Global Environmental Change 52 (2018) 273–285

Contents lists available at ScienceDirect

Global Environmental Change

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

Designing a monitoring system to detect signals to adapt to uncertain climate change

Marjolijn Haasnoot[a,b,*], Susan van 't Klooster[c], Jos van Alphen[d]

[a] Deltares, Boussinesqweg 1, 2600 MH, Delft, The Netherlands
[b] Delft University of Technology, Faculty of Policy and Management, Delft, The Netherlands
[c] Savia, Amersfoort, The Netherlands
[d] Staff Deltacommisioner, Den Haag, The Netherlands

ARTICLE INFO

Keywords:
Monitoring
Adaptation pathways
Deep uncertainty
Early warning signals
Investment planning
Climate adaptation

ABSTRACT

Adaptive plans aim to anticipate uncertain future changes by combining low-regret short-term actions with long-term options to adapt, if necessary. Monitoring and timely detection of relevant changes, and critical transitions or tipping points is crucial to ensure successful and timely implementation and reassessment of the plan. Although efforts have been made to identify signposts to monitor, the question remains how to design a signal monitoring system that detects and anticipates (future) change to support adaptive planning. For example, to support water related infrastructure investments under uncertain climate change. What are good signposts to monitor and how to wisely analyse them to get timely and reliable signals for adaptation? In this paper, we present a framework for designing and using a monitoring plan as part of the Dynamic Adaptive Policy Pathways (DAPP) approach for decision making under uncertainty. We use the following criteria to evaluate signposts and their critical signal values: measurability, timeliness, reliability, convincibility and institutional connectivity. We illustrate the approach based on the signal monitoring system for the adaptive plan developed by the Delta Programme in the Netherlands.

1. Introduction

Anticipating the future is important when making investment decisions with long-term impacts. However, uncertainties about future needs, conditions, and developments such as climate change, and economic, social and technical developments, complicate our ability to anticipate and make decisions. Adaptive plans are being advocated to deal with uncertainties about the future and minimise regret (e.g. Walker et al., 2013). Adaptive plans consist of short-term actions, which are typically low-regret actions that keep future options open, and long-term alternatives to adapt to uncertain changing conditions, if necessary.

Several approaches exist to design adaptive plans, including Assumption Based Planning (ABP) (Dewar et al., 1993), Adaptive Policy Making (APM) (Kwakkel et al., 2010a; Walker et al., 2001), Robust Decision Making (RDM) (Lempert et al., 2003), Multi Objective Robust Decision Making (Kasprzyk et al., 2013), Engineering Options Analysis (EAO) (Smet, 2017), and Dynamic Adaptive Policy Pathways (DAPP) (Haasnoot et al., 2013). These approaches all share the central idea that the best way to deal with uncertainty is to do what needs to be done now, and to watch out for changes that indicate that new decisions are required to address changed conditions (e.g. Swanson et al., 2010). Two types of adaptive plans are distinguished in the literature (Kwakkel and Haasnoot, 2018; Maier et al., 2016): 1) protective or static adaptiveness, which aims to protect a basic plan from failing through contingency planning and monitoring (example approaches are ABP, APM, and RDM); and 2) dynamic adaptiveness, which aims to monitor the ability of the plan to meet objectives and developing alternative sequences of actions over time that can be switched to when required (example approaches are DAPP and EOA).

Approaches for adaptive plans have strong roots in the fields of water and infrastructure management, transport, and defence. The related idea of adaptive management (Holling, 1978, 2001) originates from ecosystem management (Swanson et al., 2010). Adaptive *management* focuses on increasing adaptive capacity of the system by learning from experiments (Arvai et al., 2006; Bormann et al., 1994; Pahl-Wostl et al., 2007). This suggests an important role for monitoring the performance of the system. Adaptive *planning* uses monitoring for decision making on follow-up actions of a plan.

The success of adaptive plans thus depends on monitoring and

* Corresponding author at: Deltares, Boussinesqweg 1, 2600 MH, Delft, The Netherlands.
E-mail address: Marjolijn.Haasnoot@deltares.nl (M. Haasnoot).

https://doi.org/10.1016/j.gloenvcha.2018.08.003
Received 19 April 2018; Received in revised form 31 July 2018; Accepted 26 August 2018
Available online 03 September 2018

anticipating on-going developments (e.g. climate change and socio-economic change) and ensuring that actions are indeed taken if and when necessary, or that the plan is updated in case of unforeseen developments. In general, monitoring and evaluation aims to learn and improve the progress of implementation of a plan, its process and the efficacy of the actions in achieving specified goals. Preston et al. (2011) provide a literature review on monitoring and evaluation of adaptation planning to climate change. Most of these studies focus on procedural aspects, adaptation progress, elements of the plan and governance support (e.g. Ford et al., 2013; Biesbroek et al., 2010; Klostermann et al., 2018; Marsden and Snell, 2009). These studies typically look back and try to answer the question: ‘Are actions implemented as planned and are they effective?’ This can therefore be considered as *retrospective* monitoring, and is typically done in adaptive management, where monitoring aims to learn from an experiment. In contrast, adaptive planning requires also *anticipatory* monitoring, which focuses on the question: ‘(When) should actions be implemented and are they still appropriate?’ It thus aims to anticipate uncertain future developments that could trigger implementation or adjustment of adaptive plans to new information. Essential for anticipatory monitoring is to acknowledge that, before an action becomes effective, it takes some time to study, prepare and implement it (‘lead time’). An adequate amount of time therefore required between signal and the envisioned new situation.

The idea of anticipatory monitoring originates in literature from strategic planning (Schwartz, 1996) and Assumption-Based Planning (Dewar et al., 1993). These approaches suggest monitoring of important assumptions underlying a plan to establish if these assumptions are at risk and whether additional actions need to be taken. Signposts specify the information or indicators that should be tracked. Critical values of these signposts – sometimes referred to as triggers – are used to determine when follow-up actions should be implemented, including contingency actions or next actions of an adaptation pathway.

Approaches and practices of anticipatory monitoring are often generic instead of plan-oriented. Such generic approaches examine seeds of change and monitor developments and possible events that may have an impact on a market, a sector, an organization or a policy domain in general. Some of these approaches have a strong foothold in strategic planning and futures studies, such as Trend Analysis and Horizon Scanning (OECD, 2017), whereas other approaches, such as Early Warning Systems (e.g. Waidynatha, 2010) and Security Analysis (the analysis of security threats for a sector or organization), stem from a tradition of Risk Analysis. Monitoring for Early Warning Systems and Security Analysis is based on the identification of threats and hazards. Trend analysis and horizon scanning often add two other aspects: possibility and desirability. Possibility considers the likelihood of the trend in light of other trends or natural law. Desirability deals with the preference for (or against) a certain trend, and if there are any advantages (or not) to a trend developing (Cramer et al., 2016). The information is used to score and classify and to gain a deeper understanding of the nature and meaning of existing and potential new trends and developments.

While examples exist on what needs to be monitored to support adaptive plans and efforts have been made to find early warning signals (e.g. Scheffer et al., 2009; Schoemaker and Day, 2009), yet the identification of proper signals remains a challenge (Garschagen and Solecki, 2017). So far, most studies have used expert judgement (e.g. Kwakkel et al., 2010b; Lempert and Groves, 2010; Environment Agency, 2012; Haasnoot et al., 2013; Groves et al., 2015; Kingsborough et al., 2016; Hermans et al., 2017; Tariq et al., 2017), model-based vulnerability assessment (Bryant and Lempert, 2010) and/or optimisation methods (Hamarat et al., 2014; Kwakkel et al., 2016; Quinn et al., 2017) to design signposts and related critical values for signals. A first attempt to evaluate the performance of expert-based signposts was done using transient scenarios (Haasnoot et al., 2015). The governance around monitoring to support collaborative learning for adaptive planning has been addressed in terms of who should monitor what and for whom by Hermans et al. (2017).

