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Avoided Costs of Climate Services

Lake Ice Extent (LIE) Service as an Example

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Abstract:

Lake ice is vital for functioning of the lake ecosystems and provides multiple key ecosystem services to the Arctic societies. Climate change changes lake ice conditions which affects these ecosystems and ecosystem services provided by the lake ice. To assess changes of the lake ice in the Northern hemisphere, a climate service providing information on the lake ice extent (LIE) has been set up. The LIE service generates also other types of benefits to for example sector of hydroelectricity and recreation.

Potential of climate services has not been fully realised by stakeholders and decision-makers. Economic evaluation may support communicating their value especially in times when objectives of public economy are preferred. Moreover, impacts of small climate services can be difficult to perceive, and certain types of benefits can be challenging to observe. These benefits include avoided costs using climate services.

In this thesis avoided costs of the LIE service are estimated both quantitatively and qualitatively using avoided-cost assessment. Used data includes interview results, statistical data, and previous literature. Avoided costs the service generates comprise mainly of avoided in-situ lake ice monitoring trips and travel expenses, avoided flood and infrastructure damages, and potentially avoided injuries and mortality through improved safety. Although quantitatively assessed avoided costs are quite low, level of avoided costs using the LIE service are considerable when quantitatively and qualitatively assessed avoided costs are combined. Moreover, the benefit-cost ratio (BCR) of the avoided costs is reasonable.

Findings underline the importance of understanding benefits of climate services that are difficult to quantify. Understanding these benefits also supports justifying financing of climate services. Nonetheless, results are highly uncertain and prospective assessments are required.

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Tiivistelmä:

Ilmastonmuutos muuttaa järvien jääpeitteen synty- ja sulamisajankohtia, mikä vaikuttaa niin järviekosysteemeihin kuin paikallisten yhteisöjen kannalta tärkeisiin ekosysteemipalveluihin. Järvijääpeitteen laajuudesta tietoa tuottavan ilmastopalvelun avulla pystytään arvioimaan järvijääpeitteen muutoksia. Tämän lisäksi palvelu tuottaa muita hyötyjä muun muassa energiasektorin ja virkistyskäyttäjien tarpeisiin.

Ilmastopalveluiden arvo ei kuitenkaan ole helposti päättäjien ja muiden sidosryhmien tunnistettavissa, ja on arvioitu, että ilmastopalveluiden täysi potentiaali on saavuttamatta. Taloudellisen arvioinnin avulla ilmastopalveluiden hyöty voidaan tehdä näkyvämmäksi, mikä on erityisen tärkeää aikoina, jolloin julkistaloudelliset tavoitteet saavat eniten painoarvoa päätöksenteossa. Jotkin ilmastopalveluiden tarjoamat taloudelliset hyödyt, kuten esimerkiksi niiden avulla vältetyt kustannukset, voivat kuitenkin olla vaikeasti arvioitavia. Varsinkin pienten, paikallisten ilmastopalveluiden avulla vältetyt kustannukset saattavat olla haastavia hahmottaa.

Tutkielmassa arvioidaan järvijääpalvelun avulla vältetyt kustannukset käyttämällä laadullisia ja määrällisiä menetelmiä. Käytetty aineisto sisältää haastatteluiden tuloksia, tilastotietoa ja aiempaa kirjallisuutta. Järvijääpalvelun avulla vältetyt kustannukset ovat pääasiassa vältettyjä matkakustannuksia, vältettyjä tulva- ja infrastruktuurivahinkoja sekä mahdollisesti vältettyjä onnettomuuksia ja ennenaikaisia kuolemia. Palvelun avulla vältetyt kustannukset ovat merkittävät, vaikka määrällisesti arvioidut rahalliset kustannukset jäävätkin vähäisiksi. Palvelun avulla vältettyjen kustannuksien ja palvelun tuotantokustannuksien suhde on kelvollinen.

Tulokset osoittavat, että taloudellisissa arvioinneissa on tärkeää ottaa huomioon sekä suoraan määrällisiksi muuntuvat että vaikeasti määrällisiksi muunnettavat hyödyt, jotta ilmastopalveluiden taloudellisen arvon välittäminen sidosryhmille helpottuu. Tutkimuksen tuloksiin liittyy kuitenkin paljon epävarmuutta, minkä vuoksi tarvitaan jatkotutkimusta.

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1 Introduction

1.1 Lake ice

The climate is warming almost four times faster in the Arctic than in rest of the world (Rantanen et al., 2022). Due to climate change freshwater freeze-up is occurring later and the ice break-off earlier, which shortens the duration of ice cover in water bodies when compared to time of Industrial Revolution (Imrit & Sharma, 2021). As climate change proceeds, it is expected that the duration ice cover periods will continue to shorten (Korhonen, 2019). Lake ice is essential for functioning of lake ecosystems and lake accumulation and melt dates are tied to other physical changes such as lake mixing and thermal stratification (Imrit & Sharma, 2021). Climate change will also increase probability of ice jam floods which makes flood mitigation by the hydroelectric sector and public authorities more challenging (Verta & Triipponen, 2011).

Besides physical impacts, lake ice provides several key ecosystem services to local communities living in the Arctic including recreational services such as ice fishing and skating, cultural services such as spiritual ceremonies (Knoll et al., 2019) and regulating services such as regulating hydrological cycle (Sharma et al., 2019). Solid lake ice also enables the construction of ice roads, i.e. a provisioning ecosystem service (Woolway et al., 2022). Ecosystem services are benefits societies derive from ecosystems, directly or indirectly (Costanza et al., 1997). These ecosystem services are expected to deteriorate due to changing climate (Woolway et al., 2022). On the contrary lake ice can also affect negatively on some ecosystem services. For instance, lake ice can block waterway to summer cottages located on islands.

To evaluate changes caused by climate change on lake ice extent, information on lake ice extent is crucial for both local communities and the scientific community (Malnes et al., 2015). In addition, information on lake ice extent is essential for private sector actors and public authorities. For instance, the hydroelectricity sector needs information on the timing of ice break-off to plan their production in a way that minimises the risk of flooding. (Arctic PASSION, 2024b.) A climate service observing lake ice extent (LIE) has been produced to provide information on the spatial and temporal coverage changes of the lake ice (Heinilä et al., 2021; Heinilä et al., 2022). The LIE service and its impacts are presented more in depth in sections 1.5 and 2.

1.2 Climate services

Not all impacts of climate change are avoidable at this stage, and mitigation measures seen so far may not be adequate to delimit warming to the 2 degrees target set by the Paris Agreement of Climate Change (IPCC, 2023). If humankind is not willing to mitigate climate change or accept the losses from changing climate due inadequate mitigation, action is required to better understand and adapt to upcoming changes (Rogers et al., 2018). A specific building block of climate adaptation investments are the development and use of so-called climate (information) services, more recently also termed as adaptation (information) services (Anderson et al., 2015). In this thesis, I refer to these services as climate services.

A climate service is a customised information product for which climate data has been transformed into a usable format with other relevant data (Larosa & Perrels, 2017). A wide range of different types of climate services and similar services exist (European commission, 2024) including for example oceanographic services, meteorological services, weather services and hydrological services (Freebairn & Zillman, 2002a). The classification of a service depends on which environmental information the service provides and whether it is past or current information, or a prediction (Freebairn & Zillman, 2002a). Definitions of climate services have been proposed by several actors including National Research Council, Climate Services Partnership (CSP), and Joint Programme Initiative (JPI-Climate) (Brasseur & Gallardo, 2016).

