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ORIGINAL ARTICLE

The role of uncertainty in climate change adaptation strategies—A Danish water management example

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Abstract We propose a generic framework to characterize climate change adaptation uncertainty according to three dimensions: level, source and nature. Our framework is different, and in this respect more comprehensive, than the present UN Intergovernmental Panel on Climate Change (IPCC) approach and could be used to address concerns that the IPCC approach is oversimplified. We have studied the role of uncertainty in climate change adaptation planning using examples from four Danish water related sectors. The dominating sources of uncertainty differ greatly among issues; most uncertainties on impacts are epistemic (reducible) by nature but uncertainties on adaptation measures are complex, with ambiguity often being added to impact uncertainties. Strategies to deal with uncertainty in climate change adaptation should reflect the nature of the uncertainty sources and how they interact with risk level and decision making: (i) epistemic uncertainties can be reduced by gaining more knowledge; (ii) uncertainties related to ambiguity can be reduced by dialogue

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and knowledge sharing between the different stakeholders; and (iii) aleatory uncertainty is, by its nature, non-reducible. The uncertainty cascade includes many sources and their propagation through technical and socio-economic models may add substantially to prediction uncertainties, but they may also cancel each other. Thus, even large uncertainties may have small consequences for decision making, because multiple sources of information provide sufficient knowledge to justify action in climate change adaptation.

Keywords Climate change · Adaptation · Uncertainty · Risk · Water sectors · Multi-disciplinary

1 Introduction

Climate change affects many aspects of human societies and the ecosystems on which they depend. Impacts on key sectors, such as agriculture, health, water supply, urban drainage, roads, buildings and the environment, can already be observed and are expected to increase in the future (IPCC 2007b; EU Commission 2009). The present climate projections exhibit large uncertainties arising among others from assumptions on greenhouse gas emissions, incomplete climate models and the downscaling of climate projections (IPCC 2007c). When assessing the physical impacts of climate change on water related sectors, traditional uncertainties in hydro-ecological models, such as data and parameter uncertainty and model structural uncertainty need to be addressed. For socio-economic impacts, additional uncertainties, involving aspects of costing and problem framing, need inclusion (van der Keur et al. 2008). The complete suite of uncertainties has been referred to as the uncertainty cascade (Hulme and Carter 1999; Katz 2002; Foley 2010).

Making climate change adaptation decisions is particularly difficult since they rely on uncertainties related to climate projections as well as to developments in natural systems and sectors that are affected by other uncertainties. Climate change impacts and adaptation also influence a wide range of stakeholders with different interests,

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making it difficult to distinguish uncertainties related to technical information stemming from different perceptions and understandings of issues that reflect stakeholder interests, perceived burdens and benefits. Decision-making in climate change adaptation deals with how, when and to what extent risks from climate events can and should be reduced, given private stakeholders' interests and those of society at large. Uncertainties are seldom explicitly recognised and dealt with in practical climate adaptation planning (Preston et al. 2011).

Uncertainty has for many years been recognised by UN Intergovernmental Panel on Climate Change (IPCC) as crucial (IPCC 2007a), and it will receive even more attention in the forthcoming Fifth Assessment Report (AR5) (Yohe and Oppenheimer 2011). A goal of the AR5 is to apply "a common framework with associated calibrated uncertainty language that can be used to characterise findings of the assessment process" (Mastrandrea et al. 2011). According to an AR5 uncertainty guidance note, the degree of certainty of a key finding should be characterised qualitatively in terms of the confidence in the validity of a finding and the degree of agreement as well as in quantified measures of uncertainty (Mastrandrea et al. 2011). This approach has been criticised for being oversimplified and potentially leading to misleading overconfidence, because it "omits any systematic analysis of the types and levels of uncertainty and quality of the evidence, and more importantly dismisses indeterminacy and ignorance as important factors in assessing these confidence levels" (Curry 2011).

Our objectives are: (i) to outline a common uncertainty framework, including a terminology, that is generically applicable in climate change adaptation; (ii) to assess climate change related uncertainties in water related disciplines and sectors; and (iii) to evaluate strategies on how uncertainty affects climate change adaptation decision making. We have applied this framework to four water related sectors in Denmark. Given our focus we do not discuss all aspects related to adaptive management, such as resilience, adaptive capacity and social learning (Pahl-Wostl 2007; Lebel et al. 2010).

2 Uncertainty framework

2.1 Definition of uncertainty

We adopt the definition of Klauer and Brown (2003) that a person is uncertain if s/he lacks confidence about the specific outcomes of an event. This definition holds that for most technical and natural sciences, uncertainty is primarily an objective matter, whilst acknowledging that uncertainty includes subjective aspects.

2.2 Typology

Our typology, which is adapted from Walker et al. (2003), Refsgaard et al. (2007) and van der Keur et al. (2008), characterises all uncertainties according to three dimensions *nature, level* and *source*.

The *nature of uncertainty* can be *epistemic, aleatory* and *ambiguity. Epistemic uncertainty* is the uncertainty due to imperfect knowledge and is reducible by gaining more knowledge via research, data collection and modelling. *Aleatory uncertainty*, also termed ontological or stochastic uncertainty, is due to inherent variability. It can be quantified, but is stochastic and irreducible. *Ambiguity* results from the presence of multiple ways of understanding or interpreting a system. It can originate from differences in professional backgrounds, scientific disciplines, value systems and interests.

The *level of uncertainty* characterises how well the uncertainty can be described within the range from determinism to total ignorance (Fig. 1), where determinism is the ideal, non-achievable, situation where everything is known exactly and with absolute certainty. Within this range, *statistical uncertainty* can be described using well-known statistical terms. *Scenario uncertainty,* in general, cannot be described statistically but are used when possible outcomes are known but not all probabilities of such outcomes are present (Brown 2004). *Qualitative uncertainty* occurs when not even possible outcomes are known (Brown 2004). *Recognised ignorance* occurs when there is an awareness of lack of knowledge on a certain issue, but where it is not possible to categorise the uncertainty further. *Total ignorance* denotes a state of complete lack of awareness about imperfect knowledge.