To design a signal monitoring system to support adaptive planning and derive proper signals for adaptation, the following questions need to be addressed: How to decide what to monitor? How to best analyse the derived information to get timely and reliable signals that are convincing for the responsible people to act upon?

In this paper, we present a framework for designing and using a signal monitoring system to inform adaptive planning and illustrate this for water related infrastructure investments. We describe how to identify signposts to monitor and establish critical values to derive signals and provide criteria and examples on how to evaluate them. We present the framework as part of the Dynamic Adaptive Policy Pathways (DAPP) approach, but it can be used for other adaptive planning approaches as well. The pathways approach has demonstrated significant potential as an adaptive planning approach to support decision making on water management under conditions of deep uncertainty both in literature and in practice (e.g. Haasnoot et al., 2012; Ranger et al., 2013; Barnett et al., 2014; Wise et al., 2014; Rosenzweig and Solecki, 2014; Bloemen et al., 2017; Lawrence and Haasnoot, 2017; Stephens et al., 2017; Zevenbergen et al., 2018). Although, most applications are on water resources and flood management, the approach has been used in other policy domains as well (Petr et al., 2015; Bossomworth et al., 2017; Mendizabal et al., 2018).

This paper first describes the concept of adaptive planning and the role of monitoring and signals therein. Next, the case study – the Delta Programme in the Netherlands – is introduced (Delta Programme, 2015; Bloemen et al., 2017). We then present the framework on how a signal monitoring system can be designed and illustrate this based on the adaptive plan of the Delta Programme. We end the paper with discussion on the approach in the light of the defined criteria.

2. Adaptive planning, policy pathways and the importance of monitoring and signals

2.1. Adaptive planning through Dynamic Adaptive Policy Pathways

Adaptive planning means that short-term actions and long-term options have been identified, and that monitoring and signalling supports timely implementation or adjustment of the specified plan.

Adaptive plans can be developed using the Dynamic Adaptive Policy Pathways (DAPP) approach (Haasnoot et al., 2013). Within the DAPP approach a plan is conceptualized as a series of actions over time (pathways). The approach starts from the premise that policies, actions, or decisions have an uncertain design life and might fail to achieve their objectives sooner or later; when operating conditions change they may reach an adaptation tipping point (Kwadijk et al., 2010). Likewise, when favourable conditions arise actions may reach an opportunity tipping point to implement actions, for example if benefits exceed costs (Bouwer et al., 2018). Once actions fail, additional or other actions are needed to ensure that the original objectives are still achieved, and a set of potential pathways emerges. There are different routes that can achieve the objectives under changing conditions (analogous to ‘All roads lead to Rome’). Hence, various alternative sequences of decisions or actions can be explored for multiple futures. Depending on how the future unfolds, the course of action can be adapted when predetermined conditions occur to ensure that the objectives are still achieved.

Multiple pathways are typically visualized in an Adaptation Pathways Map or decision tree, with time and/or changing conditions on the axes (Fig. 1). With this map, it is possible to illuminate opportunities, no-regret actions, lock-ins, path-dependencies, and the timing of options. An adaptive plan is then designed based on an evaluation of the alternative pathways.

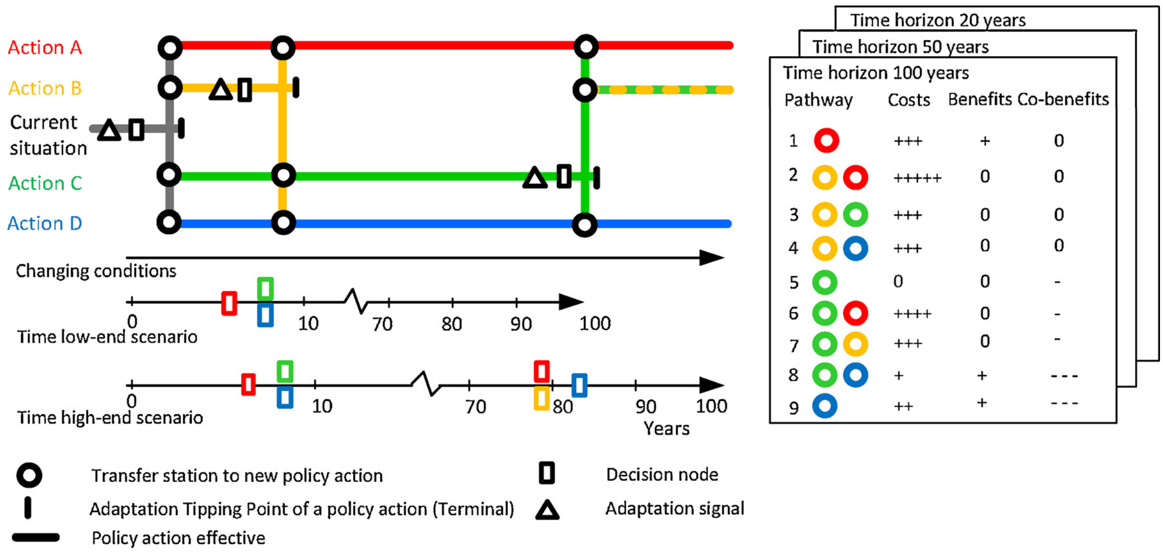

Fig. 1. An example of an Adaptation Pathways Map and the relation with adaptation signals and decision nodes (left) and a scorecard presenting the costs and benefits of the 9 possible pathways presented in the map (based on Haasnoot et al., 2013; Haasnoot et al., 2015). The timing of a decision node depends on the timing of a tipping point represented with the time axes for a low-end and high-end scenario, the action that will be implemented, and the situation in which this action will be taken. As a result, for the first adaptation tipping point the decision node of action A is earlier than the decision node of actions C and D, and the decision node of action D for the second tipping point is very close to the tipping point, as this action can build upon action C. The colours in the scorecard refer to the actions: A (red), B (orange), C (green), and D (blue) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

2.2. Adaptive planning and the importance of signals

For successful implementation of an adaptive plan, it is essential to know whether we are still on the right track and, in particular, whether there are developments or insights that require: implementation or delay of the next action of a pathway, a decision among alternative pathways, contingency actions to stay on track or mitigate unintended effects, or a consideration of potentially better options. It is important not only to know *if* this may be required but also *when* this may be required. In other words: we are seeking for the occurrence and timing of adaptation and opportunity tipping points arising from developments or events such as climate change, socio-economic or technological developments, and changes in societal values (e.g. levels of service for infrastructure or changes in community values or risk tolerability). Timely signalling of these developments helps to implement actions not too early nor too late, to avoid investing too much or too little, and to signal opportunities through innovation, new insights, changes in cost and benefits, required maintenance, and societal values.

Signals not only provide directions for implementing or adjusting the adaptive plan. They may also indicate that further research is needed, for example, when the influence of the signal is not yet clear. For example, the Delta Programme has investigated the possible consequences of signals of accelerated and higher sea-level rise than that assumed in its scenarios (Delta Programme, 2017a). These signals have not yet hastened or adjusted the implementation of the plan, but triggered additional research. Signals can also be used to indicate that the monitoring plan needs to be altered, for example, with additional or other signposts, or different analyses of the indicators.

