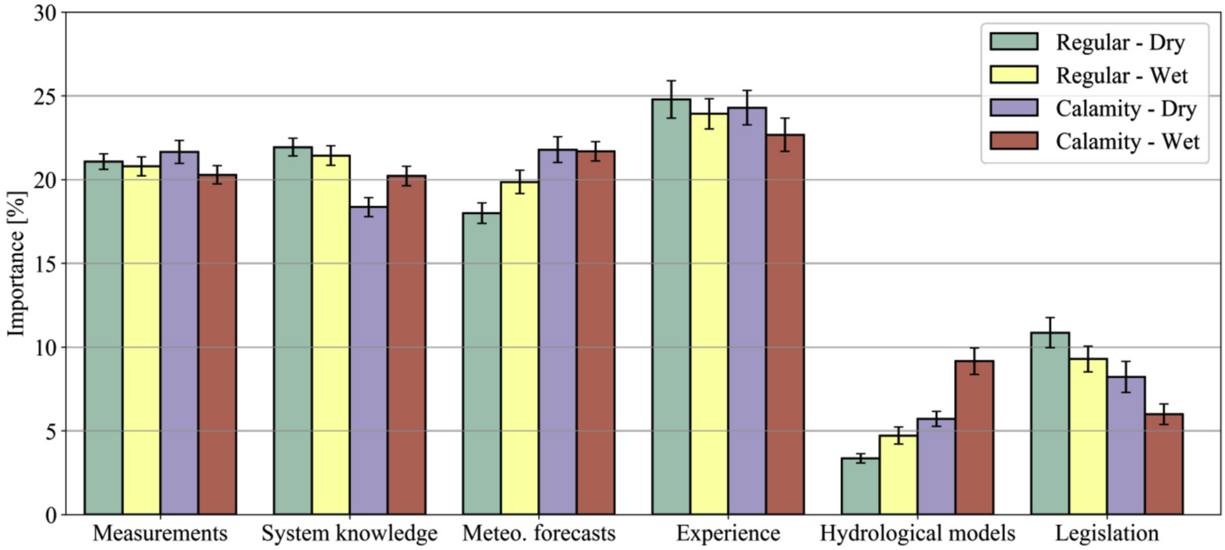

Fig. 3. Information types used by operational water managers in the four decision-making situations. The error bars represent the unbiased standard deviation.

situations. However, measurement data become slightly less important in the Calamity-Wet situation. Contrarily, the experts attach less value to system knowledge in the Calamity-Dry situation than in the other situations. During dry calamities, the experts state that groundwater level monitoring data becomes more relevant relative to system knowledge. Next, while the importance of meteorological conditions is similar in Calamity-Dry and Calamity-Wet situations, the importance is less in Regular-Dry and Regular-Wet situations. The contribution of hydrological models is relatively small, although models become more important in Calamity-Wet situations. The experts indicate that in those situations the models are applied for discharge forecasts. Striking is the relatively small contribution of legislation. The experts see this information type as a boundary condition rather than an information source for decision-making. Legislation is least important in the Calamity-Wet situation, likely because the aim of water management is to get rid of as much water as possible in these situations. Conversely, legislation tends to become a more important information source in Regular-Dry situations, as the water management aim then shifts towards maintaining water level bounds and decrees.

4.3. Application of hydrological models

Fig. 3 shows that hydrological models are less used for decision-making in regional operational water management than other information types. Although most experts see the potential of such tools, they give two reasons why hydrological models are limitedly used. Firstly, the experts consider hydrological model output to be too inaccurate and uncertain for their applications. Especially for local scale problems, model estimates often do not comply with observations in their opinion. Secondly, several experts have difficulties interpreting hydrological model output. The interpretation of such data requires understanding of the processes on which the model is based. The experts often do not know on which assumptions, input data and forcing hydrological models are based. Therefore, operational water managers tend to ignore model output for decision-making.

4.4. Information needs

The experts suggested various improvements for the provision of information. We identified three categories:

1 *Improved understanding of current water system conditions*

The experts want access to up-to-date high-resolution spatial information about current conditions. However, they struggle to get a system-wide understanding of the current condition of water systems. For example, they find it hard to integrate measurement data to larger spatial scales. Although the application of remote sensing data and hydrological models is promising, such data are at the moment insufficiently integrated in decision-making.

