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Incorporating time lags and uncertainty in cost-benefit analysis of water quality improvements

– a case study of Limfjorden, Denmark

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Abstract

Cost-benefit analyses are commonly applied to assess the net welfare effects of policies to improve surface water quality. These analyses often disregard the biophysical fact that from implementation of policy measures to resulting improvements on water quality there will typically be considerable time lags, and in many cases there is a risk that the measures will not actually lead to the expected improvement. Based on a case study, we show that explicitly accounting for such time lags and outcome uncertainty in the benefit estimation can have non-negligible impacts on cost-benefit analysis findings. Our analysis indicates that reaching the EU Water Framework Directive target for our case study will lead to large and robust welfare increases. Even if the target proves more difficult or more costly to reach than expected with known policy measures, our results suggest that attempting to do so will still lead to a net welfare gain to society. Increasing time lags and uncertainty regarding water quality improvements do decrease the benefits, but the benefits still outweigh the aggregate costs of policy measures. Only in the worst case scenario, combining a long time lag and a high level of outcome uncertainty for the water quality improvement with relatively high costs of policy measures, we are close to a break-even. Hence, we do not find evidence supporting a case for disproportional cost exemption from the WFD target being relevant for the Limfjorden case.

Key words: Cost-benefit analysis, disproportional costs, time lags, uncertainty, water quality

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1. Introduction

Cost-benefit analysis (CBA) have long been used to support policymakers' hydro-economic decisions (Johansson & Kriström, 2011), by providing an overview of the net impact on social welfare resulting from water quality improving policies and projects. In a European water context, CBA is particularly relevant in relation to the Water Framework Directive (WFD), in which it is explicitly stated that "disproportional costs" may exempt countries from reaching the target of Good Ecological Status (GES) of water bodies (Brouwer, 2008). This have fostered several CBA studies in relation to the WFD (e.g. Bateman et al., 2006; Hanley & Black, 2006; De Nocker et al., 2007; Brouwer, 2008; Environment Agency, 2009; Lago et al., 2006; Molinos-Senante et al., 2011; Kinell et al., 2012; Vinten et al., 2012; Jensen et al., 2013; Feuillette et al., 2016). These studies, however, tend to be based on very diverse approaches to benefit estimation (Paoli et al., 2012), and CBA results are seldom used as an argument for reaching lower quality goals as set out in the WFD article 4.5 (European Commission, 2019).

Disproportional costs can also be assessed in relation to the financial capacity of the public or private subjects that have to bear the costs (Klauer et al., 2016). This is usually the approach taken when disproportionate cost arguments are made (Farmer, 2019). It is, however, important that more studies investigate the potential use of benefit estimates, and, in a CBA context, how these can be linked to the costs of achieving GES, as the EU require appropriate, evident and transparent criteria for where a less stringent environmental objective may be set (European Commission, 2009). The aim for better and more valid CBAs is also a key element in the Blue2 approach by the Commission (European Commission, 2020).

To ensure that CBAs lead to appropriate policy guidance, it is critical to base these on valid estimates of both costs and benefits. As such, the estimates should accurately and realistically reflect the characteristics of the separate components of costs and benefits. One such characteristic related to the benefit component is the considerable time lag that often occur between implementation of policy measures and resulting water quality improvements (Meals et al., 2010; Vero et al., 2018). In CBAs it is common practice to account for such time lags by discounting the estimated benefits based on general assumptions regarding social time preferences. Another such characteristic is the outcome uncertainty that is an inevitable part of environmental decision making (Sigel et al., 2010). This is typically accommodated through sensitivity analyzes (OECD, 2018). Both cost and benefit estimates should furthermore account for case area characteristics. However, in practice the costs of obtaining benefit estimates are often minimized through reliance on benefit transfer (BT), i.e. re-using benefit estimates from similar studies of other case areas. Obtaining value estimates through BT is inherently less precise than conducting a primary valuation study, often due to differences in the spatial and biophysical characteristics of the study site and policy site (Hanley et al., 2006; Johnston et al. 2015). This is particularly prevalent when relying on BTs across different countries (Bateman et al., 2011).

In the present paper we suggest a novel approach to account for preferences for time lags and uncertainty in a CBA using survey-based estimates of context-specific time and risk preferences in an assessment of the net welfare result of reaching the WFD target of GES in Limfjorden, Denmark. This particular water body is heavily affected by nutrient emissions from agricultural production, making it very costly to obtain GES. Hence, the overall aim of the CBA is to provide decision support for Danish policy makers in relation to the disproportional cost clause of the WFD. We utilize benefit estimates obtained from a discrete choice experiment assessing benefits of water quality improvements in Limfjorden[1], which also explicitly incorporates and estimates people's preferences for time lags and outcome uncertainty (Larsen et al., 2020). This enables us to conduct a CBA with limited use of general time preference assumptions, rather employing context-specific estimates of time preferences, while also explicitly incorporating inherent biophysical model uncertainty regarding the linkage between policy measures and the resulting change in water quality.

The remainder of this paper is organized as follows. Section 2 provides a description of the Limfjorden case area and its current ecological status. In section 3, we provide an assessment of the benefits of reaching GES in the case area, while an assessment of the costs associated with reaching GES is provided in section 4. In section 5, we present the welfare results of our baseline scenario, for which we conduct a sensitivity analysis in section 6. In section 7, we briefly discuss our results, and in section 8 we conclude on the findings.

2. Description of the Limfjorden case area

Limfjorden is the largest fjord in Denmark. The water surface covers approximately 1,500 km^2 with a coastline of approximately 1,000 km. The water catchment area covers 7,600 km^2, approximately 17 % of the total area of Denmark. The land use in the catchment area is dominated by agricultural production, which covers approximately 70 % of the area. About 525,000 people live within the catchment area (approximately10 % of the total population of Denmark) with the largest city being Aalborg, with approximately 100,000 inhabitants (Ministry of Environment, 2011).

The WFD does not state at what scale a CBA should be carried out when investigating whether the cost of reaching the GES target is disproportional (Martin-Ortega, 2012). Guidance documents issued by WATECO (2003) and the European Commission (2009) suggest that such assessments should take place at the waterbody level. In line with this, we focus on the Limfjorden fjord itself rather than all

[1] Larsen et al. (2020) presents benefit estimates based on a Stated Choice Experiment survey for Limfjorden (Denmark), Lake Mälaren and Hjälmaren (Sweden), the Mondego River and its main tributaries (Portugal), and the Grand River and its main tributaries (Ontario, Canada). Following a CBA structure similar to the one presented here, it will be relatively straightforward to conduct CBAs for water quality improvements in the latter three areas, given that cost estimates for such improvements are available.

water bodies in the entire Limfjorden catchment area. The water surface of the fjord area is outlined in Figure 1. The Danish Environmental Agency divides the fjord area into three sub-basins, and the water quality is assessed separately for each of these (Table 1). The ecological status is currently classified as being poor for the two sub-basins that make up the majority of the fjord area. For the much smaller sub-basin of Hjarbæk Fjord, the current ecological status is classified as bad, among other things due to particularly slow water exchange in this sub-basin (Ministry of Environment and Food, 2016). A more detailed assessment of the biological conditions in Limfjorden over time is presented in Markager et al. (2006).