2.3. Pathways map and signals

Fig. 1 presents an example of an Adaptation Pathways Map and the role that signals play. The map gives an overview of policy options after the current situation reaches an adaptation tipping point. Some of these policy options have a tipping point as well. Ideally, follow-up actions are implemented and effective before an adaptation tipping point is reached. A decision node represents the latest moment one can decide to start implementing the next action(s) of a pathway and still be able to keep performing acceptably. Decision makers could decide to delay the implementation of the next action(s) (e.g. once a tipping point is reached), but this would mean that the desired outcomes are temporarily not achieved until the new actions are completely in place. Reasoning backwards from an adaptation tipping point, a decision node can thus be assessed by taking into account a certain amount of 'lead time' (Haasnoot et al., 2013; Stafford Smith et al., 2011). This lead time depends not only on the action itself and how quickly it can be activated, but also on the situation in which the action needs to be implemented (e.g., is time needed to remove predecessor actions or can one build upon actions taken earlier?).

Preferably, signals are observed before a decision needs to be taken on the action(s) to implement, and thus before a decision node. Early warning or weak signals could indicate that an adaptation tipping point *may* be approaching, while strong signals warn that a tipping is likely to occur. A weak signal will be surrounded with more uncertainty, but at least decision makers and stakeholders can already create a mind-set that future actions may be needed. They can start to study what the new situation may look like or initiate actions to prevent a tipping point from occurring.

A signal is given if the observed value of a signpost or a combination of signposts reaches a specified critical value (signal value; Fig. 2). We distinguish and focus on two categories of signposts: 1) *performance signposts* that detect the performance of a system and indicate the extent to which objectives are still being achieved; and 2) *environment (context) signposts* that monitor (external) changing conditions that jeopardize or provide opportunities for achieving these objectives. Examples for the latter would include trends and events in the physical environment, human driven impacts on the system, technological developments, or changes in societal values and perspectives. Sea-level rise would be an environment signpost, while flood damage and frequency of flooding could be related objective-detecting signposts. A third category exists of signposts that monitor for potential unintended social, economic and environmental impacts (Swanson et al., 2010), or monitor for opportunities to implement adaptation actions, such as required maintenance of infrastructure or activities of other stakeholders that make implementation of actions easier or less costly.

Environment signposts monitor the external driving forces and thus are closer to the source of change. Therefore, they often have a better signal to noise ratio, and may detect signals earlier than performance

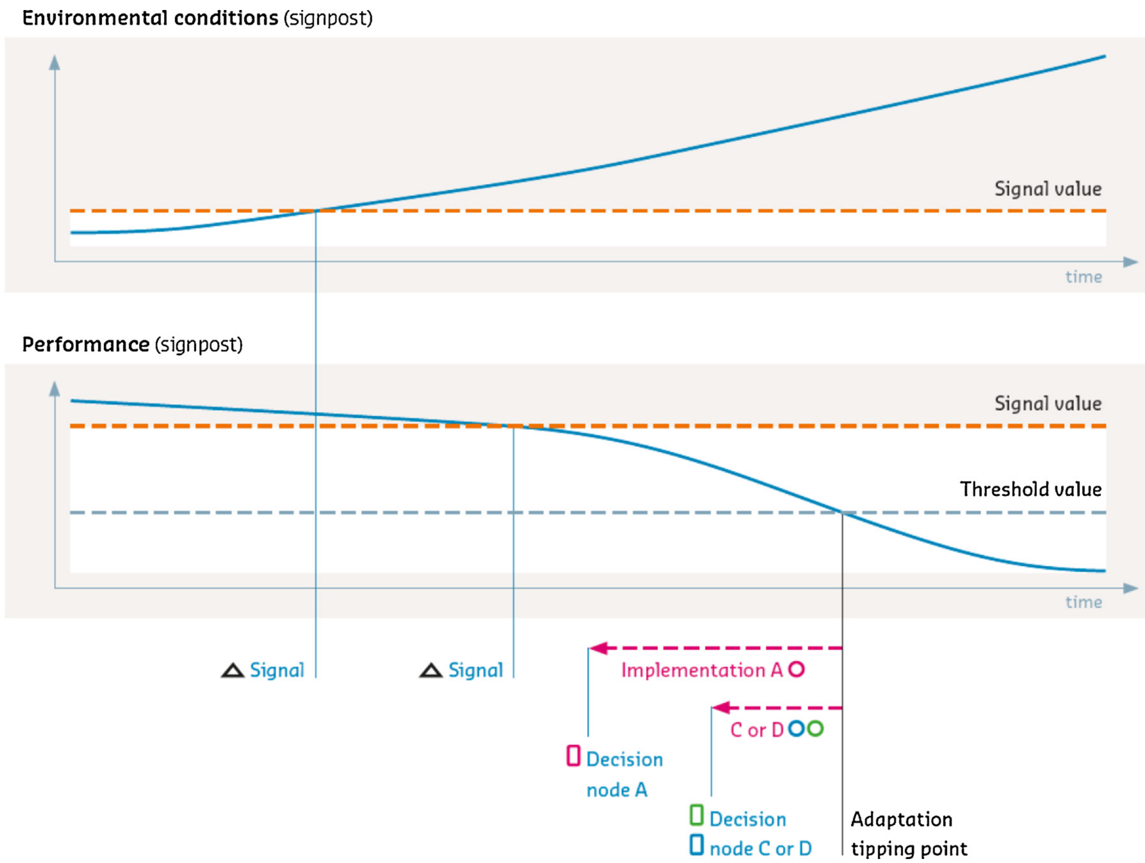

Fig. 2. Example of the relation between an adaptation tipping point (ATP) for action B from Fig. 1, decision nodes for actions A, C, and D, and adaptation signals. Over time, as conditions change, the performance of action B decreases. When it reaches a threshold value of the performance an ATP occurs. Based on an assessment of the time needed to implement follow-up actions (actions A, C, or D) decision nodes can be identified. When a signpost reaches its signal value, a signal is given. Environment signposts that monitor external context are earlier in the cause-effect chain and are less subject to a myriad of developments they may therefore give an earlier signal. Note that in practice the smooth line on the changing performance and environmental conditions will be capricious which complicates trend detection.

signposts that monitor impacts of the driving forces. Performance signposts are affected by a myriad of changing conditions, but may be more convincing, as they are related to relevant impacts and objectives and have a better connectivity to actions of responsible authorities. For example, global temperature is an environment signpost of climate change, as are river flows or precipitation intensities. Monitoring flood damages represents a performance signpost for changing flood risk as a result of climate change and socio-economic development. A mixture of signposts may help to better understand what is happening. Signposts and signal values are not fixed; they can change over time as new information becomes available.

Observations often have to be processed before signals can be detected. This processed information, or further specification of a signpost, is called a derivative signpost. For example, the average summer discharge measured for a river is a drought related derivative (environment-detecting) signpost for the river's discharge. The river discharge itself does not give enough information.

Sources for signposts include field measurements and observations, model simulations, as well as expectations, new insights into system operation, innovations, developments or (planned) interventions, and policy decisions. Defining critical (signal) values for signposts can be difficult, especially for qualitative signposts, such as new studies on relevant developments, interventions in the system by others, or for developments that are complex and difficult to understand.

2.4. Criteria to evaluate signposts and critical values

What are effective performance criteria for a signal monitoring system for adaptive planning? And how to get timely and reliable signposts and critical values that are convincing for decision makers to act upon? In literature on the role of knowledge in policy, the effectiveness of monitoring systems at the interface between science and policy is described using three quality criteria (Cash et al., 2003; Turnhout and Halfmann, 2012): salience, credibility, and legitimacy. These criteria originally were meant to be applicable to environmental assessments (see for example Eckley et al., 2001). Here, we use them to evaluate the use of signposts for informing adaptive planning. To enhance their applicability, we further specify salience and credibility with (sub)criteria in the context of adaptive planning (Fig. 3).