2 *Value added-products and triggers*

Valuable information should be presented in an adequate way to water managers. According to the experts, information is not always presented to them in the way they want to or is difficult to interpret. For example, operational water managers are generally not directly interested in groundwater level or soil moisture data; they rather want to know what the remaining soil storage capacity is.

3 *Tools for communication to stakeholders*

Operational water managers have to be able to motivate their decisions to stakeholders. However, the experts struggle with communicating their decisions to stakeholders like nature conservation organizations, farmers, industry, etc. These stakeholders can have limited knowledge of water management or fail to overlook the 'big picture'. The provision of proper information should not only contribute to decision-making itself, but should also play a role in convincing stakeholders to accept water management decisions.

5. Discussion

5.1. Experiential versus evidence-based decision-making

Based on the definition in Section 1, we classify measurement data, system knowledge, meteorological forecasts, hydrological model output and legislation as evidence-based information. Experience is classified as experiential information. Fig. 3 shows that, in their perception, experts depend for approximately 75% on evidence-based information and for approximately 25% on experiential information. So, while Boogerd et al. (1997) stated that regional water management should increase the integration of evidence-based information, this study shows that operational water management at the selected regional water management authorities is based on both experiential and evidence-based information.

Operational water managers considerably depend on experiential information for decision-making. Since there is often no structured way to process the evidence-based information, the interpretation and expertise of operational water managers remain important for decision-making. Because the hydrological system includes many inherent uncertainties, decision-making will always partly depend on experiential information. It is important to note that the interpretation of evidence-based information can differ per water manager.

One could argue that during regular conditions, operational water management functions sufficiently using the currently applied information. However, the application of experiential information may lead to the opinion-based bypass as defined in the decision-making framework (Fig. 1) and consequently to sub-optimal decisions. Water managers are not able to validate the effect of measures beforehand. Furthermore, if their decision has the desired effect, no incentive will exist to check whether the decision could be optimized. In addition, the lack of evidence limits posterior evaluation of experiential-based decisions. Finally, experiential information is limited to individual operational water managers. This information will be lost if they stop working at the regional water authority. So, there is a need to capture this tacit knowledge in the form of evidence-based information.

Therefore, efforts should continue to integrate evidence-based with experiential information for decision-making in regional operational water management in the Netherlands. Similar advice is given for water management in e.g. Japan (Nakanishi and Black, 2018), South Africa and Canada (Wolfe, 2009), and South Korea (Nam and Choi, 2014). Special focus should be given to the development of structured methodologies for interpreting evidence-based information. The continuing development of hydrological models for DSSs seems suitable for structured decision-making and should therefore be encouraged.

5.2. Application of hydrological models for operational water management

The results indicate that the importance of hydrological models for decision-making in regional operational water management is substantially smaller than other evidence-based information types. However, we consider hydrological models as suitable tools which can improve the three aspects identified in Section 4.4. Firstly, hydrological models can provide up-to-date high-resolution spatial information about current water system conditions (Wood et al., 2011). Secondly, the spatial information from hydrological models can be used to retrieve value-added products interpretable for operational water managers (Guswa et al., 2014; Kurtz et al., 2017). Thirdly, hydrological models are suitable tools to derive information in the form of indicators, which can be used in the communication with stakeholders (Eden et al., 2016; Hanington et al., 2017).

Unfortunately, a gap exists between what hydrological model developers think models should provide and what decision-makers demands from models. This gap has both a social and a technical aspect (Leskens et al., 2014). The social gap concerns the fact that model users do not see models as determinant tools for decision-making. Fig. 3 indicates that the experts consider hydrological models less important than other information types. Decision-makers simply do not have the means or knowledge to investigate all possible measures. This is represented as the limited guidance bypass in the decision-making framework (Fig. 1). Also, it was found in Section 4.3 that the experts often do not have sufficient knowledge to apply hydrological model output in decision-making. Therefore, one should not underestimate the need to sufficiently educate decision-makers and other stakeholders.