The *sources of uncertainty* can be divided into uncertainties in *input data*, such as external driving forces and system data; *model uncertainty,* originating from the model structure including process equations, the model software and the model parameters (Refsgaard and Henriksen 2004); *context uncertainty*, such as the boundaries of the systems to be modelled, future climate and regulatory conditions when these aspects are not explicitly included in the modelling study; and *uncertainty due to multiple knowledge frames*, meaning that persons may have different perceptions of the main problems. The simultaneous presence of multiple frames of reference to understand a certain phenomenon may cause ambiguity.

Some sources of uncertainty are epistemic by nature, e.g. model structural uncertainty and model technical uncertainty; input data, e.g. future rainfall, contain aleatory uncertainty and these two sources typically dominate when dealing with technical and natural science aspects. Context and framing uncertainty are often of an ambiguity nature and are increasingly important, when political issues and stakeholder interests are included in a decision situation.

The above sources of uncertainty are composite groups, each of which may be decomposed into different sources. For instance there may be several types of input data with different uncertainty characteristics in terms of nature and level. Many uncertainties cannot be uniquely classified, but will often fall in different classes (Warmink et al. 2010). This situation may occur, when uncertainty is aggregated from various sources, and may be resolved by decomposing it into its several sources until the classification becomes unique.

Some authors (Walker et al. 2003) do not distinguish ambiguity and epistemic uncertainty. This presupposes that more knowledge will reduce ambiguity. However, in decision making this is seldom the case, because more knowledge does not necessarily converge to a single truth as seen by stakeholders and hence to more certainty (Warmink et al. 2010). This is particularly true, when many different stakeholders' interests, perspectives and perceptions are involved. In such cases interests and perceived uncertainty can mix together in complicated ways.

The distinction between aleatory and epistemic uncertainty is not always clear. One may argue that up to a certain level, random system behaviour is also lack of knowledge, and,

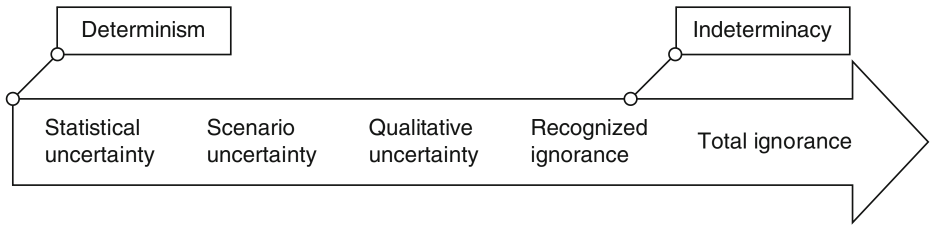

Fig. 1 Levels of uncertainty. After Walker et al. (2003) modified by van der Keur et al. (2008)

therefore, that some of these stochastic uncertainties can be reduced, if we understand the system better. However in practice, the availability of resources such as time and money severely limit the possibility to reduce this kind of uncertainty. Warmink et al. (2010) therefore define aleatory uncertainty, denoted as natural uncertainty, as random system behaviour that cannot be explained adequately given the available resources.

2.3 Uncertainty cascade in climate change impact and adaptation for water systems

The uncertainty cascade found in climate modelling related to water systems includes uncertainties from emission scenarios and global and regional models (Foley 2010). We have included uncertainties due to statistical downscaling, water systems impacts and socio-economic impacts (Fig. 2). The main uncertainties in the different steps are characterized (Table 1) with respect to the sources and nature of uncertainty following our above typology. In our cascading process we see that:

Future greenhouse gas (GHG) emissions cannot be known with certainty because they depend on future human decisions and are characterised by scenario uncertainty based on the IPCC scenarios (IPCC 2007c).

Uncertainties related to global (GCM) and regional climate models (RCM) are typically assessed by ensemble modelling, where multiple climate models with different process equations are used for making probabilistic projections (e.g. Tebaldi et al. 2005; Smith et al. 2009; Christensen et al. 2007a, 2010; Déqué and Somot 2010). A fundamental limitation here is lack of knowledge of all climate processes, such as natural feedbacks in the Earth's carbon cycle (recognised ignorance). Another important source of uncertainty is lack of knowledge of initial ocean states, such as temperature and salinity. Different plausible initial

Fig. 2 Structural elements in the assessment of climate change impacts and adaptation illustrating the uncertainty cascade

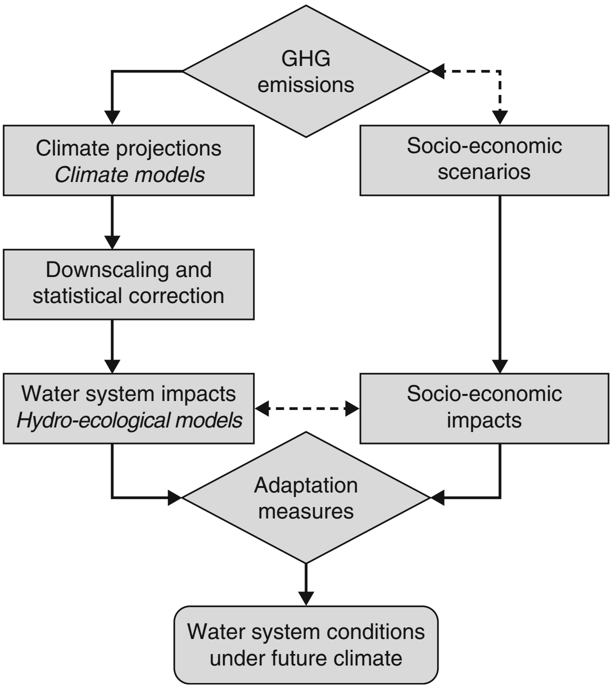

Table 1 Characterisation of key sources of uncertainty in the uncertainty cascade and their nature in relation to climate change adaptation. X, XX, XXX is a general guide on the relative importance level of the sources, although it must be emphasised that the importance of the individual sources of uncertainty is context specific

Steps in climate change adaptation analyses (chain in uncertainty cascade, Fig. 2)		Sources of uncertainty						Nature of uncertainty		
		Input data	Model			Context	Multiple knowledge frames	Ambiguity	Epistemic uncertainty (reducible)	Aleatory uncertainty (irreducible)
			Parameter values	Model technical aspects	Model structure					
Greenhouse gas emissions						XX	XXX	XXX	XX	
Socio-economic scenarios		XX			XX	XX	XXX	XXX	XX	
Future climate (Climate models)	GCMs			XX	XXX				XXX	
	RCMs			XX	XXX				XXX	
	Initial conditions/ natural variability	XX								XXX
Downscaling/statistical correction			XXX		XX				XX	XX
Water system impacts (Hydro-ecological models)		X	XXX	X	XXX	XX	X	X	XXX	X
Socio-economic impacts (Socio-economic tools)		XX			XX	XX	XXX	XXX	XX	
Adaptation measures		XX	XXX	X	XXX	XX	XXX	XXX	XXX	XX

conditions may result in significantly different climate projection pathways as climate systems have strong elements of natural variation (Hawkins and Sutton 2009).