Salience (or, in more common terms, *relevance*) refers to the extent to which the monitoring system addresses the particular concerns of the user. In the first place, signposts must be relevant to current policy and other decisions and address those elements relevant for the user. A salient or relevant signpost is thus meaningful, describes important aspects of the system or plan, and has a clear objective to answer the 'why this signpost' question. We identified three sub criteria specifically for adaptive plans:

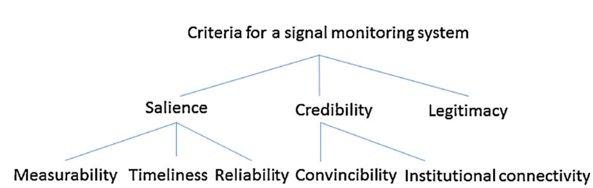

Fig. 3. Overview of generic criteria and sub criteria for a signal monitoring system to support adaptive planning.

- Measurable: the signposts and critical values can be observed.
- Timely: the signpost can resolve a change such that it indicates something is happening, and leave sufficient time to prepare and implement of a follow-up measure.
- Reliable: the probability is small that signposts and critical values give an incorrect signal or incorrectly gives no signal (no false or missed alarms).

And ultimately, signposts are preferably monitored effectively at an affordable cost.

Credibility refers to scientific and technical believability. This implies that signposts and critical values should be scientifically and technically sound and thereby convincing. This adds a fourth sub criterion for adaptive planning: convincibility. Users are more likely to accept signposts as credible when the information is consistent with perceived change or other information already available, when they trust the source as authoritative, and/or when the assessment process has been according to scientific standards (trustworthiness of source and procedures) (Tuinstra and van't Klooster, 2015; Kunseler et al., 2015). Consistency and trustworthiness increase the performance of the monitoring system and the support for follow-up measures.

For the credibility of signposts for informing adaptive planning, political believability is important as well. More than environmental assessments should monitoring systems engage with political, social and decision contexts, for example, by defining actionable messages and seeking connectivity to the organizational logics of decision-making (van der Steen and van Twist, 2012). This requires developing sensitivity for resistance and aversion to adaptive measures (Bossomworth et al., 2017), windows of opportunity (e.g. Kingdon, 2003), and power relations and processes operating within broader political contexts (Bossomworth et al., 2017; Voß and Bornemann, 2011). This implies, in other words, that signposts and critical values should also be 'institutionalizable', which leads us to the criterion of 'institutional connectivity'.

Legitimacy refers to the acceptability or perceived 'fairness' to users: it is important that in the process of identifying signposts and signal values the interests and concerns of stakeholders have been taken into account. Perceived fairness increases the involvement of stakeholders and contributes to the acquaintance with and performance of the monitoring system and support for follow-up actions.

Salience, credibility, and legitimacy have a mutual dependency as trade-offs and synergies exist among them (see also Cash et al., 2003). For example, seeing windows of opportunity through engagement with the decision context increases relevance for current policy. And taking into account interests and concerns of stakeholders may shed light on resistance, aversion, expectations and opportunities. Ensuring effectiveness is, in other words, a balancing act. Here, we will use the aforementioned criteria to describe how this balancing act is performed in the case of the Delta Programme.

3. The Delta Programme and Signal Group

The Delta Programme is a nation-wide programme to prepare the Netherlands for climate change and socio-economic developments, and more specifically 'to protect the Netherlands from flooding and to ensure adequate supplies of freshwater for generations ahead' (Delta Programme, 2010; Van Alphen, 2013). Climate change may result in continued sea-level rise, increased rainfall intensities, and more extreme river discharges, with larger flood risk. In the summer, river inflows decrease causing salt intrusion to go further inland and thus a reduced freshwater availability. In addition, net precipitation decreases resulting in an increased demand for water in regional areas. Economic development and population growth may increase the value of assets exposed to flooding and drought, and may change the water demand.

The adaptive plan of the Delta Programme is based on a participatory process and comprehensive model-based study to assess the vulnerabilities and effectiveness of promising actions using four scenarios incorporating future climate and socio-economic conditions (Van Alphen, 2016). The final plan consists of so-called key 'delta decisions' and pathways maps presenting short-term actions and mid to long-term options to adapt to changing conditions, if needed (Delta Programme, 2015). The timing of the actions loosely relates to the scenarios reflecting future climate change and socio-economic developments. Adaptation can thus be implemented at different paces depending on how the future unfolds. Its monitoring plan should therefore provide the necessary information on any needs for further implementation of actions or adjustments to the plan.

The Delta Programme established a Signal Group of ten experts from various knowledge institutes on climate, water, and socio-economy (Delta Programme, 2017a) and charged them with mapping external developments and signalling when implementation or adjustment to the plan is required.

The Signal Group acknowledges its dependency on other stakeholders: people involved within the different sub-programmes of the Delta Programme, decision-makers, and various knowledge institutes. The knowledge of these stakeholders about the water system and impacts is used for monitoring purposes. They not only provide insights into new trends and developments to adjust the monitoring system and keep its data up-to-date, but also help to interpret signals and potential consequences for decision making. Their involvement is considered crucial to comply with the signpost criteria, especially convincibility and institutional connectivity.

The (anticipatory) Signal Group works together with the Delta Program's retrospective monitoring group that monitors implementation and effectiveness of the plan. Albeit their different focus, there is some overlap in the signposts to monitor. Both groups work together to inform each other about relevant developments and insights.

First activities of the Signal group have included an initial screening of signals and signposts, and the development of the approach presented in this paper. This resulted in the 'early warning' for potential accelerated sea-level rise and the increase of heavy rainfall events and related pluvial floods (Delta Programme, 2017b). Next year, the Delta Programme will apply the signal monitoring system. Based on the results of this initial application, the signal system and its procedures will be adjusted as more insight is gained on the potential performance of the criteria, signal values and their importance for adaptive planning.

4. Five steps to design a signal monitoring system for adaptive planning

Once the core of an adaptive plan is designed as described in Section 2.1, the next step is to design a signal monitoring system based on signposts and signal values. For this purpose, a step-wise approach was developed in the Delta Programme that consists of five questions to be answered (Fig. 4). Answering these questions helps to derive at a signal map presenting a set of signposts and signal values that suffice the criteria described in Section 2.4. Steps 1 and 2 focus on what needs to be known to make the right decision at the right moment. Step 3 aims to identify what needs to be monitored to know this. Steps 4 and 5 focus on how the derived information should be analysed to obtain the relevant information for decision making.

The criterion of 'salience' is addressed in step 1–4, with step 4 addressing the sub criteria of timeliness and reliability. Step 5 aims to ensure 'credibility'. Executing the steps together with stakeholders helps to address 'legitimacy'. In practice, safeguarding legitimacy and facilitating a meaningful dialogue is not facile. For example, during stakeholder interactions in the Delta Programme, it became clear that the added value of an anticipatory monitoring system was not always self-evident. Some stakeholders argued that the Delta Programme already uses scenario analysis and that there is already a system in place to monitor, evaluate, and update plans every six years. Also, eventually, various stakeholders were not interested in the details of the monitoring