A common denominator of all the definitions is the emphasised role of climate service information for decision-making as climate services provide information that can be used to support planning and implementing timely and efficient climate change adaptation and mitigation measures (Brasseur & Gallardo, 2016). Besides support of decision-making, climate services produce both non-market and market-based benefits (Anderson et al., 2015). Non-market benefits and values cannot be traded in a market and vice versa, market-based values can be directly exchanged in markets. However, the value provided by climate services has not been fully recognized nor communicated to the decision-makers and other stakeholders. Consequently, climate services are underused. (Perrels, 2020; Vaughan & Dessai, 2014.)

Climate services have features of public goods; consumption of climate services is often non-rival and non-excludable. Therefore, they are mainly publicly funded. (Freebairn

& Zillman, 2002b.) Often climate services can also be classified as a merit good, which means that without policy interventions such goods are consumed less than the optimal amount as prospective users underestimate the expected (net) benefits (Perrels, 2020). In addition, the information provided by some climate services (e.g. early warning systems) is vital for the functioning of societies, which makes their provision often seen as a responsibility of the government (Freebairn & Zillman, 2002b). Centralised production of climate services offers also scale and scope benefits; when the basic components are built, it is relatively inexpensive to add more services (Hallegatte, 2012). This notion is particularly valid for climate services of which the information content is *predominantly* based on hydrometeorological and climatic data and analysis. The current version of the LIE service that is used as an example in the study can be considered such kind of service.

Climate services offer important information to support planning of climate change adaptation measures which makes investment in them often beneficial and necessary. Public investment decisions to adaptation measures such as climate service production are linked to the prevailing macroeconomic conditions and the interpretation of the sustainability of public debt. (Freebairn & Zillman, 2002b.) Although transition to a climate resilient society is kept high on the priority list by the EU and the amount of public finance is expected to increase in upcoming years to support climate change mitigation and adaptation, it is not certain whether the requirements of finance from governments will be fulfilled due to other objectives related to public debt (Cerniglia, Saraceno & Watt, 2023). The War in Ukraine still ongoing for the third year, return to positive interest rates, slowing economic growth and increased public debts as heritage from the COVID-pandemic have accentuated the importance of public debt sustainability, and the allowable manoeuvring space for public finance deficits has been brought up in public debates (Gerniglia, Saraceno & Watt, 2023).

To ensure the continuity of financing to climate services especially in times where short-term economic gains to revitalise protracted economic stagnation may be preferred over other objectives, meteorological organisations have been required to justify their funding due to budget pressure throughout the years (Perrels et al., 2013; Leviäkangas & Hautala, 2009). This has made economic evaluation of climate services gain interest. From economic evaluation approaches cost-benefit analysis is often used (Anderson et al., 2015). However, some benefits can be difficult to perceive. These include costs that would have occurred in the absence of a climate service, i.e. avoided costs that are accounted as benefits in cost-benefit analysis. (Anderson et al., 2015.) Avoided cost may also work as an indicator of the economic impact of an individual climate service as avoided-cost assessment measures the economic value that could have been used elsewhere (Perrels et al., 2013). Especially impacts of local climate services can be difficult to discern although their aggregate value may be reasonable, not only for climate change adaptation but overall well-being.

1.3 Literature review

Previous literature regarding economic evaluation of climate services utilising avoided-cost assessment and benefit transfer is briefly covered in this section. Economic evaluations of similar services (e.g. meteorological services) are included in the review as well since they do not differ significantly from economic evaluation of climate services. In addition, previous studies regarding the socio-economic impacts of the LIE service are introduced.

Two studies related to the socio-economic impacts of the LIE service have been conducted. Donner (2022) discussed the suitability of different socio-economic assessment methods for the service and argues that a combination of cost-benefit analysis and Value Tree Analysis (Strahlendorff et al., 2019) is the most suitable method for assessing the benefits of earth observation data and services. Dewulf and Mamais (2022) have estimated the economic benefits of TARKKA+ service platform by assessing value chain of the service and estimating avoided costs using the service. Quantified economic benefits range from 6,62 million euros to 24,82 euros annually (Dewulf & Mamais, 2022).

Avoided-cost assessment is widely used in the economic evaluation of climate services and similar services. Leviäkangas and Hautala (2009) contribute to the literature assessing the value of meteorological information by estimating the value that Finnish Meteorological Institute (FMI) provides to the society. They estimate that FMI produces benefits worth 262-285 million euros annually to the analysed sectors with benefit-cost ratio (BCR) between 5:1 and 10:1, and that perfect information increases the benefit up to 100 % (Leviäkangas & Hautala, 2009). Similar study was conducted in Croatia, where Leviäkangas et al. (2007) estimated the benefits of hydrological and meteorological climate services. They applied avoided cost method including literature reviews, statistics, interviews, and workshops as well as analytical and qualitative model building and impact modelling. In comparison, benefits of hydrological and meteorological climate services in Croatia ranges from 27 million euros to 39 million euros per year. Estimated benefit-cost ratio is 1:3. (Leviäkangas et al., 2007.)

Within avoided-cost assessment framework, Frei, von Grünigen and Willemse (2014) have combined qualitative and quantitative approaches when assessing the meteorological information to Swiss road transport as they were able to monetise only two of the benefits. Monetised benefits meteorological information to Swiss road transport is worth 65,7-79,77 Swiss francs with benefit-cost ratio of 1:10 (Frei, von Grünigen & Willemse, 2014). Similarly, von Grünigen et al. (2014) have conducted avoided-cost assessment in aviation in Swiss context to assess the benefits of terminal aerodrome forecasts (TAF). They applied a decision model and estimated that the benefit of TAFs ranges from 13 to 21 million Swiss francs annually (von Grünigen et al., 2014). Information provided by meteorological services is valuable also for the transportation sector in Finland (Leviäkangas & Hautala, 2009). The value of weather information for Finnish road transportation has been estimated using the WSCA method (Perrels et al., 2012). In the study the estimated value of weather information for Finnish road transport with respect to avoidance of accidents was approximately 36 million euros per year (Perrels et al., 2012).

Ebi et al. (2004) have used entirely qualitative avoided-cost assessment when estimating costs and benefits of heat warning systems in the US and estimated that 117 lives were saved using a heat warning system. A similar study by Chiabai et al. (2018) shows that the used valuation scheme for human life influences the results significantly as their cost-benefit ratio ranged from 12:1 to 3700:1. They conducted cost-benefit analysis assessing economic benefit of avoided mortality.

Socio-economic studies of climate services are often conducted for total sectors or countries whereas economic evaluations on individual services are often commissioned by climate service providers or public authorities. For instance, Perrels and Juhanko (2023) have assessed socio-economic benefits of EPS-Sterna polar orbiting satellite constellation for EUMETSAT (The European Organisation for the Exploitation of Meteorological Satellites). Avoided-cost assessment was applied as a part of the evaluation to assess the value of avoided or reduced delays through improved probability of recognising adverse weather in winter in aviation. Approximately 15 million euros would be avoided in Nordic aviation according to the study. (Perrels & Juhanko, 2023.)