For prediction of local water systems, climate variables are typically required at smaller spatial scales than those simulated by climate models. Furthermore, climate models often do not represent statistical properties of observed climate variables such as precipitation, which disenables impact modellers to use the outputs from climate models directly into impact models. Data from climate models are typically downscaled and statistically corrected (e.g. Wilby et al. 2002; Christensen et al. 2007b; Fowler et al. 2007; Kilsby et al. 2007) but different downscaling methods may give different input data, thus total errors can arise from both sources (e.g. Sunyer et al. 2011).

Identification and assessment of possible climate change adaptation measures uses basically the same tools as those for assessing climate change effects, i.e. combined hydro-ecological models and socio-economic tools, and hence all the uncertainties involved here are inherited. As adaptation decisions often involve considerable uncertainties, stakeholder and societal risk perception may, in some cases, become important, especially for situations where attitudes to risk may change over time. Furthermore, different stakeholders may have different perceptions of the consequences of alternative adaptation measures, reflecting their specific interests in relation to the affected case. This may contain more ambiguity than in other elements of the uncertainty chain.

3 Adaptation options

Options for adaptation can be classified as the *intent*, *timing* of the action, and their *temporal and spatial scope(s)* (Fig. 3). Other options of special interest include *no regrets*, and adaptation decisions can be characterised by their *flexibility, reversibility and robustness.* Uncertainty impinges differently on each class of actions in Fig. 3.

Intent In most sectors some adaptation actions will be autonomous and others will be planned. The former tend to be taken by individuals rather than public agencies, often in response to changes in the ambient environment or to changes in market conditions. They often consist of reactive measures of short-to-medium term duration and are frequently of local scope. Planned actions on the other hand are normally taken by public agencies or large private sector entities, often in anticipation of climate change and with a longer term perspective and wider spatial scope.

Within planned actions we have some that consist of 'hard' or 'structural' measures (e.g. investment in physical assets) and others of 'soft' or 'non-structural' measures (e.g. increases

Fig. 3 Classification of adaptation measures. From Burton (2009)

<table>
<tr><th colspan="7">ADAPTATION</th></tr>
<tr><th>Based on</th><th colspan="6">Type of adaptation</th></tr>
<tr><td>Intent
In relation to climatic stimulus</td><td colspan="3">Autonomous
E.g unmanaged natural systems</td><td colspan="3">Planned
E.g. public agencies</td></tr>
<tr><td>Timing of action</td><td colspan="2">Reactive
From observed modification</td><td colspan="2">Concurrent
During</td><td colspan="2">Anticipatory
Prior modification</td></tr>
<tr><td>Temporal scope</td><td colspan="3">Short Term
Adjustments, instantaneous, autonomous</td><td colspan="3">Long Term
Adaptation, cumulative, policy</td></tr>
<tr><td>Spatial scope</td><td colspan="3">Localized</td><td colspan="3">Widespread</td></tr>
</table>

in the prices of water services). In the context of high uncertainty (especially of the epistemic kind) one could argue that non-structural planned measures are preferred to structural measures, on the grounds that as new knowledge is gained it will be easier and less costly to modify the response than it would be with the structural planned actions. One could argue that if there is a real risk of system collapse, then physical planned actions are appropriate. But in such cases it may be better to require relocation (or at least contingent plans for relocation), which would constitute a non-structural measure. In addition, one has to take account of the uncertainty related to behavioural actions (ambiguity) on non-structural incentives (e.g. taxation), which constitute a major part of uncertainty in non-structural measures (Arnell et al. 2004).

Timing of action In general, adaptation measures combine reactive and anticipatory forms: increased frequency of storms mandates the need to develop early warning systems and protective physical structures, but it also increases the need for more effective action once storms occur. With greater uncertainty it would be preferable to rely on reactive measures, because they are taken with more information at hand, but that is not necessarily the case. A high level of uncertainty may include the possibility of an outcome that would make reactive measures ineffective or very costly in terms of loss of life and property. In such cases it may be desirable to go for the anticipatory action, although ideally it should be in a form that is flexible and reversible.

Temporal and Spatial Scope Similar considerations prevail with respect to temporal and spatial scope. Other things being equal, the greater the spatial scope of an action and the longer its duration, the greater will be the uncertainty associated with its consequences. In adaptation, actions often need to be taken with long time periods in mind. Investments in road design or the dimensions of sewerage systems are influenced by conditions over the lifetime of the capital, which is measured in decades. Since conditions at the end of the period are highly uncertain, political and economic concerns can exclude adaptation options. However, non-climate proofing of investments with a long lifetime can also be very costly. The compromise can be to plan on the basis of a 'likely' scenario, but then leave open the possibility that more costly changes can be made later, when more precise information is available.

No-regrets, flexibility, reversibility and robustness In all adaptation decisions the consequences of uncertainty are reduced when actions fall into the category of no-regrets, or that have properties of flexibility, reversibility and robustness. No-regrets actions are those that one would wish to take for other reasons and that also have benefits in terms of reducing the impacts of possible climate change. If these actions are truly justified on other grounds than their climate benefits, then the uncertainty of their climate benefits is of no consequence as it does not affect the decision. Such cases, however, are very rare; in most circumstances, the action can be modified to increase the climate adaptation benefits and there is a choice to be made of how much such modification is justified.