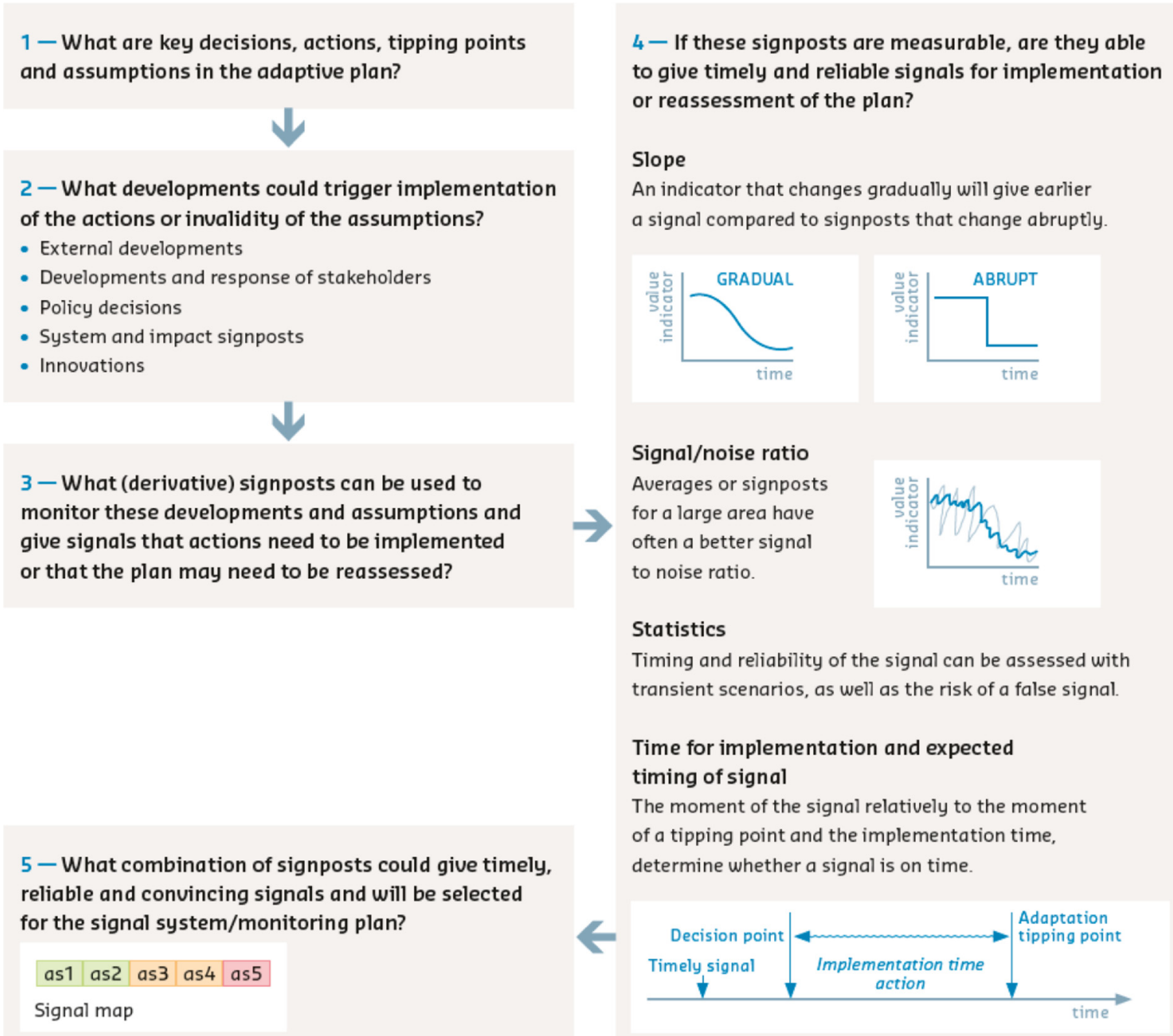

Fig. 4. Steps to develop a signal monitoring system for adaptive planning.

system (see also step 5). Involving stakeholders may also imply dealing with conflicting and contested interests and concerns of stakeholders (e.g. Bossomworth et al., 2017).

Below we further describe and illustrate each of the steps using examples from the signal monitoring system developed for the adaptive plan of the Dutch Delta Programme.

Step 1. What are key decisions and actions, adaptation tipping points, and critical assumptions in the adaptive plan?

The first step aims to identify key elements of the adaptive plan: decisions or actions, adaptation tipping points, and critical assumptions in the plan. Key decisions or actions are strategic decision moments often situated at the bifurcation of pathways and which largely determine future options. They typically have a high path-dependency, or are expensive or difficult to implement. Critical assumptions are assumptions that are essential to the plan's success; if they become invalid, the plan may fail. These include, for example, assumptions on future scenario developments used in the analysis or on characteristics of the system – such as cause-effect relations in the model used to evaluate the effectiveness of policy actions.

Based on the adaptive plan of the Delta Programme, we identified the key decisions for fresh water supply and flood risk management. To protect the Netherlands from flooding, the following actions are planned for the near term (< 10 years): strengthening and raising flood defences (mainly dikes) to cope with increasing levels of sea and river flows; increasing the discharge capacity of the rivers by widening the river bed; increasing pump capacity at the Afsluitdijk closure dam to compensate for decreasing capacity to discharge water from Lake IJsselmeer to the Wadden Sea under gravity during low tides; and beach nourishment to maintain the coastline that is under pressure from erosion (see Fig. 5). In the long-term, most of these actions will be continued and – if needed – enlarged to cope with more change. Additional long-term options include: adapting the water distribution between the main Rhine river branches and increasing the water level in Lake IJsselmeer.

To ensure sufficient fresh water supply in the near term, more water will be provided through flexible operation of the water level by 0.2 m in Lake IJsselmeer during the summer half-year. To provide enough water to the midwestern part of the country, the capacity of the supply channel near Gouda will be increased to 15 m^3/s. Mid- to long-term water supply options include: further increasing the capacity of the Gouda supply channel to 24 m^3/s or creating an additional upstream inlet in the case of increased salt intrusion; measures to protect salt intrusion through the rivers; or simply accepting higher salt concentrations (and consequently regional changes in land or water use).

Assumptions include the scenarios used in the analysis, which describe the range of explored future climate change and socio-economic developments. For example, the maximum river flow that can enter the Netherlands through the Rhine River is assumed to be 18,000 m^3/s; at