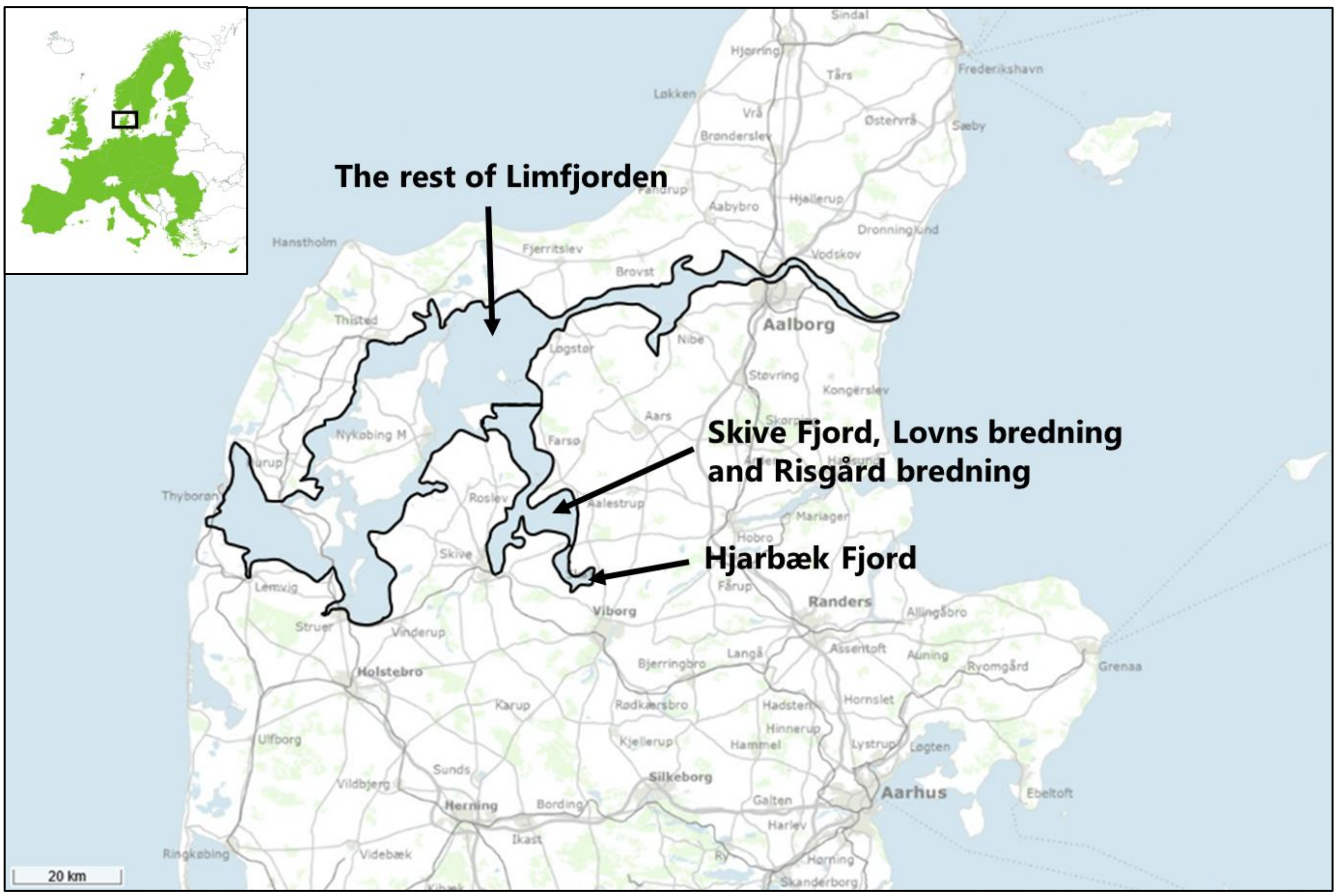

Figure 1 The Limfjorden fjord area and its three sub-basins

The WFD defines poor ecological status as *"Waters showing evidence of major alterations to the values of the biological quality elements for the surface water body type and in which the relevant biological communities deviate substantially from those normally associated with the surface water body type under undisturbed conditions"* (European Parliament, 2000, p. 38). Major water quality improvements are thus needed to reach GES, which is defined in the WFD as a water quality only slightly deviating from what would be the natural biological conditions. In an initial screening of the costs and benefits of reaching GES in different river basins in Denmark, based on simple BT, Jensen et al. (2013) suggested that further investigation of Limfjorden was warranted, as the benefits and costs appeared to be of quite similar size for this water body. This screening, as well as other CBAs in a Danish context, are, however, based on simple BT relying on a very limited number of Danish water quality valuation studies (Zandersen et al., 2018). The recent primary valuation study of water quality improvements in Limfjorden by Larsen et al. (2020) now facilitates conducting a CBA based on benefit estimates from a targeted primary valuation study. These benefit estimates are likely much more precise than previously used BT-based benefit estimates. Furthermore, precision of the cost estimation for Limfjorden has also improved recently. Hence, there now exists a solid basis for carrying out a better and more valid CBA than previously conducted for this area.

Table 1 Sub-basins constituting the Limfjorden fjord area

Sub-basin	Water catchment area (km^2)	Water body area (km^2)	Current ecological status
Hjarbæk Fjord	1,178	24	Bad
Skive Fjord, Lovns bredning and Risgård bredning	1,443	223	Poor
The rest of Limfjorden	4,979	1,245	Poor

Source: Ministry of Environment (2011) and Ministry of Environment and Food (2016).

3. Assessment of benefits of achieving GES in Limfjorden

Although the surface water quality may affect fisheries and tourism in the area, both of which has a marketed value, no data or dose-response functions were available to predict how water quality improvements would affect these sectors. We instead focus exclusively on the non-marketed benefits associated with achieving GES in Limfjorden. Thus, the total aggregate benefits (marketed plus non-marketed) are likely to be higher than the estimates used here. While a large component of the non-marketed benefits is most likely recreational values, i.e. use values, there is clearly also a significant non-use component related to e.g. increased biodiversity. Stated preference surveys are designed to measure the welfare economic values of the expected changes in non-market goods and services, including both use and non-use values. No other methods are capable of estimating non-use values. The Choice Experiment (CE) method is one of the most popular stated preference methods, partly due to its ability to estimate marginal values of changes to characteristics of a good or policy (Hanley et al., 2001; Mariel et al., 2021). It is, moreover, one of the most widely applied stated preference methods when it comes to water quality valuation (e.g. Hanley et al., 2006; Johnston et al., 2017; Bateman et al., 2011).

In this study we apply results from a recent CE study[2] assessing people's WTP for water quality improvements in Limfjorden (Larsen et al., 2020). A particular focus of the CE study were the time lags and uncertainty related to the timing and the extent to which decreased influxes of agricultural nutrient pollutants will actually affect water quality. In addition to a water quality attribute and a cost attribute, two attributes concerning time lags and outcome uncertainty, respectively, were therefore included in the experimental design used in the CE study. This setup enabled direct estimation of the effect that these aspects have on people's preferences for water quality improvements. Thus, in a CBA context, this avoids the need to make assumptions regarding their effect. This distinguishes the CE study from the majority of the previous water-related primary valuation studies. Other things equal, we argue that these targeted estimates will contribute to ensuring a high validity of the CBA.