Hallegatte (2012) has utilized benefit transfer to estimate the value of hydro-meteorological information and early warning systems in Europe and in developing countries. In the study the estimated avoided cost ranges from 460 million to 2,7 billion euros and produce 3,4 to 34 billion added value per year (Hallegatte, 2012). In addition, it was estimated that several hundred lives are saved each year thanks to early warning systems. Meteorological and hydrological information could prevent 20 % - 60 % from total losses through improved planning, timely adaptation, optimized production with relation hydro-meteorological conditions (Hallegatte, 2012).

Avoided cost assessment combined with estimating the benefit-cost ratio is a common approach to economically evaluate climate services. Typically benefit-cost ratio of climate services is part of the evaluation, and ranges from 3:1 to 10:1. Avoided mortality is often used to assess the value provided by climate services. Often the total value of a climate service for multiple or certain sectors for a country or a region is assessed.

1.4 Aim of the thesis

The thesis aims at estimating avoided costs of a lake ice extent climate service and builds on conceptual work by Donner (2022). Results of the study can be utilised as a part of economic evaluation of the service that will be performed in the Arctic PASSION project.

Research questions I aim to answer are listed below.

1. What are the estimated avoided costs of the LIE service and how do they accumulate?
2. What are the key factors influencing the level of avoided costs?

A climate service providing information on the lake ice cover in Northern hemisphere is utilized as an example. The lake ice extent (LIE) service is a part of the Arctic PASSION project which has been set up to co-create and implement an observation system of the Arctic that will promote for example evidence-based decision-making (Arctic PASSION, 2024a). The service has been in use since 2017 and is provided by

Finnish Environmental Institute. The service is funded by the European Union. (Finnish Environmental Institute, 2024.) The LIE service is a part of a climate service platform called TARKKA+. TARKKA+ is a public service that offers images of water bodies in Finland using Sentinel data (Dewulf & Mamais, 2022). The LIE service can be accessed through Map Viewer of the TARKKA+ service (TARKKA+, 2024).

The second section introduces impacts of the LIE service. In the third section theoretical framework regarding economic evaluation of climate services and CBA are provided. In the fourth section, methodology and data of the study are presented which leads to estimation of avoided costs using the LIE service in the fifth section. In the sixth section, results are discussed. Lastly, conclusions are made.

2 Impacts of the LIE service

Illustration on the information provided by the LIE service is shown in Figures 1a and 1b. The LIE service is unique, it is the first climate service observing the extent of ice cover of lakes in Finland (Arctic PASSION, 2024b). Existing climate services related to lake ice in Finland have mainly focused on the thickness of lake ice (e.g., Vesi.fi, 2024). The service produces one observation per day although weather and amount of light limit the availability, for example, during polar night service does not produce information from areas located north of the polar circle. Furthermore, the spatial resolution of the service is low for small lakes and narrow parts of some lakes. (Heinilä et al., 2021.)

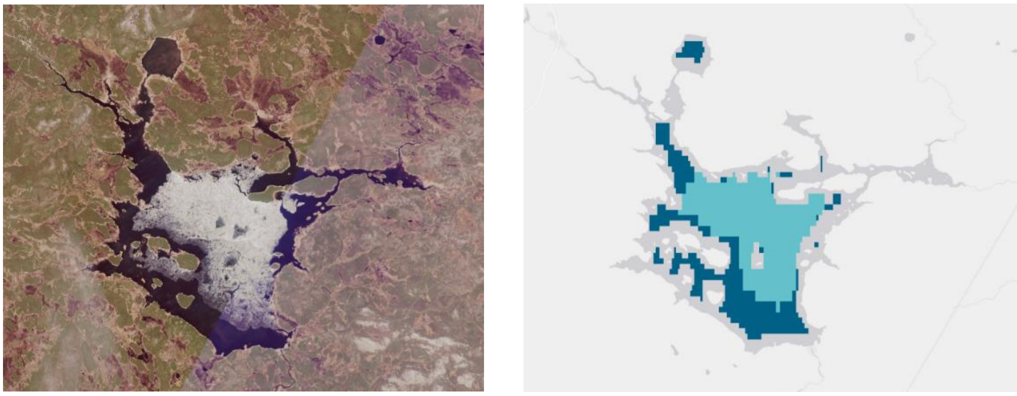


Figure 1a & 1b. Lake ice conditions of Lokan tekojärvi on 21.5.2023 (on the left) and the same presented by the LIE service. On light blue area the lake ice is either partly covered by snow or not covered in snow, the dark blue is open water. Cloud-cover is presented with grey colour (not shown the pictures). (Contains edited Copernicus Sentinel data, Finnish Environmental Institute, 2023/5/21.)

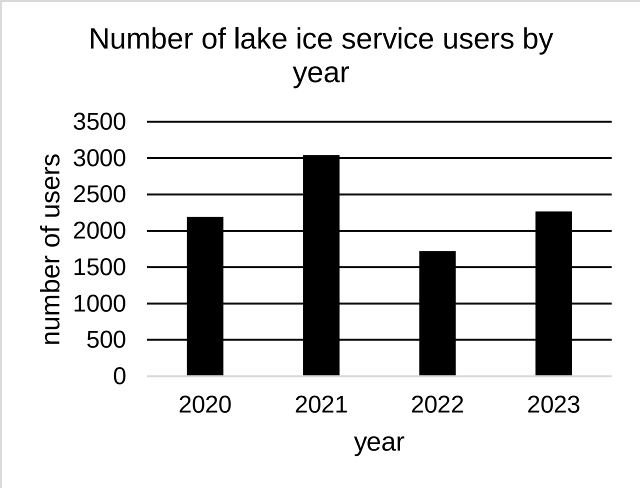
The key objective of the LIE service is to provide information on the changing spatial and temporal coverage of the lake ice to the scientific community (Heinilä et al., 2021; Heinilä et al., 2022). Information is valuable for climate change studies and more specifically e.g. climate modelling and weather forecasts. Moreover, limitations of using in-situ monitoring to evaluate the lake ice extent can be overcome by using satellite data-based sources. (Heinilä et al., 2021.) The LIE service and similar services are also used in recreation, by the hydroelectricity sector and by public authorities of which especially ELY centres utilise the service (Arctic PASSION, 2024b). The hydroelectricity sector and public authorities are referred to as professional users in the thesis.

Hydroelectricity sector uses the service and other sources to get an overview of the lake ice situation, to plan energy production of hydropower plants optimally and to support adaptation to climate change. By optimising the energy production carefully, hydroelectricity sector can avoid damages on infrastructure near the riverside caused by fluctuating water levels. (Donner, 2022.) Both hydroelectricity producers and ELY centres use information of the LIE service and other sources to assess and inform increased flood risk (Arctic PASSION,2024b). Stable water levels also promote accumulation of river ice that is necessary for ice roads (Arctic PASSION,2024b) and are important from the viewpoint of river and lake ecosystems (Hayes et al., 2022). Use of the LIE service and similar services saves a lot of working time in daily basis for both ELY centres and hydroelectricity sector; information provided by the LIE service and other sources reduce the need for in-situ monitoring trips and supports planning of unavoidable monitoring trips (Arctic PASSION, 2024b). For instance, use of drones can be directed more efficiently by using the LIE service and similar services. The LIE service is also used to assess the safety of on-ice routes by the Finnish border guard. (Arctic PASSION, 2024b.)