4 Water sector examples—a Danish context

4.1 Climate change projections for Denmark

The current national strategy for adaptation (Danish Energy Agency 2008) to climate change in Denmark is based on climate change projections for the period 2071–2100 for the IPCC

A2 and B2 SRES scenarios, using climate scenario data from the HIRHAM4 model (Christensen et al. 1996), as utilized in the European climate downscaling project PRUDENCE (Christensen et al. 2007a). According to these projections, Denmark will probably warm by approximately 1–2°C, relative to the pre-industrial level, in the near future and by approximately 2–3°C towards the end of the century. The largest temperature increase is expected during winter. Equivalent projections for the mean annual precipitation show a small increase in the short term, becoming more pronounced in the long term. The strongest positive precipitation response is seen during winter, whereas little or no change is predicted during summer. Extreme precipitation events are generally expected to be stronger. The general picture is of warmer and wetter winters; drier summers with enhanced extreme precipitation events and longer dry periods, although the above climate projections are subject to very considerable uncertainties (Boberg 2010).

4.2 Climate change impacts and possible adaptation measures for water related sectors in Denmark

The key uncertainties related to climate change adaptation in a Danish context are illustrated by examples from the water-related sectors agriculture, freshwater ecology, water infrastructures in rural areas and urban water infrastructures (Tables 2, 3, 4 and 5). The examples have been selected to illustrate the variety of the climate change adaptation issues and uncertainties with a focus on issues requiring a planning horizon of more than 20 years, when a climate change signal could begin to dominate the natural climate variability, and where a relatively long economic lifetime of adaptation projects makes it important to give careful consideration to uncertainty. In Tables 2, 3, 4 and 5, climate change impacts are characterised with respect to risk level and dominating uncertainty following the uncertainty terminology outlined in Section 2, while the adaptation options are characterised according to cost level (High/Medium Low) and the classification outlined in Section 3. The three cost levels apply for internal comparisons within each of the four sectors, but may not be applicable for comparisons from one table to another.

4.2.1 Agriculture

Potential impacts Projected climate change will lead to warmer season crops, in particular grain maize, taking over part of the cereal area (Olesen et al. 2007). Agricultural land use will also be determined by market and European Union (EU) Common Agricultural Policy factors and technological changes leading to changes in economic competiveness of different crops and cropping systems. Higher frequencies of summer droughts will lead to higher demands for irrigation leading to increased water demand in late summer. Changes in crop productivity and crop type will lead to higher fertiliser demand. Higher temperatures lead to increased soil organic matter turnover causing higher soil contents of mineral nitrogen. This, in combination with higher winter rainfall and larger rainfall intensities, will increase the risk of nitrogen and phosphorus losses to the aquatic environment. Higher winter rainfall will also increase the chance of inundation of agricultural fields during autumn, winter and spring. This increases the need for tile draining of soils. There are indications of thresholds in both crop yield responses to climatic changes leading to increased variability in crops yield (Porter and Semenov 2005; Kristensen et al. 2011) and to increased risk of nitrate leaching (Fig. 4). It is also likely that the increasing temperatures, in particular winter temperatures, will lead to increased risks of attack by pests and diseases (Olesen et al. 2011).

Table 2 Examples of water related climate change adaptation issues related to agriculture in Denmark

Climate change impact					Adaptation							
Type of problem	Consequence	Risk level	Dominating uncertainty		Option	Cost level	Intent	Action	Temporal scope	Spatial scope	Additional uncertainty	
			Source	Nature							Source	Nature
Increased summer droughts and higher water requirements cause by longer crop growth duration in warmer climate	Increase in irrigation requirements	Med	Projections of climate change, CO_2 effects on evapotranspiration, market price for agricultural products	Epistemic+ Aleatory	Adapt crop choice to existing water abstraction permissions (*non-structural)*	Low-Med	A (P)	R (C)	S	L	Same as for impact	
					Increase water abstraction permits (*non-structural)*	Low	P	A (C)	L	W	Multiple frames	Ambiguity
Increased winter rainfall	Increased inundation of agricultural fields during winter/spring	High	Projections of climate change, hydrological parameters of soils	Epistemic	More efficient tile drains (*structural)*	High	A	A (C)	L	L	Same as for impact	
					Conversion to perennial energy cropping (*non-structural)*	Low	A	A (C)	S (L)	L	Multiple frames	Ambiguity
	Increased inundation of river valleys	High	Projections of climate change	Epistemic	Abandon agriculture in flood prone areas (*non-structural)*	High	A (P)	R (A)	S (L)	L (W)	Multiple frames	Ambiguity
					Stream straightening and stream weed cutting (*structural)*	High	P	A (C)	L	W	Multiple frames	Ambiguity
Threshold conditions	Sudden changes in reliability in the production and quality of food and fibres	Med	Climate and impact models	Epistemic	Crop breeding to avoid impact (*non-structural)*	Med	A	R, A	S	L	Same as for impact	
Change in diseases and pests	Sudden and large reduction in crop yields and quality	Med	Inherent uncertainty and impact models	Epistemic+ Aleatory	Plant breeding, quarantine policies and pest/disease forecasting *(non-structural)*	Med-High	P	R	S	W	Same as for impact	

Notes to characterisation of adaptation measures (see Fig. 3 and Section 3 for further details):

Intent: A: autonomous; P: planned

Action: R: reactive; C: concurrent; A: anticipatory

Temporal scope: S: short term; L: long term

Spatial Scope: L: localized; W: widespread

Possible adaptation measures Adaptation options to increasing wet conditions during autumn, winter and spring include improved drainage of agricultural fields (renewing tile drains) and conversion of agricultural land with risk of inundation to perennial energy crops (e.g. willow), or, in severe cases, land abandonment. Increased risks of summer drought may be countered by enhancing irrigation capacity, but also by having crop mixtures with variation in timing of irrigation needs. In case of severe water restrictions, there may be a need for improved forecasting of water availability for irrigation. The risks of increased erosion and nutrient losses during high intensity rainfall events may be reduced by improved soil cover, in particular by growing catch crops during autumn and winter (Olesen et al. 2011). The risk of changes in low yield can to some extent be avoided through targeted plant breeding, and there is also some scope for breeding against plant diseases, although other options for integrated pest and disease control should also be considered and adjusted to the changing environmental conditions. Breeding should probably also address the possibilities for improved water use efficiency under higher CO_2 concentrations, although the genetic basis for this is poorly known and also unlikely to have major impact as reduced water loss from leaves is likely to lead to lower CO_2 uptake.