The attributes and levels of the CE survey, as well as the descriptions provided for respondents, are reported in Table 2. In addition to the information presented in Table 2, short descriptions of each attribute level were included for the water quality and the risk attribute in order to increase credibility and policy consequentiality (Zawojska et al., 2019). The different water quality levels were defined in terms of three easily understandable ecosystem services regarding both biological quality elements (abundance of fish and fauna, and suitability for swimming and angling) and physico-chemical elements (water transparency). This is closely related to the definitions presented by Hime et al. (2009). The intention was to ensure that the water quality levels could be directly interpreted as ecological status levels corresponding to the classification used in the WFD. Hence, a good water quality corresponds to GES in the WFD terminology.

In order to simplify the scenario description, the CE study estimated WTPs for water quality improvements based on a division of Limfjorden into two areas rather than three sub-basins presented in Table 1; one area corresponding to the sub-basin "The rest of Limfjorden", and the other area, "Skive Fjord etc.", covering the remaining two smaller sub-basins. The ecological status currently differs between the two sub-basins included in "Skive Fjord etc.", with one being classified as bad and the other being classified as poor. In order to account for this, each choice set included a costless business-as-usual (BAU) alternative. This was presented as the expected ecological status in 4 years' time which

[2] The study was part of a large international project focusing on legacies of agricultural pollutants (the LEAP project; https://uwaterloo.ca/legacies-of-agricultural-pollutant/). The entire survey questionnaire as well as full study documentation is available in Larsen et al. (2021).

will most likely be poor in both “The rest of Limfjorden” and “Skive Fjord etc.” if current practice in the catchment area is continued. Figure 2 provides an example of a choice set used in the survey.

Table 2 Attribute levels and descriptions presented in the CE

Attribute	Levels	Attribute description shown to respondents
The expected water quality	Poor; Moderate; Good	In the following we will distinguish between t**hree different levels of water quality**: *Good, Moderate and Poor*. The differences between these levels are described below. It is not expected that the water quality will affect your drinking water or the treatment of this. Each water quality level is associated with a specific color, which is used on the small overview map to show how **the water quality is expected to be on average** in Skive Fjord etc. and in the rest of Limfjorden. **If no new policy is adopted, it is expected that water quality in both Skive Fjord etc. and the rest of Limfjorden will be classified as *Poor* in 4 years**. The expected water quality may however improve by implementing new policy measures.
The risk of water quality not improving	No risk; 10 % risk; 40 % risk	Some measures do not always work as expected. **Some proposals will therefore face a risk that the water quality will not improve,** even though the adopted measures usually works. This risk is based on practical and scientific expert judgement.
The time it takes for water quality to be achieved	4 years; 8 years; 20 years	It takes time before the impacts of new measures will take full effect. Scientists can predict the number of years it takes before a new policy leads to a specific water quality. Once this number of years has passed, water quality will stay at the achieved level.
How much your household’s annual tax payment increases as a consequence of the proposal	100 DKK; 200 DKK; 350 DKK; 700 DKK; 1400 DKK; 2800 DKK	Implementation of the proposals for a new policy comes at a cost, which will be covered by increasing the **municipality tax**. Hence, **each policy proposal is associated with an increased annual tax payment for your household**. The increase can vary from 100 kr. and up to 2800 kr. per year per household. The potential increase in your household's aggregate annual **tax payment will be implemented in 2020**, even if, as described, there may be uncertainty regarding the expected improvements, and it will take several years before they are achieved. The extra tax payment will be the same amount in all future years. If the current policy is continued with no changes, your household's tax payment will not increase. Note that the possible increase in your annual tax payment will be used exclusively for implementation of measures that are necessary achieve the expected water quality improvements in Limfjorden. The policy proposals will thus not affect the water quality in other parts of Denmark.

Note: This is a translation of the original descriptions, which were presented in Danish. Payments are in the currency Danish Kroner, 100 DKK ~ €13.5

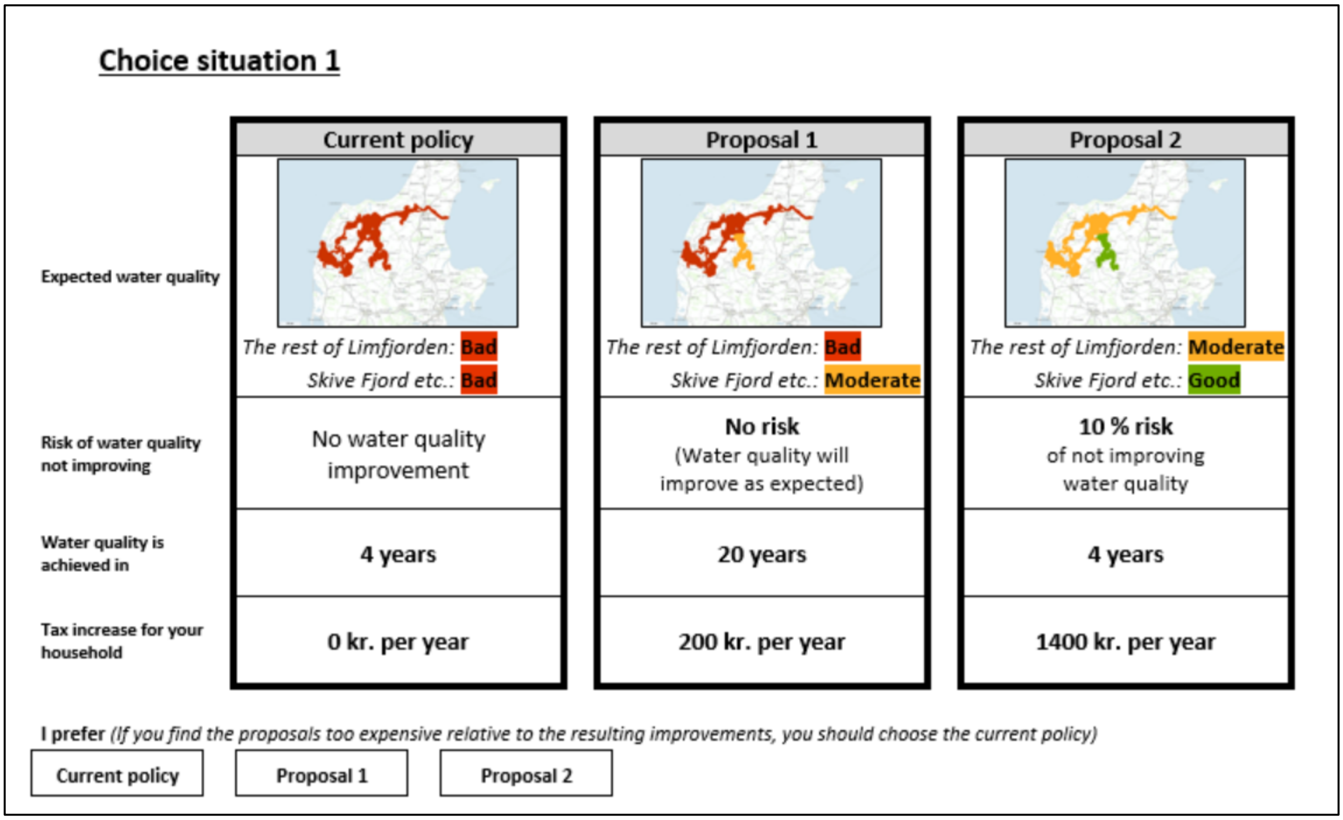

Figure 2 Example of a choice set Used in the CE (translated from Danish)

Using online questionnaires, the CE survey data was collected during May and June 2020. A random sample of 401 respondents living in municipalities close to Limfjorden[3] (see table 4) were invited from a pre-recruited representative web-panel maintained by a professional survey company. After removal of protest bidders[4] and speeders[5] the final dataset consists of 383 respondents.