Related to recreational use, the LIE service is used to support planning of fishing, outdoor activities such as tour skating, walking, and canoeing (Donner, 2022; Arctic PASSION, 2024b). Many users have addressed the need for information on the lake ice cover to assess whether waterway to a cottage is open. If the service shows that ice conditions are not convenient for some recreational activity, the user can decide to cancel the trip, postpone the trip, or to go to another lake. (Arctic PASSION, 2024b.) The LIE service is also used to monitor the ecological balance of the lakes and due to general interest, i.e. “nice-to-know” value. Main targets of development stated by the respondent of the LIE service survey were low spatial resolution, occasionally low temporal resolution, and clearer base map. (Arctic PASSION, 2024b.)

The LIE service is used mainly during ice melting or ice accumulation seasons when 36,4 % of the users use the service once a month or less frequently, 29,5 % daily or almost daily, 22,7 % a couple of times per month and 11,4 % several times a month (Arctic PASSION, 2024b). Data on number of users for 2019-2023 are collected by the Finnish Environmental Institute. Annual number of users is presented in Figure 2. It is assumed that a unique IP-address equals one user.

Figure 2. Number of LIE service users by year (data collected by Finnish Environmental Institute)



Information provided by the service platform of the LIE service, TARKKA may be used to improve the ability of ELY centres to meet their monitoring requirements (i.e., regulatory benefits). TARKKA can also lead to potential benefits to entrepreneurship and innovation, time savings, increased transparency and trust of Finnish Environmental Institute activities and improved information for the academia. (Dewulf & Mamais, 2022.) However, these benefits are based on the entire TARKKA service portfolio, not just the LIE service.

3 Theory

3.1 Economic evaluation of climate services

Several economic evaluation approaches have been established to support choosing the most cost-efficient and beneficial policies that maximise the well-being of a society (e.g. Nurmi, 2019). In the case of public funding and climate services, cost-benefit analysis (CBA) is often used (Volden, 2019). Other economic evaluation approaches include for instance multi-criteria analysis, market uptake study, and cost-effectiveness analysis (Perrels & Juhanko, 2023). In addition, game theory-based models and information theory can be applied to economically evaluate climate services, and macroeconomic modelling can be used to assess macroeconomic impacts of climate services (Pollitt & Mercure, 2018; Bosello, Delpiazzo & Dasgupta, 2018).

The selection of an appropriate approach is determined by availability and resolution of the data, maturity of the climate service, available resources for the evaluation, and adequate valuation methods available to measure and monetise costs and benefits (Anderson et al., 2015; Perrels & Juhanko, 2023). In small economic evaluations the costs of conducting a CBA can exceed the benefits of the evaluated policy. Thus, also expected level of the benefits must be evaluated beforehand. (Boardman et al., 2018.) Applying CBA may require data that are not available. When less data is available, less specific evaluation approach such as economic impact assessment or less specific CBA can be applied (Perrels & Juhanko, 2023). Regardless the chosen economic evaluation approach, evaluation of climate services usually consists of four steps. First, the value chain of climate services needs to be understood. Perrels et al. (2012) have constructed Weather Service Chain Analysis (WSCA) to both support the evaluation process and to help recognise the improvement potential of each part of climate service value chain. After assessing the value chain, benefits (and costs in CBA) are identified, quantified and if needed, monetised. Lastly, uncertainties are addressed. (Bosello, Delpiazzo & Dasgupta, 2018.)

CBA is used to assess whether welfare gains exceed costs that are required to realize some policy and to find the most cost-efficient option among several policy options. In welfare economics, on which CBA is based, the concept of Pareto or allocative efficiency is used as a definition for efficiency. (Boardman et al., 2018.) In a Pareto-efficient state improvements marginal rate of transformation equals marginal rate of substitution, which implies that improvements cannot be made without making some of the actors worse off (Boardman et al., 2018). Due to market distortions, such as asymmetrical information, state of Pareto efficiency is never practically reached. Other focal microeconomic concepts regarding CBA are willingness-to-pay (WTP), willingness-to-accept (WTA) and consumer surplus (Boardman et al., 2018). WTP measures how much consumer is willing to pay for an additional unit of some good, i.e. for an increase in consumer surplus, whereas WTA measures how much consumer is willing to accept as a compensation for a negative change in consumer surplus. Consumer surplus is used to measure change in well-being of the user calculated by subtracting price of a good from the utility. Consumer surplus is presented mathematically in Equation 1. (Boardman et al., 2018.)

Equation 1. Consumer surplus

$$CS = B - P * X^*$$

where CS is consumer surplus, B total benefits and $P * X^*$ consumer's expenditures (Boardman et al., 2018).

To assess social welfare of across policies, net present values (NPV's) of different policy options are compared, i.e. NPV is used as a decision rule. Net present value is obtained by subtracting net costs from net benefits, and when they are positive, it implies that Pareto-efficiency has not been achieved (Boardman et al., 2018). Costs in CBA are mainly opportunity costs that measure the value of outputs that society must give up to implement some policy. Welfare effects are discounted to obtain net present value. (Boardman et al., 2018.) Net present value is calculated as defined by Equation 2,

Equation 2. Net present value

$$NPV = \sum_{t=0}^{N} \frac{B_t - C_t}{(1 + i)^t}$$

where N is the period of which the value is calculated, t is time, B is social benefit, C is social cost and i is social discount rate. Views on appropriate social discount rate differ. (Boardman et al., 2018.) Net benefits and net costs refer to aggregate benefits or costs to all members of the society in public CBA's, i.e. social benefits, and social costs. For abbreviation purposes usually only terms benefit and cost are used. (Boardman et al., 2018.) Sometimes benefit-cost ratio (BCR) is used as a decision rule instead of net benefits. Using BCRs to compare different policy options is prone to manipulation as they do not allow comparison of the actual net benefit. (Boardman et al., 2018.) When assessing the level of net benefits of an individual policy and comparison with other policy options is not made, BCR can be useful. Implementation of CBA in practise is organised in consecutive steps (Boardman et al., 2018). Various guidebooks typically distinguish seven to ten steps.

Three types of CBA have been established depending on the timing of the analysis; before (ex ante) the project, after (ex post) the project or while the project is ongoing (in medias res) (Boardman et al., 2018). In an ex ante -case, if a project or a policy has higher net present value than other options, and the Kaldor-Hicks compensation test applies, it is chosen (e.g. Nurmi, 2019; Wegner & Pascual, 2011). Fulfilment of the Kaldor-Hicks criteria implies that the net present value of the decided policy option cannot be negative (Wegner & Pascual, 2011). Perrels (2020a) has suggested that to ensure the effectiveness of the economic evaluation, ex post evaluations should be conducted systematically in the context of climate services. Ex post valuations are often more practical than ex ante valuations. Decision made based on ex ante evaluation can rarely be changed while ex post analyses provide information on how to do something more efficiently in the future. (Smith & Larimer, 2013.)