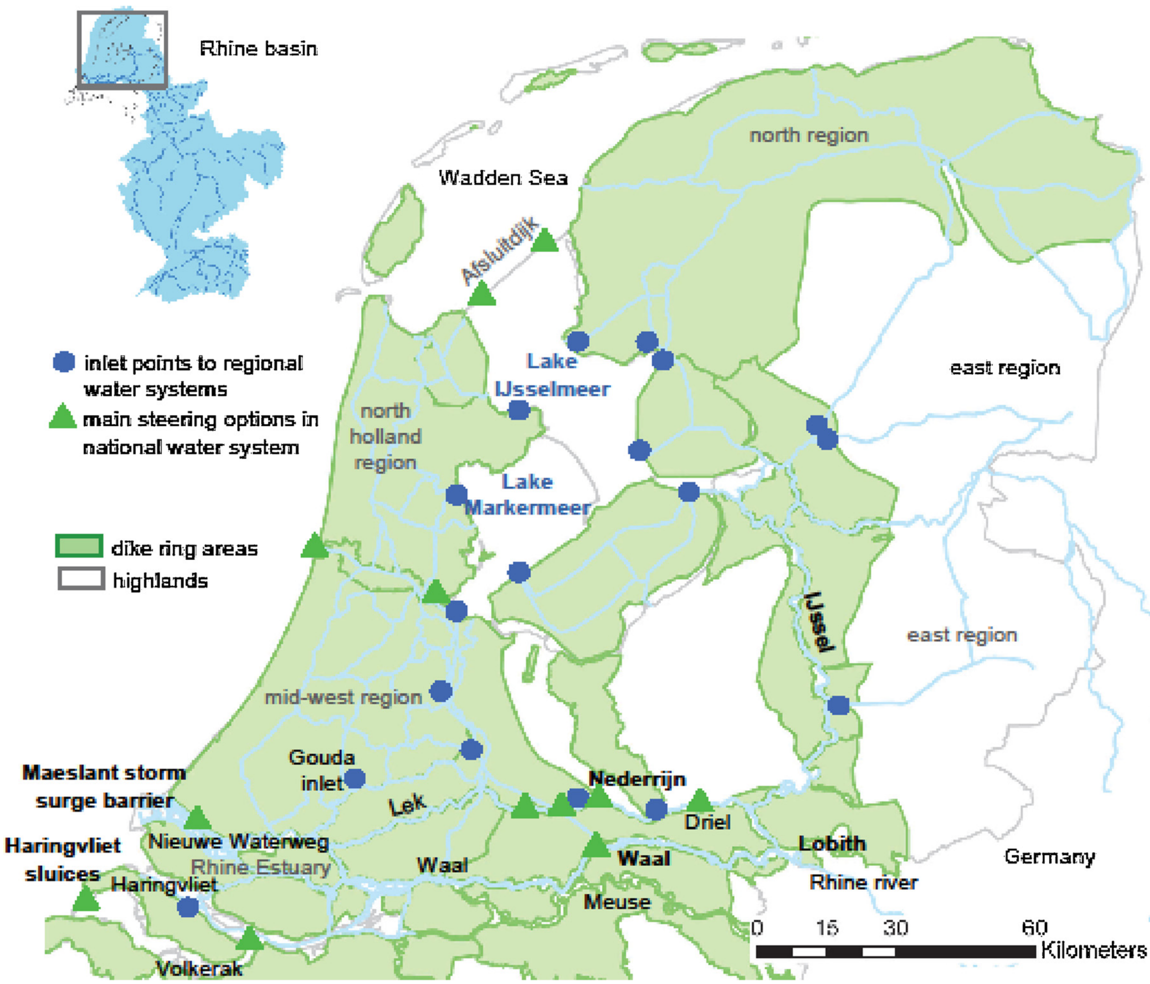

Fig. 5. Netherlands with relevant water management characteristics.

higher flows the river will flood upstream in Germany. Similarly, the models used to assess flood impacts assume relations between flood levels, damages, and casualties; success rates for evacuating people in cases of flood events; costs of actions; distribution of river flows across the country; and limits to autonomous adaptation to the changing conditions by stakeholders (e.g. farmers).

Step 2. What developments could trigger implementation of the key decisions or actions or could result in the failure of key assumptions?

Next, developments are identified that could trigger implementation of the key decisions, or lead to tipping points or invalidate assumptions. To ensure that all relevant developments are included and to examine those beyond more traditional climate change or water system indicators, two concepts are used (Table 1). The STEEP concept (Social, Technological, Economic, Ecological, and Political), traditionally used for scenario development, helps to identify external developments that can influence decision making (Bradfield et al., 2005). The DPSIR (Drivers, Pressures, State, Impact, Response) concept, used for environmental modelling, helps to describe the causal chain and relevant signposts therein (OECD, 1993). As the aim is to prompt policy analysts to consider a wide range of developments, their causes, and their impacts, the precise classification of these factors within the matrix is not important.

Table 1
Matrix of developments and causal chain to support identification of relevant developments and related signposts for Steps 2 and 3.

		Changes			
		Climate change	Socio-economic developments	Knowledge and innovation	Societal preferences
Causal chain	Drivers				
	Water system				
	Impacts				

The Delta Programme aims to identify signposts for the following developments and related key assumptions: climate change, socio-economic developments, societal preferences, and knowledge and innovation. Regarding flood risk management, they relate to 1) hydraulic loads resulting from sea-level rise, storm surge, extreme river flows, and upstream policies; and 2) impacts of flooding: knowledge on dike strength and damage functions, and urban and economic developments.

For fresh water supply, developments and assumptions were identified that impact on 1) water demand, and 2) water availability. For water demand, these include: precipitation deficit, sea-level rise, and the related salinization that demands more water to keep ditches fresh, land use changes through different crop use or changes in the acreage of agricultural, urban and natural land, population growth, use of sprinkling installations, and other innovations. For water availability, the considered developments include: precipitation, sea-level rise increasing salt water inflow to rivers, upstream developments that reduce river inflow, and policy decisions, such as modifying the operation of the Haringvliet barrier.

Table 2
Overview of the signposts and why they were selected.

Developments, assumptions	Signpost	Why	Additional signposts	Why	Who
Sea-level rise	Projected sea-level rise along the Dutch coast in 2050, 2100, 2200	Assumption in the scenarios, important development that requires action, relevant for safety against flooding strategy.	Measured global mean sea-level rise (GMSL)	• GMSL has better signal to noise ratio for earlier signal identification	Signal Group
	Volume of sand supplied per year	Impact signpost for sea-level rise and the effect on the strategy of sand nourishment.	Surface intertidal areas in Wadden Sea, Eastern /Western Scheldt		DP Coast, Wadden, SW Delta
	Frequency of closing of storm surge barriers Maeslant, Eastern Scheldt, Hollandse IJssel	Impact signpost of sea-level rise and storm surge, relevant for strategy in the Rotterdam area.	• Storm surge frequency, North-western > 8Bft • Alarm for closing barrier	• Driving force affecting closure • Alarms occur more frequently and are likely to give earlier signal	DP Rijnm.Dr, SW Delta
	Number of days in winter without drainage capacity from Lake IJsselmeer	Impact signpost for sea-level rise, relevant for strategy in the IJsselmeer area.			DP IJM
Discharges of the rivers Rhine and Meuse	Projected extreme high and low river discharges in 2050, 2100,	Assumption in the scenarios, important development that requires action, relevant for water supply and safety against flooding along the rivers.	• Extreme high and low discharges in 10 rivers in North-western Europe • Average discharge in summer half year • Discharge distribution Rhine • Upstream developments	• Combining multiple stations increases the possibility for detecting signals • Average gives earlier signal than extreme values • Uncertain crucial assumption • Developments such as water use or flood management strategies influence inflow	Signal Group, with DPV, DPR
Land use and population	Projected spatial developments, incl. land use, economic value, and population in 2050	Assumption in the scenarios, relevant for strategies as it determines safety levels and water demand. To be detailed on the dike ring level for periodic evaluation on protection levels.			Signal Group
Drought	Precipitation deficit (annual maximum)	Assumption in the scenarios, important development that requires action, relevant for fresh water supply strategy.	• Drought damage • Groundwater levels • Water demand • Increase in sprinkling installations • Not meeting agreed minimum lake level (days)	• Impact signpost, also affected by land use • Impact signpost on water system • Signpost of autonomous adaptation and how drought is perceived by farmers.	Signal Group, DPZW, CBS DPIJM
Salinization	Intake stops of fresh water (frequency and duration)	Impact signpost for salinization and relevant for fresh water supply strategy	• Max. salinity at intake locations in lower river area	• Driving force for water supply actions, impact signpost of sea-level rise	DPZW
Pluvial flooding	Extreme rainfall (frequency and intensity)	Signpost for climate change in urban and rural area, to adapt strategy.	• Damage assessment measurements in combination with damage functions:	• Assumption in scenarios	Signal Group/ KNMI
Heat stress	Tropical days(> 30C and nights (> 20C) (frequency/year)	Impact signpost for urban areas that may trigger the need for additional action	• Fatalities during tropical days/ nights		Signal Group /KNMI
Knowledge and innovation	e.g. damage curves, cost estimates, measures, strength flood defences	Assumptions in strategy			All

Step 3. What (derivative) signposts could be used to monitor these developments and assumptions and give signals that actions need to be implemented or that the plan may need to be reassessed?

Once the key decisions, relevant developments, and crucial assumptions have been mapped out and insight gained into what needs to be known to implement or adjust the adaptive plan, the next step is to identify what needs to be monitored. More specifically, what indicators must be measured to signal the onset of the identified developments in Step 2, to point out that the crucial assumptions may have become invalid and/or to signal an adaptation tipping point may be approaching. For example, temperature and river discharges are both indicators for monitoring climate change and related effects in the Netherlands.