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[3] The so-called Limfjorden Council coordinates measure-implementation regarding water quality improvements in Limfjorden. Hence, the relevant market extent for the survey was defined as the municipalities that are members of the Limfjorden Council, which also largely overlaps with the Limfjorden catchment area.

[4] A follow-up question asked respondents who chose the BAU alternative in all choice sets, to state their reason for doing so. Based on responses to this question, respondents who were suspected not to accept the scenario description and CE setup, and hence not state their true preferences in the choice sets, were removed. Protest bidders made up 2-6 % of all respondents.

[5] Campbell et al. (2017) find respondents spending as little as 2.5 seconds responding to a choice set, including the time required to load a webpage (the next choice set), which likely takes 1-2 seconds. With this lower bound as reference, it was decided to remove respondents spending less than 2.5 seconds in average on the three first choice sets, as previous studies have found that the first couple of choice sets may be particularly important and time-consuming for respondents to understand the choice set question format (Day et al., 2012; Carlsson et al., 2012; Hess et al., 2012). In total, protest bidders and speeders made up 4-8 % of all respondents.

The data were analyzed using a random parameter error component logit (RPECL) model specification. All non-cost attributes were specified as normally distributed random parameters, whereas the cost attribute was specified as a log-normally distributed random parameter. An alternative specific constant (ASC) was included for the BAU alternative. An error component, additional to the usual Gumbel-distributed error term, was furthermore included to capture any remaining BAU effects in the stochastic part of utility. The model was estimated in WTP space, and the coefficients are hence directly interpretable as the marginal annual WTP per household for changes in the attribute levels, as compared to the BAU levels. Detailed information on the econometric modelling can be found in Larsen et al. (2020). Results from the RPECL model are presented in Table 3. The model fits the data fairly well, as evident from the adjusted pseudo-R^2, and there is a clear tendency for both outcome uncertainty and time lags to have a negative impact on the WTP for water quality improvements. As expected, the negative impact increases with larger outcome uncertainty and longer time lags.

Table 3 Results from RPECL model in WTP space for the Danish surface water data

Attributes	**Mean WTP (DKK/household/year)**		**Standard Deviation (SD)**	
	Estimate	**Std. Error**	**Estimate**	**Std. Error**
The rest of Limfjorden, Moderate WQ	1,564***	113	135	142
The rest of Limfjorden, Good WQ	2,526***	149	1,520***	89
Skive Fjord etc., Moderate WQ	631***	69	86*	48
Skive Fjord etc., Good WQ	968***	89	479***	74
10 % risk of no improvement in WQ	-312***	45	0.8	29
40 % risk of no improvement in WQ	-640***	78	639***	92
Expected WQ reached in 8 years	-109**	47	4.4	50
Expected WQ reached in 20 years	-395***	60	186	178
Cost	-0.0017***	0.0002	0.0011***	0.0003
ASC (business as usual)	-734***	192		
Error component (alt1, alt2)			1,892***	201
Model characteristics				
No. of respondents (choice obs.)	383 (4596)			
LL(0)	-5,049			
Final LL	-3,365			
Adjusted pseudo-R^2	0.330			

Note: '***' indicates significance at the 0.01 level; '**' at the 0.05 level; '*' at the 0.1 level.
Simulations done using 1,000 draws based on the scrambled Sobol sequence. Standard errors constructed using the robust sandwich estimator.

BAU water quality levels: Poor. BAU risk level: No risk. BAU time lag level: 4 years.

In order to calculate a baseline estimate for the welfare benefit that an improvement to GES in Limfjorden will lead to, the mean WTP per household for this improvement is scaled up with the number of households in the sampling area. The mean WTPs per household are obtained by summing the estimates for obtaining good water quality for "the rest of Limfjorden" and "Skive Fjord etc.". The extent of the market is defined as the sampling area for the CE survey, i.e. the municipalities mentioned in the first column of Table 4. Although households located in other municipalities may also benefit from the water quality improvement, we do not know the extent to which this might be the case, since only the municipalities mentioned in Table 4 were surveyed in the CE study. If indeed the actual extent of the market is bigger than assumed here, our aggregate welfare estimates will underestimate the actual welfare change, *ceteris paribus*. Table 4 presents the aggregate annual welfare benefit estimate of reaching GES in Limfjorden with certainty in 4 years' time.

Table 4 Assessment of baseline welfare benefits of reaching GES in Limfjorden

Municipalities from which respondents were sampled in the valuation study	Total number of households (2020)[1]	WTP for GES in the entire Limfjorden (DKK/household/year)	Baseline welfare benefit (1000 DKK/year)
Herning, Holstebro, Ikast-Brande, Lemvig, Randers, Skive, Struer, Viborg, Brønderslev, Frederikshavn, Hjørring, Jammerbugt, Mariagerfjord, Morsø, Rebild, Thisted, Vesthimmerlands, Aalborg	504,854	3,494	1,763,810

[1] Source: Statistics Denmark – FAM55N

4. Assessment of costs of achieving GES in Limfjorden

The Danish river basin management plans (RBMPs) contain assessments for each river basin regarding the annual N-loss reduction that is required to reach GES in 2027, the deadline for WFD compliance. The RBMPs currently in place primarily cover the period from 2015 to 2021 (the second WFD planning period), yet also estimate the reduction in the annual N-loss that is expected to be required from 2021 to 2027 (the third WFD planning period). In order to reach GES in Limforden in 2027, it is expected that it will be necessary to reduce the N-loss with 1767 ton from 2015 to 2021, and another 1861 tons from 2021 to 2027 (Ministry of Environment and Food, 2016). As stated in the WFD this reduction has to be based on cost effective measures, i.e. the measures that achieve the GES target at minimum costs. The RBMPs also contain assessments of the costs of the measures that fulfill this, based on a model that follow a cost efficiency approach for each of the sub-catchments in Denmark[6] (see Hansen et al., 2019). The costs include annuitized investment and operating costs but exclude administrative expenses. The investment costs are annuitized based on a project period of 20 years and an interest rate of 4% (Eriksen et al., 2020). The model used is described in (Jacobsen and Hansen, 2016) and the measures and costs are described in more detail in Eriksen et al. (2020).