Dominating uncertainties Partial analyses of the uncertainty chain (Olesen et al. 2007) show that there is large uncertainty associated with future land use, which will have considerable interactions with and dependencies on future climate, but this nexus has not been sufficiently investigated (Schröter et al. 2005). Uncertainties associated with impact models have so far been little explored (Rosenzweig and Wilbanks 2010; Rötter et al. 2011).

4.2.2 Freshwater environment

Potential impacts Climate change will most probably lead to more variation in discharge in streams with higher flow (and flooding) in winter and less in summer, possibly with periodic drought in some streams. This may impoverish flora and fauna in streams (Table 3). Higher precipitation will enhance leaching of nutrient from soils and bank erosion and, thereby, the external loading of nitrogen, phosphorus and sediment to lakes. This, in turn, will lead to a poorer ecological status of lakes, with higher levels of potentially toxic cyanobacteria (blue-green algae) in eutrophic lakes and lower water clarity (Adrian et al. 2009). The projected increase in temperature will result in higher biological metabolic rates and oxygen consumption and thus lower oxygen concentrations in streams. This can lead to lower self-purification capacity and consequently lower stream water quality, ecological status and a reduced biodiversity. Higher temperatures will most likely reinforce eutrophication of lakes due to changes in the fish community (smaller fish, faster reproduction, higher predation on algal grazers) that via a set of positive feedback mechanisms leads to reduced water clarity (Jeppesen et al. 2010). Moreover, toxic cyanobacteria thrive well at high temperatures (Paerl and Huisman 2008). Consequently, the critical nutrient loading to obtain good ecological status according to the EU Water Framework Directive (WFD) will likely be lower, and a further reduction of the external nutrient loading will be required to counteract this deterioration (Jeppesen et al 2009, 2011).

Possible adaptation measures Adaptations include a shift to lower input and more perennial agriculture, improved nutrient and soil management with less loss of nutrients to surface waters, reduced loading from point sources and, where appropriate, re-establishment of lost wetlands, establishment of riparian buffer zones, re-meandering of channelized streams and less drastic weed-cutting in streams. Potential measures to reduce

Table 3 Examples of climate change adaptation issues related freshwater ecology and quality in Denmark. See notes on adaptation measures below Table 2

Climate change impact					Adaptation							
Type of problem	Consequence	Risk level	Dominating uncertainty		Option	Cost level	Intent	Action	Temporal scope	Spatial scope	Additional uncertainty	
			Source	Nature							Source	Nature
Change in precipitation → Higher variability in flow; flooding of riparian zones and streams	Reduced biodiversity, lower chan-ce of fulfilling WFD	High	Climate models+ downscaling+ Hydrological models	Epistemic+ Aleatory	(Re)-establishment of wetlands and buffer zones, *(structural)*	Med	P,A	A,C	S	L (W)	Multiple frames	Ambiguity
					Accepting flooding *(non-structural)*	Low	A	A,R	S	L,W	Multiple frames	Ambiguity
Increase in nutrient loading to lakes → Higher eutrophication	Lower chance of fulfilling WFD	High	Context (land use and agricultural practice)+Climate model structure+ hydro-ecological model parameters and structure	Epistemic+ Aleatory	Reduce external loading from sewage and agriculture *(structural)*	High	P	A;C	S	L,W	Multiple frames	Ambiguity
					Re-establishment of wetlands and buffer zones *(structural)*	Med	P,A	A,C	S	L (W)	Multiple frames	Ambiguity
					Re-meandering of streams *(structural)*	Med	P	A	S	L	Multiple frames	Ambiguity
					Reduced weed cutting *(structural)*	Med	P	A,C	S	L,W	Multiple frames	Ambiguity
					Accepting flooding *(non-structural)*	Low	A	A,R	S	L,W	Multiple frames	Ambiguity
					Reduce internal loading in lakes by biomanipulation and/or sediment capping *(structural)*	Med	P	A,C	S	L	Same as for impact	
Higher temperatures → Changes in stream and lake ecosystems; higher meta-bolism in streams; higher risk of oxygen depletion	Reduced biodiversity; lower chan-ce of fulfilling WFD	High	Climate models+ Hydro-ecological model parameters+ structure	Epistemic+ Aleatory	More trees in the riparian zone and establishment of overhanging bank vegetation *(structural)*	Low	A,P	A,C	S	L	Multiple frames	Ambiguity

Table 3 (continued)

Climate change impact					Adaptation							
Type of problem	Consequence	Risk level	Dominating uncertainty		Option	Cost level	Intent	Action	Temporal scope	Spatial scope	Additional uncertainty	
			Source	Nature							Source	Nature
Higher temperatures → Shift in biological structure leading to higher eutrophication and higher frequency of toxic algae in lakes	Lower chance of fulfilling WFD	Med	Climate models+ Hydro-ecological model parameters+ structure	Epistemic+ Aleatory	Reduce external organic and nutrient loading by better treatment of sewage, more sustainable agriculture*(structural)*	High	P	A,C	S	L,W	Multiple frames	Ambiguity
					(Re)-establishment of wetlands and buffer zones *(structural)*	Med	P,A	A,C	S	L (W)	Multiple frames	Ambiguity
					Re-meandering of streams *(structural)*	High	P	A	S	L	Multiple frames	Ambiguity
					Reduced weed cutting. *(structural)*	Med	P,A	A,C	S	L,W	Multiple frames	Ambiguity

Table 4 Examples of change adaptation issues related to water infrastructure in rural areas in Denmark. See notes on adaptation measures below Table 2