The technical aspect relates to the discrepancy between the information supplied by models and the information decision-makers need. The experts think that model output contains large uncertainties and therefore hydrological models are inaccurate and unreliable. Although hydrological models should indeed not be seen as perfect representations of reality, they can be applied to identify and quantify uncertainties concerning water management decisions (Refsgaard et al., 2007; Todini, 2007; Warmink et al., 2010).

Furthermore, the experts indicate that they have a need for a better presentation of information. Focusing on hydrological models, they state that model output is often difficult to comprehend for implementation in water management. Several studies affirm this statement. Colosimo and Kim (2016) state that decision-makers do not have the time needed to review and study which information is available and needed for decision-making while Leskens et al. (2014) found that decision-makers tend to discard information that seems to increase the complexity they already have to deal with. Hanger et al. (2013) found that decision-makers generally do not have a lack of information, but a need for better filtered and accessible information. Therefore, scientists who wish to aid decision-making must generally not offer scientific knowledge, but rather develop information that clearly applies to specific decision-making settings (Maiello et al., 2015). One way of properly representing evidence-based information is the selection of suitable indicators. Indicators should help operational water managers to retrieve system-wide understanding of historical, current, and future conditions of water systems. Hydrological modelling tools provide a means to get such system-wide information on historical, current and future time scales. Indicators have already been developed for water resources management (Ioris et al., 2008; Juwana et al., 2012), river management (De Girolamo et al., 2017; Richter et al., 1996, 1997), coastal zone management (Diedrich et al., 2010), climate change adaptation (Hanger et al., 2013; Spiller, 2016), ecosystem management (Guswa et al., 2014), forest management (Carvalho-Santos et al., 2014), hydropower management (Kumar and Katoch, 2014), urban water system management (Dizdaroglu, 2015; Spiller, 2016) and agricultural management (Wang et al., 2015). If suitable indicators are selected, model output can be made more understandable for operational water managers. Furthermore, easy to interpret model output can be used for communication with stakeholders. Future studies should focus on the selection and validation of suitable indicators for regional operational water management.

6. Conclusion

Regional operational water management in the Netherlands depends on both experiential and evidence-based information for decision-making. We identified by means of interviews with regional operational water managers that these experts typically use six information types for decision-making. Measurement data, system knowledge, meteorological forecasts, hydrological models and legislation are evidence-based information types, while the experience of water managers is experiential information. While the experts largely depend on evidence-based information for decision-making, the experts also depend considerably on experiential information. This may lead to opinion-based bypasses and subsequently to sub-optimal decisions. Operational water managers can improve the decision-making process by continuing efforts to integrate evidence-based information in structured methodologies.

Regional operational water managers depend significantly less on hydrological models than other evidence-based information types for decision-making. Although hydrological models can help in improving the understanding of historic, current and future water system conditions, can help in deriving interpretable information and can be used as tools for communication with stakeholders, hydrological models are considered as unreliable for decision-making. Also, operational water managers often have limited knowledge to correctly interpret hydrological model output. We have proposed several means to overcome these problems, for example by increasing efforts to educate decision-makers and other stakeholders and the selection of suitable indicators for evidence-based decision-making.

Compliance with ethical standards

The authors declare that they have no conflict of interest. Informed consent was obtained from all individual participants included in the study.

Acknowledgements

This work is part of the OWAS1S research programme (Optimizing Water Availability with Sentinel-1 Satellites) with project number 13871, which is partly financed by the Netherlands Organisation for Scientific Research (NWO). We want to thank all OWAS1S programme partners for their contributions. Furthermore, we want to thank all experts for their cooperation and time. Finally, we want to thank the various contact persons at the regional water authorities for arranging the interviews.

Appendix A. Interview questions

This appendix shows the questions of the semi-structured interviews performed in this study.

1 **Do you wish to remain anonymous?**
2 **What is your function at the regional water authority?**
3 **How long are you working as [*function*] at the regional water authority?**
4 **What are the problems that you have to deal with?**
5 **What are the decisions that you have to make?**
6 **Who else is involved in taking these decisions?**
7 **Which information do you use in decision-making?**
8 **Why do you use this information for decision-making?**
9 **What do you think of the application of hydrological models in regional operational water management?**
10 **Which information do you want to have for decision-making?**

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