The expected annual cost of achieving the reduction required from 2015 to 2021 in the Limfjorden catchment has been estimated to be approximately 80 million DKK. This includes collective measures (mini wetlands, wetlands, afforestation and set a side of low laying areas), targeted regulation (catch crops and early seeding are used as the most cost effective measures), the effects of previous programs (wetland schemes), and reduced losses from sewage overflows. In Table 5, a more detailed presentation of the measures that are currently assessed to fulfill the N-loss reduction requirement for the period 2021-2027 in the Limfjorden catchment at the lowest cost is presented.

Table 5 Costs and effects related to measures implemented in the third planning period in the Limfjorden catchment

Measures	Area	Effect/year	Cost /year	Cost efficiency
	Ha	Kg N	1000 DKK	DKK/kg N
Catch crops	31,450	308,915	14,664	47
Norm reduction 10%	420,926	429,157	18,942	44
Norm reduction (+10%)	21	22	3	136
Early seeding	868	3,815	174	46
In between crops	19,652	79,354	6,387	80
Wetlands	6,200	834,645	40,379	48
Forest	1,422	20,704	1,644	79
Set-a-side (permanent)	12,960	184,156	15,461	84
Sum	**493,499**	**1,860,776**	**97,654**	**52**

Source: Jacobsen (2020)

Note: The cost estimates are based on a standard potential for each measure less the potential that has already been used in the second planning period (Hansen et al., 2019).

[6] The presented costs of achieving the reduction required in 2015-2021 are based on the current RBMP in which Denmark is divided into 90 sub-catchments, of which 3 relate to Limfjorden. In the coming (third) RBMP Denmark is, however, divided into 88 sub-catchments of which 9 relate to Limfjorden. The presented costs of achieving the reduction required in 2021-2027 is based on this division.

In the RBMPs the N-loss reductions and related costs are assessed on a catchment level. However, as the most important measures in Denmark regarding streams and lakes are related to physical quality improvements and phosphorous reduction, respectively, the presented cost estimates primarily cover achievement of GES in the Limfjorden fjord. These thus fit well into the present CBA, where we focus on the fjord area only, as described in section 2. It should, however, be noted that some of the measures also will have positive effects for the water quality in some streams and lakes within the catchment. The presented cost estimates may thus be high estimates of the actual costs regarding only the fjord area. This is further augmented by the fact that the value of side effects, such as decreased CO_2 and NH_3 emissions or increased public access to prior agricultural areas, have not been deducted from the cost estimates, despite inclusion of such side-effects having the potential to change the ranking of the cost-effectiveness analysis (Jensen et al., 2019).

In Table 6 we use the total cost estimate from Table 5 as our baseline cost estimate. This estimate is based on an assumption that the reductions required in the period 2015 to 2021 has been achieved. As the benefits in section 3 are estimated with the water quality level assessed prior to the 2015-2021-reduction[7] as its baseline, it is, however, interesting to investigate how a cost estimate covering the required reductions for the entire period 2015-2027 will affect our estimated welfare results. This estimate is presented as the “Alternative costs 1” in Table 6, and equals the baseline estimate plus the cost estimate for the period 2015-2021 (80 million DKK/year). For the same period (2015 to 2027) we also present a high cost estimate, called “Alternative costs 2”. This estimate is based on the fact that The Danish Ministry of Environment and Food has indicated that the national reduction requirement may increase from 6,200 tons N to 10,000 tons N in the period 2021-2027. Increasing the reduction requirement in the Limfjorden-related sub-catchments with the same change (+61%) would increase the reduction requirement from 1861 tons N to 3002 tons N for these catchments. This would increase the costs to 194.7 million and around 15% of the area would need to be taken out of agricultural production. The “Alternative costs 2” is calculated by adding this additional cost estimate to the cost estimate for the period 2015-2021.

The welfare benefit estimates of reaching the GES target in Limfjorden presented in the previous section were based on the annual WTP for this improvement of the households in the area. The WTP is measured in consumer prices (i.e. including taxes) whereas the cost estimates presented in Table 5 are measured in factor prices, i.e. excluding taxes. To make sure that the results of CBAs guide policy makers towards a welfare economically optimal allocation of resources, the costs and benefits of a policy need to be stated in the same prices. Accordingly, we convert the factor price based cost estimates in the second column of Table 6 to market price levels using a standard conversion factor of

[7] This was the latest available data by the time of the valuation study on which the benefit estimates are based.

1.28 as recommended by the Danish Ministry of Finance (Ministry of Finance, 2019). The converted cost estimates are presented in the third column of Table 6.

Other things equal, the costs associated with improving Limfjorden to GES will be funded by the Danish state through taxes. Tax collection creates distortion effects to the economy, also referred to as deadweight loss, which also need to be accounted for in the assessment of welfare costs. We incorporate this marginal cost of public funding by adding 10% to the costs, as recommended by the Danish Ministry of Finance (Ministry of Finance, 2019). In the fourth column of Table 6, we present the resulting annual welfare cost estimates of achieving GES in Limfjorden.

Table 6 Assessment of welfare costs of reaching GES in Limfjorden

Cost estimate	Costs, factor prices (1000 DKK/year)	Costs, consumer prices (1000 DKK/year)	Welfare costs incl. tax distortion costs, consumer prices (1000 DKK/year)
Baseline costs (2021-2027, current estimate)	97,654	124,997	137,497
Alternative costs 1 (2015-2027[a], current estimate)	177,654	227,397	250,137
Alternative costs 2 (2015-2027[a], high estimate[b])	274,700	351,616	386,778

[a] Cost estimate covering the required N reductions for the entire period 2015 to 2027

[b] High estimate is based on a national reduction of 10,000 tons N rather than 6,200 tons N.

5. Calculation of baseline welfare gain

The general CBA practice regarding policies that imply future costs or benefits, is to discount these using general discount rates that are based on expert knowledge or governmental guidelines (OECD, 2018). The cost estimates in the previous section have been subject to such discounting as the estimates were annuitized using a 4% social discount rate, as generally recommended by the Danish Ministry of Finance (Ministry of Finance, 2019). The benefit estimates, however, provide a direct and context-specific estimate of the annual reduction that a delay of the expected water quality improvement will have on WTP for water quality improving policies. Hence, there is no need to apply a general social discount rate to these estimates. With both costs and benefits stated in annual terms, we are able to base our CBA on an annual welfare result, rather than the net present value of all future years where these occur. This simplifies the CBA, yet does not affect the conclusions drawn from this, as the annual welfare results only differ from the total welfare results in terms of a scaling based on the project period.