To conduct comprehensive CBA, pertinent and accurate estimation of benefits is essential. Meaningful comparison of market-based benefits and non-market benefits requires monetising non-market benefits. Monetisation of non-market values is conducted using non-market valuation methods. (Anderson et al., 2015.) Non-market valuation methods can be divided into two main categories; stated preference methods and revealed preference methods (Boyle et al., 2017). To estimate non-market value of climate services it is often unavoidable to combine several non-market valuation methods (Leviäkangas and Hautala, 2009).

Benefit transfer applies results of previous studies in a new context to estimate benefits and costs of a policy. Individual values and functions both can be transferred. Method is relatively inexpensive and simple to implement which has made it popular. (Boyle et al., 2017.) In non-market valuation of climate services, use of benefit transfer is common. For example, when assessing the benefit of avoided mortality, value of human life is often used in benefit transfer as non-market benefits offered by climate services may be safety improvements that can lead to avoided mortality (Anderson et al., 2015). Monetisation of human life is not to assign value to the human life itself, but to estimate the value of life through decisions people make to decrease the mortality risk, i.e. WTP to avoid mortality (Boardman et al., 2018). In addition, lost production, hospital care cost, administration cost and material damage cost are included in the value of human life (Leviäkangas et al., 2007). Several estimations for the value of human life exist including for instance Copenhagen Consensus value for human life and statistical value of life (VSL). Estimations differ by country considering differences in safety norms and range from 1,8 million to 5,4 million 2005-USD (2,5-7,6 million 2024-€) (OECD, 2012.)

The value of climate services is determined by actions of its user (Anderson et al., 2015; Hallegatte, 2012). While information climate services provide may decrease uncertainty related to some action or decision, the user decides whether she is going to alter one's actions based on the information. Namely, in economic evaluation of climate services the outcome with less uncertainty is compared with outcome with more uncertainty. (Bosello, Delpiazzo & Dasgupta, 2018.) Climate services are most beneficial when produced to meet the needs of the user, i.e. their production is demand-driven (Findlater et al., 2021). The value of meteorological information is also determined by the quality, accuracy, and timeliness of the information (Frei, von Grünigen and Willemse, 2014). Besides the information content of the service, successful climate services must be supported by research, include information with different spatial and temporal scales, require active management, and have participation by academia, government, businesses, and civil society (Brasseur & Gallardo, 2016). Usually, the value of climate services grows when climate data are combined or are combinable with non-climate data (Anderson et al., 2015).

Better information does not automatically translate into more informed decisions (Rogers et al., 2018; Findlater et al., 2021). For instance, impact of weather information on behaviour regarding leisure activities varies by day. Other factors including habit persistence and space-time constraints may have higher impact on the decision regarding recreation than weather. (Liu et al., 2020.) The impact of information about external circumstances on decision-making has been studied widely in the field of information science (e.g. Adams, 1973; De Freitas, 2015; Liu, Susilo, & Ahmad Termida, 2020). Whether information is used in decision-making depends heavily on the field. On fields where the information has notable direct economic benefits, adoption rates of information into decisions are often high (Roudier et al., 2014). Roudier et al. (2014) found that in the field of agriculture 75 % of the cases they surveyed, climate information led to behavioural change.

3.2 Avoided-cost assessment

The value or an improvement of a climate service can be assessed by estimating avoided costs using the service (Anderson et al., 2015; Perrels & Juhanko, 2023). Avoided costs are costs for preventing environmental deterioration with an alternative consumption or production process (OECD, 2008). Avoided costs can be estimated in both ex ante or ex post analyses and measure both non-market and market-based benefits using a climate service, so avoided costs can include also avoided non-market losses. Non-market avoided costs can be for instance avoided illnesses and avoided mortality. (Anderson et al., 2015.)

Approach is only suitable when the costs would actually occur in absence of the service and can be sector-specific or benchmark-based. In sector-specific avoided-cost assessment economic outcome with improvement in a climate service is compared to outcome without the improvement in a certain sector. (Anderson et al., 2015.) Benchmark approach assesses how economic losses of previous events would have been reduced by improved climate services. Estimation of avoided costs using both benchmarking and sector-specific approaches often relies on expert opinion which may induce biases. (Anderson et al., 2015.)

3.3 Challenges of economic evaluation of climate services

It may be difficult to distinguish benefits and impacts of an individual climate service as the user might use several climate services to decide whether to, for instance, take adaptation measures or not (Anderson et al., 2015). In addition, benefits obtained through personal adaptation for weather and climate are often excluded from economic evaluations due to complexity and uncertainty of their estimation. Personal benefit using climate service information can be deciding whether one should take an umbrella when going outside. (Hallegatte, 2012.) When it comes to costs, separating cost of one individual climate service may also be challenging. Several actors can use the same basic components making allocation of costs to individual climate service difficult, and several observation systems can be utilised in one climate service.

(Anderson et al., 2015.) Temporal aspects of benefits and costs of climate services can further complicate the economic evaluation. Materialization of a climate service benefits often takes longer when compared to the costs (Perrels, 2020). In CBA this complicates the selection of discount rate (Anderson et al., 2015).

When evaluating climate services, Tall et al. (2018) point out that it is necessary to distinguish the differences between outputs, outcomes, and impacts to appropriately evaluate climate services. Output in the case of climate services can be for instance number of people seeing a weather forecast while outcomes are behavioural changes that occur after receiving the information provided by the forecast. Impacts on the other hand are changes that take place after the behavioural change. (Tall et al., 2018.) Difficulty to assess the influence and value of a climate service use increases when shifting from measuring outputs to impacts. In addition, knowing outputs and outcomes is often necessary to measure the impacts. (Tall et al., 2018.)

Most often criticism regarding CBA considers technical issues; issue of standing (whose benefits and costs are taken into consideration), picking the right discount rate (what are the preferences of future generations), distributional issues and uncertainties (e.g. Nurmi, 2019; Boradman et al., 2018). In the case of climate services, especially choosing the discount rate can be challenging (Anderson et al., 2015) and addressing income induced distributional issues. Income effect refers to asymmetrical preferences' due differences in income. (Nurmi, 2019.) In the case of climate services avoided costs method may in some cases have income induced biases as costs that are avoided in the wealthier neighbourhoods during a natural hazard tend to be higher than elsewhere (Mandle et al., 2021).

Different methods to overcome these weaknesses have been attempted. For example, applying time-decreasing discount factor may lead to more accurate results (Nestico & Maselli, 2020) and weighing benefits across agents depending on their preferences may help reduce biases caused by the income effect (Nurmi & Ahtiainen, 2018). Comparison of ex ante and ex post assessment could also increase accuracy of a CBA (Boardman et al., 2018). To add, functioning of CBA in general has been questioned by some academics. For instance, Flyvbjerg & Bester (2021) argue that costs are systematically underestimated, and benefits overestimated in CBA. It has also been suggested that results of CBA's are not actually used in the decision-making process, or their influence on the decisions is insignificant (Bardal, 2020).

4 Data and methodology

Avoided costs using the LIE service are estimated quantitively or qualitatively depending on the type of the avoided cost. Some of the avoided costs could not be quantified due to uncertainties, lack of data or time restrictions. First, benefits of the service are mapped out by user group. Avoided costs are then located and estimated using valuation methods summarised in Table 1. Qualitative analysis methods include an interview and content analysis on existing literature and available data. Lastly, avoided costs are compared to the production costs of the service to calculate BCR of the LIE service to assess its net impact. Although the LIE service provides information for the whole Northern hemisphere, only impacts in Finland are assessed in the study.