Climate change impact					Adaptation							
Type of problem	Consequence	Risk level	Dominating uncertainty		Option	Cost level	Intent	Action	Temporal scope	Spatial scope	Additional uncertainty	
			Source	Nature							Source	Nature
Water supply. Changes in groundwater recharge or acceptable influence on streamflow in critical low flow periods	Change in how much groundwater can be abstracted in a sustainable manner due to either problems in aquifer or low flow conditions in stream.	High	Climate models+ hydro-ecological model parameters+ structure (geology)	Epistemic	Relocation of groundwater abstraction—influencing also the protection zones (item below) *(structural)*	Med	P	P	L	L	Same as for impacts	
					Changes in objectives and risk willingness *(non-structural)*	Low	P	C	S	L	Multiple frames	Ambiguity
Water supply. Changes in wellfield capture zones	The selected areas for groundwater proctection will be the wrong area.	Med	CHG emissions+ climate models+ hydro-ecological model parameters+ structure (geology)	Epistemic	Increase protection areas to account for worst case *(structural)*	High	P	P	L	L	Same as for impacts	
					Changes in strategy, increased risk to protect wrong area *(non-structural)*	Low	P	C	S	L	Multiple frames	Ambiguity
Inundations of roads	Road traffic interrupted	Med	CHG emissions+ climate model structure	Epistemic+ Aleatory	New design to avoid inundation *(structural)*	High	P	P	L	W	Same as for impacts	
					Close roads+warning in critical periods *(non-structural)*	Low	P	C	S	L	Multiple frames	Ambiguity
Undermining of road foundation due to increasedgroundwater table	Roads deteriorate	Med	Climate models+ hydro-ecological model parameters and structure (geology)	Epistemic	New designs to accept high groundwater table *(structural)*	High	P	P	L	W	Same as for impacts	
					New designs to avoid high groundwater table *(structural)*	High	P	P	L	W	Same as for impacts	
					Drainage or pumping scheme to keep groundwater table low *(structural)*	Low	P	C	S	L	Same as for impacts	

Table 5 Examples of water related climate change adaptation issues related to urban water infrastructure in Denmark. See notes on adaptation measures below Table 2

Climate change impact					Adaptation							
Type of problem	Consequence	Risk level	Dominating uncertainty		Option	Cost level	Intent	Action	Temporal scope	Spatial scope	Additional uncertainty	
			Source	Nature							Source	Nature
Increasing precipitation extremes	Increased flood risk in flat areas and local depressions	High	Climate models+ downscaling+ hydrologic and hydraulic models	Epistemic+ Aleatory	Larger pipes *(structural)*	Med	P	C	L	W	Multiple frames	Ambiguity
					Local retention *(structural)*	High	P	C	S	W	Multiple frames	Ambiguity
					Changing land use practices (relocation) *(structural)*	Med –High	P	A	M	L	Multiple frames	Ambiguity
					Contingency planning,incl. forecasting *(non-structural)*	Low	P	C	S	L	Multiple frames	Ambiguity
Increasing sea surge levels	Increased flood risk in coastal regions	High	Climate models+ downscaling+ hydrologic and hydraulic models+ areal planning	Epistemic+ Aleatory+ Ambiguity	Dikes *(structural)*	High	P	A (R)	L	L	Multiple frames	Ambiguity
					Changing land use practices *(non-structural)*	Low-High	P	R (A)	S—L	L	Multiple frames	Ambiguity
Changing precipitation patterns	Increased risk of unstable foundations of buildings and infrastructure	Med	Hydrology+context	Epistemic+ Aleatory	Changing building design standards, higher use on tile pipes *(structural)*	Med	P	C	M	L	Same as for impact	
Increasing risk of heat waves	Water supply standards are not met	Med	Context (design and operation practices)	Aleatory+ Ambiguity	Use of intermediate cooling systems on water supply *(non-structural)*	Low	P	C	L	L	Same as for impact	

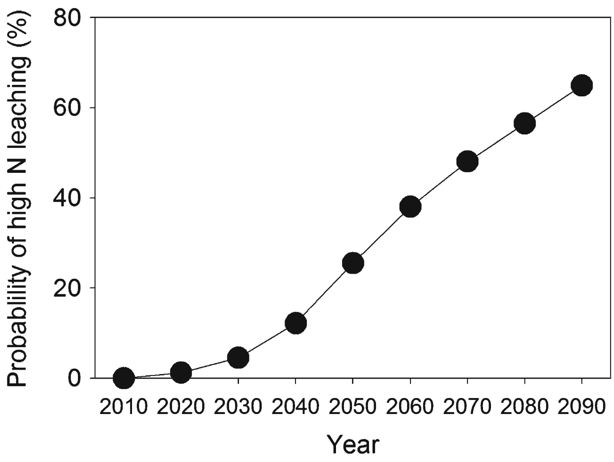

Fig. 4 Probability of mean N leaching from winter wheat (*Triticum aestivum L.*) exceeding a threshold level of 70 kg N ha^{-1} for sandy soils. Results were calculated for projected climate conditions for the 21st century for the A1B emission scenario (Børgesen and Olesen 2011)

local temperature increases are the establishment of trees in the riparian zone and more overhanging bank vegetation. Relevant restoration measures in lakes include methods to reduce internal phosphorus loading (Cooke et al. 2005) and methods to reduce the amount of coarse fish (Hansson et al. 1998).

Dominating uncertainties We are not aware of studies that have been made to compare the effects of the various sources of uncertainties listed in Table 1. Our expectation is that the dominating sources of uncertainty are related to climate models, precipitation and runoff of water and nutrients, change in land use and management induced by climate and environmental change, and how biota and ecosystem functions change with climate.

4.2.3 Infrastructure in rural areas—water supply and roads

Potential impacts Water supply, which is almost 100% groundwater derived in Denmark, will be affected by climate change, because both groundwater recharge and low flows and ecological conditions in streams and wetlands may be affected (van Roosmalen et al. 2007). This will influence the amount of water available for water abstraction, the effect of groundwater abstraction on water quality and the ecological state of freshwater bodies. Furthermore, there is a risk that the groundwater protection measures will be applied to the wrong areas, because the groundwater abstraction catchments are climate dependent. For roads in rural areas the two main potential problems are inundations resulting in traffic interruption, and undermining of road foundations due to increased groundwater table.