Table 7 Welfare results of different scenarios

Scenario	Risk of not achieving GES	GES reached in	Benefits (1000 DKK/year)	Costs (1000 DKK/year)	Net annual value (1000 DKK/year)	B/C ratio
Baseline scenario	None	4 years	1,763,810	137,497	1,626,313	12.8
Scenario 1: Comply with WFD just within 2027-deadline	None	8 years	1,708,771	137,497	1,571,274	12.4
Scenario 2: Scenario 1 and “Alternative costs 1”	None	8 years	1,708,771	250,137	1,458,634	6.8
Scenario 3: Scenario 1 and “Alternative costs 2”	None	8 years	1,708,771	386,778	1,321,994	4.4
Scenario 4: Delayed compliance with WFD	None	20 years	1,564,264	137,497	1,426,767	11.4
Scenario 5: Delayed and uncertain compliance with WFD	10%	20 years	1,406,983	137,497	1,269,486	10.2
Scenario 6: Delayed and very uncertain compliance with WFD	40%	20 years	1,241,315	137,497	1,103,819	9.0
Scenario 7: Scenario 6 and “Alternative costs 2”	40%	20 years	1,241,315	386,778	854,538	3.2

Table 7 reports the baseline annual welfare result, as well as the benefit-cost (B/C) ratio, based on the baseline welfare costs and benefits outlined in Table 4 and 6. We refer to this as the Baseline scenario. The results indicate very clearly that improving the water quality in Limfjorden to GES in 4 years will be a net benefit to society. According to the WFD, GES should be reached in Limfjorden no later than in 2027. Policy measures implemented to target N-loss reduction today, should hence lead to GES of water bodies with a time lag of seven years at most. It is evident from the WTP estimates in Table 3 that the extent of this time lag affects how people value a water quality improvement. In Scenario 1 (Table 7) we adjust the benefit estimates with the effect of an eight year time lag, to obtain a conservative estimate of the annual welfare result of GES being reached just within the WFD deadline. It is evident that the time lag affects the annual benefit estimate, as this decreases with 55 million DKK, yet not nearly to an extent that changes the fact that the annual benefits far outweighs the annual costs. Both the Baseline scenario and Scenario 1 thus indicate that the costs of complying with the WFD will be far from disproportionate in the case of Limfjorden.

As stated in section 4, in addition to the baseline cost estimate, two more cost estimates can be considered in terms of the present CBA. In Scenario 2 and 3 (Table 7), we replace the baseline costs in Scenario 1 with the "Alternative costs 1" and "Alternative costs 2", respectively. It is clear that these alternative cost estimates affect the welfare result, and in Scenario 3 the B/C ratio drops to almost one third of that in Scenario 1. Still, however, the net annual welfare value is far from negative.

6. Sensitivity analyses

The estimates of costs and benefits are based on a range of assumption. We thus analyze the baseline welfare results further with a focus on how these are affected by three different assumptions: 1) The water quality improvements not being reached within the WFD deadline, 2) the spatial variability in WTP across the sample area, and 3) the specific input sources used in this CBA.

6.1. WFD target is not reached within given time frame

As stated above, the WFD target of GES in all water bodies in EU should be reached in 2027 at the latest. In the WFD it is however explicitly stated that an exemption from this is possible "[…] *in cases where the natural conditions are such that the objectives cannot be achieved within this period*" (European Parliament, 2000, p. 10). Although nothing currently indicates that the natural conditions of Limfjorden generally fits into this category, it is interesting to investigate the effect that a time lag beyond 8 years would have on the welfare result. In Scenario 4 (Table 7) GES is assumed to be delayed further, so that it is only reached within 20 years. This delay clearly affects the annual benefit estimates, as these decrease with 145 million DKK when compared to Scenario 1. Yet, such a delay and the associated reduction in benefits will not in any way change the overall conclusion from the baseline.

In the event that the natural conditions in Limfjorden make it so complicated to achieve water quality improvements that Scenario 4 becomes relevant, it is also conceivable that there will be uncertainty regarding the mere possibility of improving the water quality at all. In Scenarios 5 and 6 (Table 7) this uncertainty is accounted for in the benefit estimate, for two different levels of outcome uncertainty. This has a relatively large effect on the annual benefit estimates, which decrease with 157-323 million DKK. Again, the overall conclusion is maintained. Though the estimated annual benefits decrease when outcome uncertainty is introduced, they still far outweigh the estimated annual costs. In

Scenario 7 (Table 7) we present a "worst-case scenario" given our benefit and cost estimates, corresponding to Scenario 6 but with the baseline cost estimates replaced by the higher "Alternative costs 2". Even in this case, the overall conclusion is maintained.

6.2. Taking account of the spatial variability in WTP estimates

In the previous sections, the welfare benefits were based on the mean estimate of the annual WTP per household across the entire sample, which was multiplied with the total number of households in the sampled area. We would, however, expect a household's WTP to vary with the household location, as suggested by both theory and empirical evidence in the distance decay literature (Bateman et al., 2006; De Valck & Rolfe, 2018; Hanley et al., 2003; Schaafsma et al., 2013; Olsen et al., 2020). In order to investigate whether this aspect affects the aggregate benefit estimates in the present study, in this section we instead base the aggregation on municipality-based mean WTP estimates. Although WTP jump discontinuities may be subject to other natural or manmade barriers than municipalities (Olsen et al., 2020), information on the household municipality location is the only spatial information readily available from the CE survey data. Given that the sampled area covers both municipalities bordering Limfjorden as well as their neighboring municipalities further away from Limfjorden, the spatial variability at municipality level is likely to capture distance-decay at least to some extent. Differences in municipality WTPs would not affect any of the results above, if the sample was perfectly representative in terms of the number of households that is located within each municipality. This is however not the case for the CE survey data[8].

As described in section 3, the mean WTP estimates in Larsen et al. (2020) are derived from an RPECL model. This model enables estimation of household-specific WTP parameters through the derivation of the conditional distribution based on the sampled respondents' choices. Following e.g. Greene et al. (2006), Hensher et al. (2006) and Hess (2010), this is achieved by applying Bayes' rule to construct the conditional density for the random parameters of interest:

$$f(\beta_n|Y_n, X_n, \Omega) = \frac{f(Y_n|\beta_n, X_n, \Omega) f_\beta(\beta_n|\ \Omega)}{f(Y_n|X_n, \Omega)}$$

where Ω denotes the underlying parameters of the distribution of β_n. The sequence of choices made by individual *n* is denoted by Y_n, and X_n encompasses all elements of the vector of explanatory variables, x_{ntj} for all alternatives and choice tasks. The conditional mean can then be approximated for each random parameter by simulated maximum likelihood:

[8] Results of a χ^2 test comparing household numbers in the sample and population is presented in Appendix 1.

$$\hat{E}(\beta_n|Y_n, X_n, \Omega) = \frac{1}{R}\sum_{r=1}^{R}\hat{\beta}_{nr}\prod_{t=1}^{T}\frac{\exp(\hat{\beta}_{nr}x_{ntj})}{\sum_{k=1}^{J}\exp(\hat{\beta}_{nr}x_{ntk})} \Bigg/ \frac{1}{R}\sum_{r=1}^{R}\prod_{t=1}^{T}\frac{\exp(\hat{\beta}_{nr}x_{ntj})}{\sum_{k=1}^{J}\exp(\hat{\beta}_{nr}x_{ntk})}$$

where $\hat{E}$ expresses the average of β for the individual *n*, over the *r* = 1,…,R simulated draws. It hence expresses the household-specific WTP estimates.