4.1 Data

Available data comprises of interview results, user survey results, web traffic tool data on number of users, and previous literature as presented in Table 1.

Table 1. Available data and valuation method by user group or a sector

User group is specified in the brackets.

Sector, user group	Available data	Valuation method
Recreation (consumer)	survey results, statistics, previous literature, data on number of users	avoided travel expenses, benefit transfer, qualitative
Hydroelectricity (producers)	survey results, interview, statistics, previous literature	avoided travel expenses, benefit transfer, qualitative
Research and education	survey results, interview, previous literature	qualitative
Public authorities		
ELY centre	survey results, statistics, previous literature	avoided travel expenses, benefit transfer, qualitative
Finnish border guard	survey results, previous literature	qualitative, benefit transfer

Results of five interviews in total were utilised: one with the representative of ELY centre, three with the hydroelectricity sector representative and one with sea ice researcher. Interview with the representative of ELY centre and two interviews with the hydroelectricity sector representative were done previously in the project by other interviewers for the unpublished economic evaluation of the LIE service. Conducted interviews were semi-constructed. In previously conducted interviews interviewees were asked for what purposes they need lake ice extent information, how do they use the information, what other sources they use, how often these sources are used and what are the benefits of using the sources.

These interviews were complemented with a follow-up interview with the hydroelectricity sector representative and additional questions sent via email to both the representative of ELY centre and the hydroelectricity sector to obtain information that is essential for avoided cost calculating including one-way distances to in-situ monitoring sites, number of in situ-monitoring trips and working hours that in-situ monitoring trips take. Interview questions are in Appendix 1. Although sea ice and lake ice have different features, sea ice researcher was interviewed to gain understanding on the role of lake ice extent information on safety.

A survey targeted for users of the LIE service has been conducted in the Arctic PASSION project and its results will be used in the economic evaluation of the LIE service that is conducted in the project. Results of the service are used also in the thesis. Survey was located on the web page of the service and the responses of the survey have been anonymised. The survey was conducted in early 2023 and is funded by the Arctic PASSION project. Survey has 44 responses, and its questions regarded uses of the service, how frequent and beneficial the use is, and what kind of impact it has had on decision-making regarding for instance recreation. Respondents were also given an opportunity to address any targets for development.

Annual administration costs of the LIE service are approximately 30 000-40 000 € and have been asked directly from the service developers (Arctic PASSION, 2024b). If development costs would be accounted for, annual attributable costs are higher. Annual administration and development costs combined are 88 000-108 000 € per year. Service platform TARKKA+ has been under development almost constantly after its establishment. (Arctic PASSION, 2024b.)

4.2 Avoided-cost assessment

In the thesis, non-market valuation techniques are applied within the avoided-cost assessment. Travel expense formula adopted from the travel cost method and benefit transfer for cost of using a car per kilometre and value of human life are utilised. Travel cost method falls into category of revealed preference methods where observed behaviour is used to assign value to a non-market good (Boyle et al., 2017).

Quantifiable avoided costs resulting from using LIE service are mainly avoided is-situ monitoring costs and travel expenses. Information on the cost of one avoided trip for both professional and recreational users is required to calculate the total travel costs avoided. To estimate cost of one trip, techniques used in travel cost method are applied. Cost of an avoided trip is estimated by summing all the expenses used for the trip including the actual travel costs, equipment costs and cost of time. (Boyle et al., 2017). Avoided travel expenses were calculated using Equation 3 presented by Boyle et al. (2017):

Equation 3. Travel expenses

$$p_n = \left\{(0{,}33 * \left(\frac{y_n}{1553}\right) * t_n) + (c_n * d_n)\right\},$$

in which p_n is the cost of an avoided trip, y_n is the annual income of the user, t_n is the round-trip travel time to the lake, c_n is the cost of travel per kilometre, and d_n is the distance to the lake. Annual income is divided by the average annual working hours in Finland 2023 to obtain hourly wage (Official Statistics of Finland, 2024b). In estimation of value of time it is estimated that it is related to one's wage with the assumption that it is feasible to switch between working time and leisure flexibly. Multiplying the value of time by 0,33 is often used as a measure of value for recreational time. (Boyle et al., 2017.) In calculation of avoided trip expenses of professional users, value of time is multiplied by one instead of 0,33 to account for the total hourly wage.

In travel cost analysis, the trip expenses are calculated for each individual and include often other information such as other costs (Boyle at al., 2017). For simplification purposes, cost of avoided trip is extrapolated for all users based on averages provided by Official Statistics Finland (2019; 2024a) and Trafi (2019). These averages include median salary (Official Statistics Finland, 2024a) and in the case of recreation, average distance to a summer cottage (Official Statistics Finland, 2019). Average of cost of using a car per kilometre is calculated by Trafi (2019).

Cost of an individual trip is multiplied by the number of trips avoided. In the case of professional users, the number of avoided trips and lengths of the trips were directly asked in an interview with the hydroelectricity sector representative and via email from the representative of ELY centre which made avoided in-situ monitoring cost estimation straightforward. Hypothetical total avoided costs were estimated by aggregating the avoided costs of the interviewed hydroelectricity company and ELY-centre for all hydroelectricity companies and other ELY centres. In Finland, there are 15 ELY centres and 220 hydro power plants in total (ELY centre, 2024; Energiateollisuus, 2024). It is assumed that each of these actors must do same number of in-situ monitoring trips to water bodies nearby without the information provided by the LIE service. As these number may vary between professional users, impact of the number of avoided trips is assessed in sensitivity analysis.

When it comes to recreation, estimation of benefits in the form of avoided travel expenses is highly intricate due to complexities of human behaviour. It is not feasible to calculate avoided costs by using the LIE service in recreation accurately. More data on the actual behaviour is required to get reliable and valid results. However, the survey results indicate that the LIE service does affect decision-making in recreation. Level of avoided costs if every user was to avoid one trip per year is estimated based on the share of users that use the service for recreational activities. 62 % of the LIE service users are “general” users (Donner, 2022). It is assumed that “general” user refers to recreational user, which means that the service has approximately 887 recreational users on average annually. It is assumed that cost of avoided trip consists of trip to the site and back. Impact of the number of avoided trips on the avoided travel expenses is analysed in the sensitivity analysis.

4.3 Impact of an individual source of information

Users of the LIE service utilise also other sources to monitor the lake ice meaning that the avoided costs do not fully stem from using the LIE service. In addition, different information sources are used to complement each other. Distinguishing avoided costs using the LIE service is attempted in the analysis by multiplying avoided costs by the contribution of an individual information source. As more precise information on the marginal contribution of each source is lacking it is assumed that each source has an equal weight in the contribution to benefit creation and that the sources cannot be used to complement each other. Estimation is presented in Equation 4.

Equation 4. Contribution of an individual source to avoided costs

$$impact\ of\ an\ individual\ source = \frac{1}{n_{other\ sources}}$$

At most, six other sources are used by the hydroelectricity sector and two other sources are used by ELY centres. Hence, avoided costs of hydroelectricity sector are multiplied by 0,16 and by 0,5 in the case of ELY centres.