For the Delta Programme, a set of signposts was identified using Table 1, and then discussed with the users of the signal monitoring system. This set includes signposts situated at the start of the causal chain (drivers/pressures), the middle (water system), and the end (impacts). For each signpost it is described why it was selected and who should collect the information, which was important in the discussion with the Delta Programme users of signal monitoring system (Table 2). For example, projected sea-level rise along the Dutch coast will be monitored as it is one of the assumptions described in the scenarios, and is an important developed that triggers implementation of adaptation action of the adaptive plan for both flood risk and fresh water supply. In addition, global mean sea-level rise is monitored as this is expected to give an earlier signal compared to observations along the Dutch Coast. Derivative signposts were developed based on the expected signal to noise ration and further tested on their performance for timeliness and reliability in the next step.

Step 4. If these signposts are measurable, are they able to give timely and reliable signals for implementation or reassessment of the plan?

In the fourth step, signposts are evaluated on whether they are likely to give timely and reliable signals. For this purpose, several approaches exist. Qualitative expert judgment to assess the timeliness of a signal can be based on the expected rate of change (abrupt changes are less likely to give a signal), and the relative timing of tipping points, lead time follow-up actions and expected timing of signals (e.g. mentioned by Haasnoot et al., 2013 and Ranger et al., 2013; also see Fig. 4 at the bottom of step 4).

To evaluate the reliability and strength of climate signals, Moss and Schneider used a qualitative assessment to determine whether there was confidence in theory, consensus among researchers, and the presence of observations and/or model results to support this (Giles, 2002; Moss et al., 2010). In their first assessment, the Delta Programme evaluated the strength of a signal on the existence of both model simulations on future developments and observations (or that the model outcomes were supported by observations), as well as a plausible explanation for the signal (whether theory supports model results or observations).

Statistical methods, such as signal to noise ratio and trend analysis, can be used to quantify when and with what significance a signal can be credibly resolved under different possible futures (e.g. see Ceres et al., 2017; Diermanse et al., 2010, in prep; Haasnoot et al., 2015). Not only signals, but also the possibility of false signals, or missed signals can be assessed with statistical methods. Synthetic transient scenarios can be used that describe possible futures, including both natural variability and trends over time (e.g. see Haasnoot et al., 2015).

For the Delta Programme, such a statistical analysis was performed for the yearly maximum precipitation deficit, sea water levels, and average river discharge during the summer half year using an ensemble of synthetic time-series for the current climate and a climate change scenario (Haasnoot et al., 2015; Haasnoot and van't Klooster, 2018). Fig. 6 shows an example for precipitation deficit and an assessment of when this signpost gives a signal in case of a climate change of 4 °C in 2100 according to the Wplus scenario (Van den Hurk et al., 2007). At each time step the significance level was calculated. Depending on the time-series, and thus on how the future unfolds, a trend in the precipitation deficit is signalled between approximately 2025 and 2035 with a significance level (p-value) of 5% in half the time-series for the Wplus climate scenarios (Fig. 6). Here, a small p-value means it is likely that the time-series is non-stationary (probability of 95%). This signal may trigger reconsideration of water supply measures, such as increasing inlet capacity. Using the average summer discharge will give a signal around 2035–2045, triggering actions that increase the water storage. This signal could be used as one of the signals for riverine flood risk measures as well, as a decrease in summer flows is projected in a scenario with an increase in peak flows in winter, and changes in extreme flows are difficult to detect timely with large reliability. Sea-levels are likely to give an earlier signal: on average between now and 2035. The timeliness of the signal can only be studied in relation to the timing of an adaptation tipping point (see e.g. Haasnoot et al., 2015).

The use of a particular significance level depends on the purpose and context of the statistical testing. It depends for instance on the potential consequences of getting false or missed signals. False signals could result in misplaced actions and overinvestments, while missed signals could result in no action, underinvestment and being too late to timely respond and having adverse impacts. Finding the appropriate significance level will thus depend on the required balance between the timeliness and reliability, and therefore the impacts of (not) taking actions, and time and investments needed to the next potential actions of a pathway. For example, in some cases, it is necessary to know for (almost) certain that 'no harm' is done from the actions taken after a signal, thus a very low p-value is required as significance level. In other cases, a lower level of reliability may be acceptable to make low-regret decisions. Sometimes, it is possible to wait with making decisions until a more reliable signal can be derived. In practice, for large long-term investments, such as flood defence infrastructure, a higher reliability is required, but if the risk of adverse effects becomes too high one could still decide to take action in case of a weak signal based on observations, especially if projections confirm the signal and if it takes 20–30 years to implement them. For preparatory actions or further research, weak signals with a lower reliability may be sufficient to act upon. The significance value may thus be used to categorise the strength of the signal, for example: < 5% strong (highly certain and reliable) signal, 5–15% moderate signal, < 25% weak (uncertain) signal.

For the Delta Programme, signal values were specified in terms of whether a trend or change in frequency is observed and not for a specified threshold value of signposts or significance values. So far, the focus has thus been on identifying signposts with a favourable signal to noise ratio in order to obtain signals as early as possible, and for a limited set of indicators statistic methods were used.

Step 5. What combination of indicators could give timely, reliable, and convincing signals, and will be selected for the signal monitoring system?

Promising signposts are selected to constitute the signal monitoring system, which give reliable, timely, and convincing signals. A combination of signposts is needed for several reasons. First, different signposts signal different uncertainties, developments, and adaptation tipping points. Second, signposts meet different criteria. For example: some are more convincing to take action, while others may be less convincing, but give earlier signals. Signposts related to socio-economic impacts are affected by multiple changes and are likely to be more affected by noise, while signposts that directly measure the change at the source of a causal chain have the benefit of giving an early signal. From a policy perspective, it seems logical to select signposts that are related to socio-economic impacts in terms of norm values or objectives, as these are the variables on which the policies are evaluated. However, these indicators may not give timely and reliable signals since they are often linked to infrequently occurring extreme conditions, which makes them unsuitable for detecting (systematic) trends for implementation of

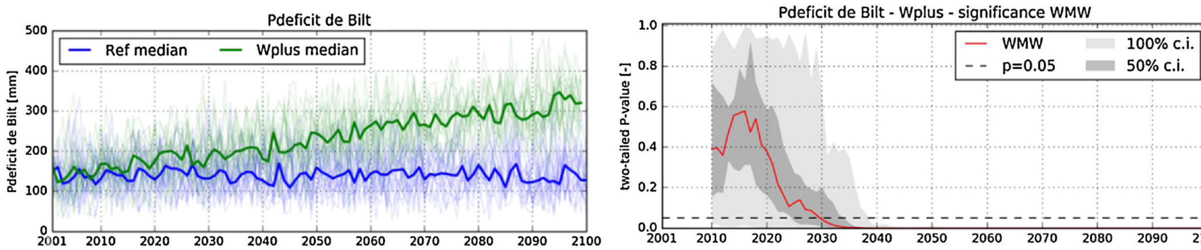

Fig. 6. Example res from statistical analysis (right) for synthetic time-series of the precipitation deficit for the current climate (ref) and a climate change scenario of 4 °C in 2100 (Wplus) (left). The right figure shows the significance level (p-value) over time calculated with the Wilcoxon-Mann-Whitney test (WMW). Traditionally in statistical analysis a p-value of 0.05 (5%) is considered significant. The grey areas give the range; the 50% and 100% confidence interval.

an adaptive plan (Haasnoot et al., 2015). Other indicators can therefore be used instead as a 'proxy' signal for change, like average discharge as an indicator which shows that extreme discharges are likely to increase in frequency, or precipitation deficit as a proxy for agricultural damage. Third, some objectives, such as flood or drought risk, are not directly observable (Kingsborough et al., 2016) and will require monitoring a range of indicators. Fourth, tracking multiple signposts helps achieve a stronger signal, because it acts as a validation and therefore is more reliable, timely and convincing. Especially in complex systems, a single signal is unlikely to provide sufficient evidence to alter an adaptation strategy. A correction for correlation between signposts is needed to avoid over confidence. Also, monitoring multiple signposts, will allow analysts and decision makers to better understand the signals and the changing system (Hall and Borgomeo, 2013).