Based on these estimates and information about which municipality each respondent lives in, it is possible to derive mean WTP estimates for each municipality. Multiplication of these mean estimates with the total number of households within each municipality yields the aggregate welfare benefits of a specific scenario for each municipality. Table 8 provides estimates of the municipality-specific annual mean WTPs and the annual aggregate WTP of the Baseline scenario, Scenario 1 and Scenario 6, the two first representing certain WFD compliance within the 2027-deadline, and the last representing delayed and very uncertain WFD compliance. The annual mean WTP estimates clearly display variation across municipalities for the three presented scenarios. It is worth noting that the only difference between the estimates for the Baseline scenario and Scenario 1 is that all mean WTPs are approximately 110 DKK/year lower in the latter. This similar effect across municipalities is the result of the model estimates indicating little heterogeneity in preferences for the 8-year lag parameter (the standard deviation for this parameter is insignificant in Table 3). In Table 8, we also present the implied total welfare benefit estimates of the different scenarios, by summing the aggregate annual WTPs for all the municipalities. These estimates are very similar to those presented for the Baseline scenario, Scenario 1 and Scenario 6 in Table 7, with the estimates being slightly larger when taking the spatial WTP variation into account. The general conclusions from section 6.1 hence still hold[9].

[9] Following the same approach, we also calculated the total welfare benefit estimates based on median annual WTP estimates for each municipality. This approach may to a greater extent account for extreme outliers within each municipality. The median municipality WTP is generally lower than the mean municipality WTP, leading the total annual welfare benefits to decrease with around 100,000 DKK for all scenarios. This does, however, not change the conclusions from section 6.1.

Table 8 Municipality-specific mean and aggregate annual WTPs for the Baseline scenario, Scenario 1 and Scenario 6

Municipality	Population (2020)	Baseline scenario		Scenario 1		Scenario 6	
		Mean WTP (DKK/year)	Aggregate WTP, all households (1000 DKK/year)	Mean WTP (DKK/year)	Aggregate WTP, all households (1000 DKK/year)	Mean WTP (DKK/year)	Aggregate WTP, all households (1000 DKK/year)
Brønderslev	16,629	3,700	61,521	3,591	59,707	2,777	46,178
Frederikshavn	29,943	3,677	110,090	3,568	106,824	2,573	77,034
Herning	40,863	3,824	156,272	3,715	151,815	2,865	117,089
Hjørring	30,959	2,996	92,759	2,887	89,376	1,976	61,162
Holstebro	26,992	3,208	86,602	3,099	83,659	2,032	54,851
Ikast-Brande	18,429	3,623	66,770	3,514	64,760	2,545	46,904
Jammerbugt	17,631	3,467	61,122	3,358	59,200	2,384	42,039
Lemvig	9,440	4,301	40,597	4,192	39,570	3,257	30,744
Mariagerfjord	19,875	4,090	81,295	3,981	79,128	3,045	60,512
Morsø	9,936	2,866	28,480	2,757	27,395	1,757	17,459
Randers	47,459	3,741	177,559	3,632	172,382	2,684	127,361
Rebild	12,894	3,863	49,815	3,754	48,408	3,114	40,147
Skive	22,290	2,848	63,486	2,740	61,065	1,716	38,240
Struer	10,116	4,029	40,762	3,920	39,658	3,199	32,358
Thisted	20,518	3,776	77,472	3,667	75,231	2,731	56,028
Vesthimmerland	17,369	3,660	63,569	3,551	61,678	2,843	49,377
Viborg	44,669	3,453	154,260	3,344	149,393	2,386	106,602
Aalborg	108,842	3,422	372,471	3,313	360,604	2,408	262,082
Total welfare benefits, all municipalities (1000 DKK/year)			1,784,902		1,729,851		1,266,168
Costs (1000 DKK/year)			137,497		137,497		137,497
Net annual value (1000 DKK/year)			1,647,406		1,592,355		1,128,671

Note: Municipality specific annual mean WTP estimates are based on household-specific WTP estimates.

Population statistics based on Statistics Denmark's household statistics (FAM55N)

6.3. Using other inputs to the CBA

In the present study we conduct the first CBA to date based on a primary valuation study regarding the GES target in Limfjorden, despite this being not only the largest fjord in Denmark (see section 2), but also being heavily polluted by nutrient emissions from agriculture. Jensen et al. (2013) have previously carried out a CBA for policies to improve water quality in Limfjorden, but this relied on a simple BT from a valuation study of another Danish catchment area (Odense river basin)[10]. It was furthermore based on a preliminary cost analysis, and the household number in the catchment area (stated to be 240,156 households). We expect the inputs in the present study to be much more accurate, as the WTP estimates are based on a primary valuation study targeting Limfjorden, the cost estimates are based on updated analyses tools, and the household number is based on an area that is greater than the catchment area[11]. We furthermore expect the direct inclusion of time preference estimates in our study to be more valid than the traditional reliance on social time preference assumptions, as the former is based on the respondents' stated preferences in the relevant context. Notwithstanding this, it is interesting to investigate how our results are affected by the use of inputs that would have been more readily available, and hence cheaper to obtain.

In Table 9, we present the welfare results of five different scenarios where some of the inputs from the present study are replaced by alternative inputs. Scenarios 8 to 10 correspond to our Baseline scenario with the cost estimates, WTP estimates and household numbers, respectively, replaced by the corresponding inputs used in Jensen et al. (2013). Compared to the baseline in Table 8, it is evident that all these three inputs have a considerable negative effect on the net annual welfare result. This is particularly the case for the WTP estimates and the household number. This is not surprising, first of all given that the WTPs are based on a simple, naïve BT from Odense river, which is a considerably smaller water body than Limfjorden. Secondly, the assumed spatial extent of the market in Jensen et al. (2013) only covered less than half of the number of households used in the present study. These effects are, however, not to any extent changing the conclusions from section 6.1.

As time lags are arguably always present in relation to water quality improvements, it is important to include these in welfare economic analyses of such improvements. In the present study we benefit from direct estimates of the effect of time lags beyond 4 years. Without these estimates, we would have had to rely on another approach to account for such time lags. The traditional approach would

[10] The BT relied on value estimates obtained from a CE survey conducted as part of the project "Costs and benefits of nutrient reductions to Danish Waterbodies", and the related AquaMoney project (Jensen et al., 2013).

[11] It is evident from the CE study by Larsen et al. (2020) that the relevant market to consider extend beyond the catchment boundaries. As described in section 3, the Limfjorden catchment does e.g. not extend into Frederikshavn municipality, yet from Table 8 it is evident that households in this municipality have a considerable WTP for water quality improvements in Limfjorden.

be to assume that the population only begin to receive the estimated annual baseline benefits (in our case the benefit of obtaining GES in 4 years) after an additional number of years equivalent to the time lag. To calculate an annuitized measure of benefits, it is necessary to make assumptions regarding the project period (i.e. for how many years the population would enjoy the estimated annual benefits) and the social discount rate, in order to discount and annuitize the total benefits over the project period[12].