It is more difficult to assess the impact of other sources in decisions related to recreation. With two sources the impact for recreational users is 0,50 which means that the user seeks information from one other source in addition to the LIE service. This other service may be a weather forecast, other satellite data provider or activity specific source such as a map of skiing routes combined with in-situ observations of other skiers. The number of other sources of information used by the Finnish border guard and other public authorities is unknown. As they are professional users, it is assumed that they utilise average number of information sources used by other professional users meaning that the potential avoided costs of safety improvements are multiplied by 0,22. Uncertainty related to the significance of the LIE service is addressed in the sensitivity analysis.

4.4 Benefit-cost ratio

To assess the net impacts of LIE service, the attributable production costs of the service are compared to the benefits, in this case being avoided costs, i.e. the benefit-cost ratio (BCR) is calculated. BCR is calculated using Equation 5,

Equation 5. Benefit-cost ratio

$$BCR = \frac{benefits}{costs}$$

where $benefits$ refer to the sum of monetised and quantified benefits of the service per year and $costs$ are production costs of the service. Normally BCR is calculated for the whole lifetime of a policy by discounting its future benefits and costs. However, due to uncertainty of the lifecycle of the service, annual BCR is estimated.

5 Results

5.1 Benefits of the LIE service

Benefits of the lake ice (Table 2) are summarised and grouped into non-market and market-based benefits based on impacts presented in section 2. Benefits are based on who generates the benefit.

Table 2. Benefits of the LIE service

User group is specified in the brackets.

Sector, user group	Benefit	
	non-market	market-based
Recreation (consumer)	time savings, “nice-to-know” value	avoided travel expenses to the lake
Research and education	improved information for the academia, benefits for the students	possible increase in productivity through innovation or similar, time savings
Hydroelectricity (producer)	time savings, potentially avoided environmental losses, information to support flood risk assessment	optimized production, avoided in-situ monitoring costs, avoided flood costs, avoided infrastructure damage
Public authorities		
ELY centres	time savings, information to support flood risk assessment, regulatory benefits	avoided in-situ monitoring costs, avoided flood costs
Finnish border guard and other public authorities	improved safety, potentially avoided injuries and mortality	improved route planning, avoided productivity losses from avoided injuries and mortality

5.2 Avoided costs

The LIE service produces several benefits in the form of avoided costs. Interview with the hydroelectricity sector representative showed that the LIE service and other sources are used to plan the production of the hydropower plants in a way that promotes accumulation of river and lake ice in the autumn and decreases the risk of flooding in the spring. This may lead to avoided infrastructure costs. Previously conducted interviews and follow-up emails showed that the LIE service and other sources are also used to assess the flood risk by ELY centres and hydroelectricity sector which also may lead to avoided flood damages. (Arctic PASSION, 2024b.) Without information on lake ice extent, number of in-situ monitoring trips would be higher and their targeting more challenging which produces benefit in the form of avoided trip expenses (Arctic PASSION, 2024b). Results of the survey conducted in the Arctic PASSION project indicate that information on lake ice extent may lead to avoided travel expenses and avoided reduction in leisure time in recreation and potentially avoided mortality and injuries through safety improvements provided by the service (Arctic PASSION, 2024b).

5.2.1 Avoided travel expenses

Quantifiable avoided costs are mainly avoided trip expenses and presented in Table 3. The total avoided costs and the adjusted avoided cost based on the number of other sources are both presented.

Table 3. Avoided costs using the LIE service

User group is specified in the brackets.

Sector, user group	Avoided costs per year	
	total	adjusted based on number of other information sources
Recreation (consumer)	71 000 €	36 000 €
Energy sector (producer)	317 000 €	53 000 €
ELY centres	20 000 €	10 000 €
Total	408 000 €	99 000 €

For the professional users, one-way distances of in-situ monitoring trips range from 20 km to 110 km and often take several hours if not the whole day since monitored sites are often located in places that are difficult to access. By using the LIE service and other sources, 1652 in-situ monitoring trips were avoided by the professional users in total per year when it is assumed that every ELY centre and hydropower plant in Finland use the service. On average, avoided cost of an avoided in-situ monitoring trip is 204 €. In total, 338 000 € worth of in-situ monitoring trips were avoided. Avoided costs using the LIE service by the professional users are 63 000 € when it is assumed that the impact of the LIE service is 0,16 in decisions of hydroelectricity sector and 0,5 in decisions of the ELY centre. As the LIE service and similar services support the planning and targeting of unavoidable in-situ monitoring trips, avoided costs are likely higher.

For recreational users, estimated avoided travel expense per trip is 80 €. When every recreational user avoids one trip per year using the service, avoided travel expenses in recreation are 71 000 € on average annually (Table 4). When it is assumed that the impact of the lake ice service in decision in recreation is 0,5, avoided costs are 36 000 € per year on average. Avoided recreational trips due to unsuitable lake ice conditions is also avoided reduction in leisure time. Avoided costs in recreation are estimated separately in Table 4 for each year. The level of estimated avoided travel expenses has varied throughout the analysis period. At highest avoided travel expenses in recreation were in 2021.

Table 4. Assumed level of avoided travel expenses in recreation

Year	Travel expenses avoided in recreation if every user avoids one trip annually	
	total	adjusted based on assumed number of information sources
2020	109 000 €	55 000 €
2021	152 000 €	76 000 €
2022	86 000 €	43 000 €
2023	113 000 €	56 000 €
Total	460 000 €	230 000 €

5.2.2 Qualitative assessment

Qualitatively assessed avoided costs of the LIE service include avoided flood damages, avoided infrastructure damages, and potentially avoided environmental losses, injuries and mortality. In addition, since satellite data-based information on lake ice is better that information of in-situ monitoring to assess lake ice extent (Heinilä et al., 2021), using the LIE service may produce avoided costs also in the field of research.

The LIE service is likely to contribute to avoided flood and infrastructure losses since ELY centres and the hydroelectricity sector use the service to assess and communicate the increased flood risk (Arctic PASSION, 2024b). Level of avoided flood damage can be significant as flood damage induces costs range from 7 000 € to 50 000 € per building in Finland (Michelsson & Saari, 2009), and there are 25 000 buildings located in flood risk areas in Finland (Finnish Environmental Institute, 2021). The LIE service can provide information for early warning systems on increased flood risk which supports timing and planning direct actions that can be taken to mitigate the flood damages (Verta & Triipponen, 2011). However, as it is not feasible to show credibly how much the LIE service contributes avoiding flood and infrastructure losses as several other factors affect the realized damage as well, these avoided costs are not quantified. Other factors affecting the damage include e.g. location, other flood mitigation measures such as raised power sockets (Poussin et al., 2015).

Careful planning of the hydroelectric production supported by the LIE service and other sources may allow for avoided environmental losses which also enhance recreation in the river. This is because the hydroelectricity sector monitors the lake ice situation not only to optimise the production, but also to ensure that the water level in the river does not pulsate (Arctic PASSION, 2024b), causing harm to ecosystems and ecosystem services of the river. However, the impact is uncertain and if hydropower plants use the service to optimise their production without considering the impacts the optimisation has on environment and recreation possibilities near the hydropower plant, the benefit of the LIE service for the hydropower plant might be a net cost to society. Especially during summertime hydropeaking does affect negatively recreational ecosystem services (Virk et al., 2024). Negative impact on recreational ecosystem services may also decrease the housing and cottage prices in the riverside (Klizentyte et al., 2024).