For the Delta Programme, the identification of a set of signposts was an iterative process between analysts and stakeholders based on the criteria of measurability, timeliness, reliability, convincibility, and institutional connectivity. This improved not only the salience and credibility of the signal monitoring system, but also the legitimacy. It resulted in two long lists of signposts and derivative signposts: one for flood risk and one for water supply. When additional stakeholders were asked to review the monitoring system, it emerged that having an overview and knowledge of the reasons why signposts were selected was required to build acceptance. For this, the 'ten indicators for change for the Thames Estuary study' served as inspiration (EEA, 2012). To have a comprehensible but also sufficiently comprehensive list, a distinction was made between the primary indicators that are required ('need to know') and secondary (explanatory) indicators that assist analysts to better understand the information obtained ('nice to know'). As several signposts for flood risk and water supply were the same, a combined list was made, despite the fact that the different derivative signposts are needed to detect appropriate signals.

Table 2 presents an overview of the main signposts identified in this process, including the reason of the selection and who should monitor. In addition, other changes that could affect the plan will be monitored, such as societal preferences and soil subsidence.

5. Discussion and conclusion: a signal monitoring system against the background of salience, credibility, and legitimacy

This paper presents an approach for the design of a signal monitoring system to support the timely implementation and adjustment of an adaptive plan and illustrates this approach with the case of the Dutch Delta Programme, which has recently developed its initial signal monitoring system. The following challenges still stand out:

5.1. Defining and analysing signposts to get timely and reliable signals for adaptation (salience)

The usefulness of a signpost depends upon what it is aiming to measure, achieve, and improve. For the evaluation and use of the signal monitoring system, it is important to not only identify what needs to be monitored, but also how best to analyse the signpost to yield timely and reliable signals.

Statistical methods appear to be useful in determining when a signpost may give a signal under a particular scenario, and the reliability of this indication. Different significance levels could be used to announce different types of signals. For example, the traditional significance value of 5% or less can be used for strong signals, while higher values can be used to announce moderate or weak signals. The latter can be used to start preparations to timely adapt once stronger (more reliable) signals are detected. In practice, the identification of critical values for signals may not always be possible for qualitative signposts or may be difficult to assess with current information. For the Delta Programme identifying a trend was considered sufficient to use as a signal.

The use of a monitoring system and in particular the timeliness of a signal is related to the lead time to implement an action and the life time of actions. The sum of both is referred to as the decision lifetime by Stafford Smith et al. (2011). Actions with a short lead time are less dependent on early signals. Also, actions with a short decision lifetime (often small and flexible actions), are typically actions that can be implemented based on (strong) signals. Still, there might be situations where waiting for signal detection is too risky, and decision making is needed upfront. For example, this may be the case for flood risk measures with a long lead time and large consequences in case of being too late.

5.2. Fostering imagination (salience)

Not all signals can be known, and not all relevant information can be monitored in a quantitative way. There may also be weak signals that are worthwhile monitoring but are too (deeply) uncertain: their changes may difficult to detect (in time or at all), effects may not be estimated efficiently, system variables may be unknown, and variables may be difficult to quantify (such as human behaviour, preferences, and value systems). Therefore, attention should not only go to known and measurable signals and signposts, but also to 'the unknown'. This implies that attention is extended from what is 'probable' to what is 'possible' and 'imaginable' (Dutch Safety Board, 2015). By giving attention to imaginable scenarios, the loss of relevant but uncertain information throughout the process can be prevented.

5.3. Creating institutional connectivity (credibility)

In Section 2.4 we stated that monitoring systems should engage with the decision contexts and institutions. In the case of the Delta Programme, decision making takes place at multiple scales and levels of government: within different (and interdependent) sub-programmes and governments (municipalities, provinces, water boards, ministries, etc.), and in a broader network of governmental bodies, citizens and interest groups. Due to this institutional complexity, it is essential to identify at what level and scale a decision should be made and ultimately anchored and that mutual responsibilities should be made explicit, and there should be processes in place that facilitate the co-production of knowledge by various experts/stakeholders (see also Hage et al., 2010; Hermans et al., 2017). For anticipatory monitoring practices, the challenge is to develop continuing sensitivity for the (various) (changing) logics of decision-making (van der Steen and van Twist, 2012). Stakeholder understanding of the possibilities and added value of a signal monitoring system is important. However, stakeholder acceptance is not sufficient in and of itself. For a functioning system, the input of stakeholder knowledge is also required.

5.4. Striking a balance between detail, completeness and workability (legitimacy and salience)

Anticipatory monitoring systems are often generic, in the sense that they are used to examine seeds of change and monitor developments and possible events that may have an impact on a market, a sector, an organization, or a policy domain in general. Starting with the information contained within a specific (adaptive) plan appears helpful, as it focusses and clearly specifies the indicators that need to be monitored. However, strongly emphasising the information in a specific plan alone runs the risk of overlooking other developments that could be relevant for water management and for which no actions are currently being taken. One should also pay close attention to other related developments, opportunities or unintended impacts that could demand additional actions. For example, compare scanning the complete horizon with radar antenna versus detailed observation of a relevant object with binoculars (Schoemaker and Day, 2009).

In developing a signal monitoring system, it is tempting to get lost in detail in the quest for a complete set of signposts. A workable monitoring system requires a smart selection of signposts. Developing a layered system that differentiates between primary and secondary signposts can also be helpful in this respect. Secondary signposts provide additional information that can be used to enhance the general understanding of signals and their impacts.

5.5. Safegarding legitimacy

Stakeholder interactions within the Delta Programme have shown that it is important to safeguard legitimacy. The example of the Delta Programme showed that for stakeholders, the added value of an anticipatory monitoring system is not always self-evident. Explaining the importance of anticipatory monitoring for adaptive planning, the information required (how this differs from retrospective monitoring and the required level of detail), and the reasons why signposts were selected ultimately turned out to be important for the acceptance of the monitoring system. More systematically taking the (sometimes conflicting and contested) interests and concerns of stakeholders into account will likely further contribute to acquainting stakeholders with the workings, possibilities, and added value of the monitoring system, and generate support for follow-up measures.

6. Concluding remarks

Adaptive plans aim to anticipate uncertain future changes by combining low-regret short-term actions with long-term options to adapt, if necessary. Monitoring and timely detection of relevant changes, and critical transitions or tipping points is crucial to ensure successful and timely implementation and reassessment of an adaptive plan. Here, we have presented an approach for designing a monitoring system to get signals for (climate) adaptation. Although described as part of the Dynamic Adaptive Policy Pathways approach (Haasnoot et al., 2013) and illustrated with the case of water infrastructure investments of the Delta Programme in the Netherlands, it may also be used for other adaptive planning approaches and other policy domains as well. Key features of the approach are the identification of signposts to monitor performance, developments and assumptions that could trigger implementation of (planned) actions, and evaluation of a set of (derivative) signposts and signal values based on timeliness, reliability, convincibility, and institutional connectivity. Statistical methods can be used to show trade-offs between accuracy and timeliness of signals for different futures. By applying the approach in practice on water infrastructure investment planning, we learned that designing such a system is – for the time being – an experimental process, especially in a context of large system complexity. A reflexive attitude is likely to enhance collaborative learning processes and the effectiveness of adaptive planning.

Acknowledgements

The approach presented in this paper is based on studies for the Dutch Delta Programme. We thank Willem Oosterberg, and Femke Schasfoort for their contributions on applying and further developing the method, and the Delta Programme Signal Group of the Delta Programme Knowledge Network for their involvement and feedback. A special thank to the international reviewers of the signal monitoring system: Judy Lawrence, Tim Reeder, Jan Kwakkel, and Warren Walker.

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