Possible adaptation measures We envisage that the main options related to water supply would include relocation of well fields/water works and increase of groundwater protection areas to account for uncertainty of the location of the groundwater abstraction catchments under a future climate. Non-structural measures might include changes in objectives and in our risk willingness to accept a lower reliability for supply of clean drinking water without causing adverse environmental effects. These measures could have major impacts on environment and agriculture. Similarly, the envisaged adaptation with respect to roads include both structural and non-structural measures such as new designs, real-time flood forecasting and warning of closing of roads, and pumping of groundwater to keep groundwater table low.

Dominating uncertainties The combined effects of the various sources of uncertainties (Table 1) show that for water supply we expect that the dominating source for the structural measures are related partly to the climate models and partly to the hydro-ecological models with a particular emphasis on the geological data and interpretation of geological structures. The dominating uncertainty for the non-structural measure would be ambiguity on risk willingness aspects. For road infrastructure adaptation measures we expect that the main uncertainties are climate models and hydro-ecological models.

4.2.4 Urban water infrastructure

Potential impacts Climate change is expected to lead to increases in extreme precipitation. With the current estimates of increases in design level frequencies of 30–40% for precipitation (Arnbjerg-Nielsen 2012), case studies have suggested that the present hydraulic capacity of the urban drainage system will result in a 10-fold increase in cost of urban flooding compared to current annual losses (Arnbjerg-Nielsen and Fleischer 2009). Increases in mean sea level and storm surges will affect coastal areas even more, with changes in the hazard frequencies of more than one order of magnitude. Changing precipitation patterns are expected to lead to changes in the high ground water levels which may in some cases lead to unstable buildings because of high groundwater levels. Water quality in the water supply sector may be jeopardized by heat waves leading to high temperatures in the water supply network and thus potentially higher microbial and chemical activity.

Possible adaptation measures Adaptation measures related to increased flood risks from precipitation can be divided into the following four categories: increasing drainage capacity away from depressions/flat areas, local source control and infiltration from areas upstream depressions/flat areas, changing land use practices in depressions/flat areas and improved contingency planning. While some of these measures rely to some degree on an autonomous and reactive adaptation scheme, the increase in flood risk due to sea surges must rely on both planned and anticipatory adaptation methods. The other adaptation issues (Table 5) are less important economically, and the adaptation options are easier to identify.

Dominating uncertainties Climate change impacts are all related to hydrological extremes, which are subject to substantial epistemic uncertainty. However, when considering the increases in flood risk due to precipitation extremes, the uncertainty of the climate change impact is small compared to the uncertainty of the adaptation measures. All four adaptation options involve planning from public authorities. They are ranked in Table 5 according to the degree of technical/public planning relative to the public involvement. The choice of optimum adaptation is to some extent based on this ranking, which is why ambiguity is an important additional uncertainty. Equity issues between the few percent of property owners with very high increases in risk and the vast majority of property owners with a very low and negligible increase in risk may also influence the adaptation method. Using solely economic evaluation methods, the increasing drainage capacity option can clearly be recommended. However, using other objectives the other options may turn out favourably.

5 Discussion of climate change adaptation strategies under uncertainty

Our analyses of uncertainties, risks and adaptation characteristics have revealed a number of key messages that are discussed below.

5.1 Climate change adaption decisions needed in spite of large uncertainties

It is unquestionable that the uncertainty cascade includes many sources and that their propagation through technical and socio-economic models further adds to the overall prediction uncertainties of climate change impacts. It is therefore sometimes argued that decision making about climate change adaptation actions has to be postponed until more knowledge becomes available and less uncertain decisions can be made. We argue that, in spite of all these uncertainties, we often have sufficient knowledge to make decisions on climate change adaptations, and that such adaptation decisions could be taken now.

Example 1—Urban drainage The design rainfall criteria for small drainage systems are expected to increase by 30% over the next 100 years. The confidence interval for this estimate is 5–75% (Arnbjerg-Nielsen 2012). This large uncertainty on design criteria has little influence, when drainage systems are constructed in new urban areas, because the marginal cost of implementing extra drainage capacity is very low. Hence, often an increase of 50% drainage capacity can be achieved for 10% of the overall cost. Therefore it will usually always be a good idea to increase the design level for newly built drainage systems.

Example 2—Agriculture/freshwater ecosystems Several studies have shown that nitrate leaching from agriculture is likely to increase due to climate change, and that these projections are subject to considerable prediction uncertainties originating from all sources in the uncertainty cascade (Olesen et al. 2007; Børgesen and Olesen 2011). The increased nutrient load will in turn affect the freshwater ecosystems, and a relevant question is to which extent the uncertainties on future N-leaching should affect decisions on adaptation. Figure 4 shows results from a probabilistic analysis of N-leaching for sandy soils in Denmark, where uncertainties in climate projections are inferred from the ENSEMBLES (van der Linden and Mitchell 2009) results of multiple climate models for assessing N-leaching from climate data. In spite of considerable uncertainties on N-leaching (not shown) the probability of N-leaching exceeding a critical threshold (70 kg N/ha/year) is shown in Fig. 4 to follow a clear increasing trend during the coming decades. Thus, in this case, uncertainties on the underlying nitrate leaching turn out to become less important for long-term decisions, because the critical threshold here will be passed with a high probability.

5.2 Assess adaptation now as a basis for optimal timing

Despite uncertainties, there is enough information about the future climate change impacts to realise that without any adaptation the consequences will generally be negative. It is therefore necessary to consider the adaptation options now. This does not necessarily imply that actions with large investments need to be implemented right away, but that long term planning efforts should be initiated already now.

Example—Future water supply As drinking water pumped from aquifers typically is 50–100 years old the protection measures decided through the ongoing groundwater protection programme have a long-term perspective. However, the delineated groundwater abstraction catchments for which groundwater protection action plans are being prepared may turn out to comprise the wrong areas, because these catchments are climate dependent. Although the outcome of climate change uncertainty analyses may show that the locations of the catchments are more uncertain than without considering climate change aspects, it is still important to include climate change uncertainties in the assessments now. An implementation strategy could be to design flexible action plans that can be modified, as more precise climate change predictions become available during the coming years.