Table 9 The impact of using alternative inputs for WTP, cost estimates, and household numbers

Scenario	Annual household WTP estimates	Cost estimates	Number of households	Benefits (1000 DKK/year)	Costs (1000 DKK/year)	Net annual value (1000 DKK/year)	B/C ratio
Scenario 8: Higher cost estimates	Baseline scenario	Jensen et al. (2013)	Baseline # households	1,763,810	516,015	1,247,795	3,4
Scenario 9: Benefits based on BT	BT based on Odense river valuation	Baseline costs	Baseline # households	892,077	137,497	754,580	6,5
Scenario 10: Smaller market extent	Baseline scenario	Baseline costs	Catchment area only	839,034	137,497	701,537	6,1
Scenario 11: 20 year time lag, using traditional discounting procedure	Baseline scenario,	Baseline costs	Baseline # households	807,090	137,497	669,593	5,9
Scenario 12: Worst-case scenario	Scenario 4	Jensen et al. (2013)	Catchment area only	590,486	516,015	74,471	1,1

In Scenario 11 we base the benefit estimates on this approach, assuming a 20 year time lag, hence a 16 year time lag beyond the baseline time lag. It is thus assumed that the population start to receive the baseline annual benefits from year 16, and hence that the expected water quality improvement occurs in year 20. It is furthermore assumed that no more annual benefits are received after year 49, and that the social discount rate is 4 %[13]. The annual benefit that we derive from this more typically applied approach when time lags are present is almost half the size of the annual benefits used in

[12] Both the length of the project period and the social discount rate are inherent in the direct time preference estimates in Table 3, as the respondents to the CE survey implicitly are assumed to take these into account.
[13] The Danish Ministry of Finance recommends to use a discount rate of 4 % for year 0-35 and a discount rate of 3 % for year 36-70 (Ministry of Finance, 2019). For simplicity, however, we use a discount rate of 4 % for year 0-49.

Scenario 4, which only differ in terms of the way that time lag effects are included. Clearly, the approach used to implement time lags is decisive for the magnitude of the benefit estimates. In this case, however, it still does not change the overall conclusion that there is a considerable positive net annual value to society of reaching GES in Limfjorden.

Scenario 12 represent a worst-case scenario in which the WTP estimates correspond to those in Scenario 6 (GES target is not reached until 20 years from now and there is a 40 % risk that no improvement will take place), and where we use the high cost estimates and low household number from Jensen et al. (2013). The welfare result remains positive even under this scenario, though the B/C ratio is now much closer to unity as compared to the preceding scenarios.

7. Discussion and policy recommendations

By construction, CBAs conducted *ex ante*, i.e. prior to policy implementation, require assumptions about the effect that a given policy will have on societal welfare. The estimates of costs and benefits, as well as assumptions concerning social discount rates and project period length, are fundamental inputs in any ex ante CBA. By construction, these will never be more than approximations of actual outcomes. Consequently, the validity of the policy guidance obtained from a CBA depends on the precision of these input estimates. Other things equal, incorporating context-specific, direct estimates of how time lags affect the magnitude of the benefits, as well as including direct estimates of the effect of outcome uncertainty in the sensitivity analysis, would arguably lead to conclusions of relatively high validity. Of course, the WTP estimates of time lags and outcome uncertainty in the present study are subject to estimation uncertainty related to assumptions made in the modelling stage. Furthermore, they are based on a stated choice experiment, which could be susceptible to hypothetical bias. Given that water quality is a non-marketed good and a substantial proportion of the associated values are non-use values, using a stated preference method is the only available option for estimating the welfare economic benefits – and it is not possible to assess validity and precision of these estimates against e.g. revealed preferences or actual market data. As detailed in Larsen et al. (2020), the data collection and the choice modelling analysis follows state-of-the-art practices in the field, which is likely to ensure a relatively high degree of validity. Hence, it would seem reasonable to consider using these estimates, which are not only elicited in the specific context of water quality improvements in Limfjorden, but also reflecting the time and risk preferences of the relevant target population for this water body, superior to using more generalized recommendations of e.g. the social discount rate, or even neglecting these value components in the CBA.

The results in sections 5 and 6 provide indications regarding the importance of accounting for time lags and outcome uncertainty in water related CBAs. The general conclusion is that these aspects do have an effect on the welfare results, yet not to an extent that changes the policy recommendations from the CBA in the current case. It is, however, worth noting that this cannot be considered a general conclusion for water related CBAs. For other catchment areas the costs of improving water quality may be larger, while time lags and outcome uncertainty may have a greater negative effect on the benefits. In Scenario 12 (Table 9), the combination of long time lag and large uncertainty indeed makes the B/C ratio decrease to almost unity. Accounting for time lags and outcome uncertainty is hence both relevant and important in water related CBAs.

Our sensitivity analysis in section 6.3 reveals that different approaches to inclusion of time lags result in considerably different annual welfare benefits. It is quite common in applied CBAs not to include benefits of water quality improvements until the point in time when they are expected to be realized. However, the findings from Larsen et al. (2020) suggest that welfare benefits may occur earlier. It should, however, be noted that these estimates are a construct of a CE setup that asks respondents to evaluate their preferences in terms of annual benefits. Hence, even if they do not have preferences for water quality improvements before they actually occur, they have to implicitly take account of this through their stated annual preferences, starting year 0. Yet the remarkable difference between the annual benefits in Scenario 4 and Scenario 11 indicate that some benefits indeed are received prior to the improvement being fully reached. This underlines our argument that direct estimation of the time lag effect is more valid than simply relying on the analysts' assumptions and general recommendations. It is, however, a matter that warrants confirmation in further research before firm conclusions can be drawn.

Through our focus on reaching GES in Limfjorden, we make an important contribution to support Danish policy decisions regarding this catchment. Our analysis indicates that reaching the WFD target will lead to large welfare increases, a result that we find to be very robust. Even if the target proves difficult to reach with known measures, the results suggest attempting to do so is likely to lead to a welfare gain, even if the costs turn out to large. The welfare results will arguably be lower once more water bodies in Denmark improves (as is required in the WFD), yet, the size of, and public interest in, Limfjorden, is likely to limit this effect to an extent where it does not affect our main conclusions. Overall, we hence do not find evidence supporting a case for disproportional cost exemption from the GES target being relevant for Limfjorden.

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Appendix 1

Comparison of number-of-household statistics for the sample and the population.

	Sample		Population			
	#	%	#	%	χ2	p
Municipality					29.39	0.0311
Brønderslev	6	1.6%	16,629	3.3%		
Frederikshavn	10	2.6%	29,943	5.9%		
Herning	27	7.0%	40,863	8.1%		
Hjørring	25	6.5%	30,959	6.1%		
Holstebro	28	7.3%	26,992	5.3%		
Ikast-Brande	16	4.2%	18,429	3.7%		
Jammerbugt	15	3.9%	17,631	3.5%		
Lemvig	7	1.8%	9,440	1.9%		
Mariagerfjord	12	3.1%	19,875	3.9%		
Morsø	8	2.1%	9,936	2.0%		
Randers	42	11.0%	47,459	9.4%		
Rebild	4	1.0%	12,894	2.6%		
Skive	8	2.1%	22,290	4.4%		
Struer	8	2.1%	10,116	2.0%		
Thisted	16	4.2%	20,518	4.1%		
Vesthimmerland	11	2.9%	17,369	3.4%		
Viborg	40	10.4%	44,669	8.8%		
Aalborg	100	26.1%	108,842	21.6%		

Note: Population statistics based on Statistics Denmark's household statistics (FAM55N)