5.3 Risk willingness differs among individuals and stakeholders

The willingness to accept specific risks may differ greatly between individuals and policy makers as well as among different groups of stakeholders. Stakeholders are affected by risks in different ways, e.g. there is a difference between being a house owner who could be directly affected by extreme weather, because s/he lives near the coast, and another home owner who is not directly exposed to the risks. Furthermore, the temporal and spatial scope for many stakeholders is likely to be short-term and/or localized and dependent on the perceived risks they are subject to personally, while policy makers are inclined to focus on the expected risks across the perspective of all stakeholders in society and on long-term and/or widespread adaptation measures.

Example—Agriculture and freshwater ecology Decision making on adaptation measures to ensure good ecological status will involve stakeholders (agriculture, environment) with different interests and perceptions of what constitutes the most important problem. This may result in considerable ambiguity, which needs to be reduced to achieve a political decision. In such situations it is important to separate the different types (natures) of uncertainty, because epistemic uncertainty can be reduced by obtaining more knowledge, while ambiguity requires dialogue to achieve better mutual understanding.

5.4 Risk strategies should not be based on status quo attitudes to risk acceptance

It is necessary to discard the "status quo" as the base for risk acceptance. As the present risk attitude is a function of present societies and climate, so will the future risk strategies be a function of future conditions. However, it is very difficult to predict risk attitudes of future generations. Neglecting to address the uncertainties and risks properly is likely to lead to short term solutions, which, at best, could prove insufficient on the long term.

Example—inundations of roads The standard for road designs today is that roads should not be inundated. On the other hand it is accepted that under some extreme weather conditions roads may be closed, e.g. due to snow or due to heavy wind for some of the large bridges. Future climate projections show very large uncertainties for extreme precipitation events. The key uncertainty here is aleatory by nature implying that we somehow have to live with it. If future roads were to be designed to have a very high certainty of completely avoiding inundations, it would require very costly road constructions that most likely will turn out to be designed very much with a conservative view of risk. Hence, it is likely that the construction costs in some cases can be reduced significantly by allowing roads, on rare occasions, to be inundated, and implement an online forecasting system to warn the traffic about closing of the road—equivalent to the situation for heavy snow or heavy wind at some bridges. Such change in design philosophy will require a change in the risk acceptance among policy makers and hence also among the general public.

6 Discussion of novelty in relation to IPCC

Although the definitions of uncertainty in the IPCC AR4 Synthesis Report (IPCC 2007a) and in the AR5 guidance note (Mastrandrea et al. 2011) are not conflicting with our terminology, the focus in the IPCC uncertainty work differs from our uncertainty framework. The IPCC uncertainty guidance focuses on development of a language suitable for communication of uncertainty based on evidence and agreement. While our framework cannot replace IPCC guidance due to its lack of focus on communication, it offers a more fundamental characterisation of uncertainty with focus on the nature of uncertainty (whether reducible or non-reducible), the level of uncertainty (whether it can be described statistically, as scenarios, qualitatively or is due to ignorance) and the source (origin) of uncertainty. Our framework with its more comprehensive uncertainty characterisation addresses the concerns raised by Curry (2011) who argues that the present IPCC approach is oversimplified and can lead to misleading overconfidence.

Another particular strength of our framework is that it is suitable for adaptation planning. Our examples have illustrated how uncertainty may or may not matter very much, depending on the context and how the characterisation of uncertainty into different sources and nature of uncertainty can help in decisions on adaptation strategies.

7 Summary and conclusions

The uncertainty framework has been used to study climate change impacts and adaptation options for four water related sectors in Denmark: agriculture, freshwater ecology, water infrastructure in rural areas and urban infrastructures. We find that (i) there are considerable uncertainties on climate change impacts; (ii) the dominating sources of uncertainty differ greatly among the various problems; (iii) most uncertainties on impacts are epistemic by nature implying that they are reducible; and (iv) the uncertainties on adaptation measures are complex with ambiguity often being added on top of the impact uncertainties.

The impacts of different sources of uncertainties on the risk assessment and evaluation of adaptation options are context specific. Depending on the physical system and the economic lifetime of adaptation measures being considered, different uncertainty sources in the uncertainty cascade may dominate. The relative importance of the different uncertainty sources also depends on the temporal and spatial scales of the physical impact assessments. For instance, evaluation of urban drainage designs depends on extreme precipitation characteristics with spatial and temporal resolutions in the order of, respectively, 1–10 km^2 and 1 hour or less, and hence uncertainties related to regional climate model projections and downscaling are dominating. On the other hand, for assessing the impacts on water resources on national and regional levels, the uncertainties in the GCM are often more important than those related to the downscaling. For some types of problems, uncertainties in the physical impact model may dominate compared to those in climate forcing.

For adaptation characteristics we find that (i) the two infrastructure sectors are dominated by planned adaptation measures, while the agricultural and freshwater ecology sectors include both planned and autonomous adaptation options; (ii) adaptation options include both reactive, concurrent and anticipatory actions in all four sectors; (iii) temporal scope varies from short term for all options in the freshwater ecology sector to a mixture of short-term and long-term in the other sectors; (iv) spatial scope varies between localized and widespread in all four sectors; and (v) non-structural measures are typically characterised by being reactive actions with short-term temporal and localized spatial scopes, with relatively low costs, but also with a relatively high level of ambiguity. This implies that non-structural measures, irrespective of whether they are planned or autonomous, are flexible tools, because they often can be decided reactively with short-term perspectives and localised effects, and they are relatively cheap. However, non-structural measures cannot be used to address all types of problems, and adaptation strategies will often include combinations of infrastructure investments and non-structural measures. Furthermore as non-structural measures often assumes a change of behaviour, such as accepting to live with climate effects, there often is an extra source of uncertainty related to obtaining some degree of societal consensus about a changed attitude to risk.

The uncertainty cascade includes many sources of uncertainty and their propagation through technical and socio-economic models may add substantially to prediction uncertainties. It is therefore sometimes argued that decision making should be postponed until more knowledge becomes available. However, it should be recognised that even large uncertainties may in some contexts imply small consequences for decision making. Therefore, in spite of large uncertainties, there is often sufficient knowledge (certainty) to justify action in climate adaptation (Arnbjerg-Nielsen and Fleischer 2009; Jeppesen et al. 2011; Olesen et al. 2011).

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