The information provided by the LIE service on timings of lake ice accumulation and break-up is essential for the field of research and can be utilised in for instance climate modelling and forecasts (Heinilä et al., 2021). Satellite-based data on lake ice extent is better than data from in-situ monitoring trips as it has higher spatial and temporal resolution (Heinilä et al., 2021), which may also lead to avoided costs stemming from time savings in data acquisition. In addition, information from the service helps to better understand and identify new user needs, which - in turn - are important when planning potential targets for development. Developing the service benefits its users and increases the total value of the service as developments can lead to increased time savings and more informed recreational decisions which can transform also into economic effects. At present the LIE service produces time savings through avoided in-situ monitoring trips (Arctic PASSION, 2024b).

The LIE service provides potential safety benefits. For instance, survey conducted in the Arctic PASSION project showed that Finnish border guard uses the service to assess the safety of routes that are located on ice (Arctic PASSION, 2024b). If information of the LIE service leads to avoided injuries or saved lives, both non-market and market-based benefits are significantly higher than estimated. The value potential of an expected number of one saved life per year would increase the total benefits by 1,8 million to 5,4 million 2005-USD (2,5-7,6 million 2024-€) depending on the applicable value of statistical life (VSL) (OECD, 2012). Next to the concept of VSL, measures related to remaining lifetime productivity are used as avoided cost value indicator. In the UK, the average productivity loss of an accident-based mortality is estimated at 555 660 1997-GBP (1 043 900 2024-€). (OECD, 2012.) When it is assumed that number of information sources used by Finnish border guard is the average of information sources of other professional users, productivity loss and VSL are multiplied by 0,22. Then, avoided productivity loss due one avoided mortality is approximately 122 250 1998-GBP (230 000 2024-€) and VSL 0,4-1,2 million 2005-USD (0,6-1,7 2024-€).

Contrastingly, an interviewee from the field of sea ice research argued that the service does not provide safety improvements as extent of the lake ice cover is not the most important indicator of safety, nor are the spatial and temporal resolution of the service high enough. For instance, the service can rarely show ice conditions of the shore and cannot provide information on cloudy days or when it is dark. For assessing safety of lake ice, indicators to look for are thickness and consistency of the ice instead of extent of the lake ice cover. Nevertheless, assessing consecutive lake ice observation may provide indicative information on the firmness of the ice (Arctic PASSION, 2024).

5.3 Benefit-cost ratio

Benefit-cost ratio (BCR) is calculated for the quantified avoided costs. In an active production stage, BCR is 3:1 and when the service is not under development, BCR is 11:1. If direct economic impacts are added to the calculation, BCR is considerably higher. Same applies if using the service contributes to avoided mortality. For example, if the service contributes avoiding one mortality and loss in production is added to estimation of BCR, it ranges between 13:1 and 46:1 depending on the production cost. On the other hand, when it is assumed that the impact of the LIE service is 0,16 for the hydroelectricity sector and 0,5 for ELY centres and recreation, BCR ranges between 1:1 and 3:1.

5.4 Sensitivity analysis

Sensitivity analysis is conducted to address the main uncertainties of the quantified avoided costs. Uncertainties regarding recreation (Table 5) and professional users (Table 6) are assessed separately. Apart from the analysis on the impact of other information sources on the results, sensitivity analysis is conducted for total avoided costs (see Equation 4).

Table 5. Sensitivity analysis of annual avoided travel expenses in recreation

	Number of users		Number of avoided trips per user		Significance of the LIE service in relation to other sources	
change	- 25 %	+ 25 %	0,5	2	- 25 %	+ 25 %
avoided costs	53 000 €	90 000 €	36 000 €	143 000 €	18 000 €	53 000 €

Main uncertainties in recreation regard the behaviour of the users. Especially the number of avoided trips is challenging to estimate. If half of the users avoid travel expenses of one recreational trip per year, avoided travel expenses would be 36 000€ in total whereas if every user avoids two trip expenses per year, avoided travel expenses in recreation would be 143 000 €. Number of recreational users is also uncertain as it is assumed that “general” user equals recreational user. If the assumption of one avoided trip per user is kept constant and number of users was to increase by 25 %, avoided travel expenses would be 90 000 € and vice versa, if number of users decrease by 25 %, costs would be 53 000 €. Impact of other sources on the level of quantified avoided costs is also highly uncertain. If the impact is 25 % lower than assumed (0,5), avoided costs in travel expenses in recreation would be 18 000 € per year, and if the impact is 25 % higher than assumed, avoided travel expenses are 53 000 €.

Table 6. Sensitivity analysis of avoided annual in-situ monitoring costs of professional users

	Number of hydroelectric companies using the service		Number of avoided in-situ monitor trips		Significance of the LIE service in relation to other sources	
change	- 25 %	- 50 %	- 25 %	+ 25 %	- 25 %	+ 25 %
avoided cost	238 000 €	159 000 €	262 000 €	413 000 €	47 000 €	79 000 €

While the interview with ELY centre representative showed that every ELY centre uses the service, it is uncertain whether all hydropower plants utilise the service. If 25 % less hydroelectric companies use the LIE service, avoided in-situ monitoring expenses would be 238 000 €, and if half of the hydroelectric companies use the service, the expenses would be 159 000 €. As it is assumed in the analysis that every hydroelectric company utilises the LIE service, increase in the number of hydroelectric companies is not assessed. Number of avoided in-situ monitoring trips seems to affect the results considerably. If number of avoided trips was to decrease by 25 %, avoided in-situ monitoring trips would be 262 000 €, and if the number would increase by 25 %, total avoided in-situ monitoring costs would be 413 000 €. Impact of other sources was assessed as well. When impact of other sources is 25 % lower, avoided in-situ monitoring expenses in professional use are 47 000 € and vice versa, when impact is 25 % higher, they are 79 000 €.

6 Discussion

6.1 Avoided costs

Besides the benefits the LIE service provides to the scientific community, various actors benefit from using the LIE service in the form of avoided costs. Several types of avoided costs were identified, some of which hold significant value. The properly quantifiable avoided costs of the LIE service are quite low. This is likely because only avoided travel expenses were quantified and the service has a limited user group and uses, and due to targets for development addressed by the users although targets of development have been addressed by the developers actively. Especially low temporal and spatial resolutions of the services are likely to limit its use outside academia. For instance, true colour images provided in the TARKKA + service platform give spatially more accurate information when compared to the information of satellite pictures (see Figure 1a). However, even if the service met the needs of its users flawlessly, the wider economic impact would remain low since not everyone needs information on lake ice extent. Number of users is key indicator on the level of avoided costs as showed also by sensitivity analysis. Alongside with number of users, actions of the users are highly important on the level of avoided costs. This has been shown also in previous literature (e.g. Anderson et al., 2015).

When qualitatively assessed avoided costs are considered, avoided costs increase notably. For instance, contribution of the LIE service to only one saved life would increase the level of both non-market and market-based avoided costs dramatically. Importance of avoided lives in economic estimation has been also observed in earlier studies (e.g. Hallegatte, 2012). Due to uncertainty regarding the safety improvements, avoided productivity loss is not included in estimation of quantified avoided costs. It is often better to demonstrate benefits qualitatively instead of conducting an uncertain quantitative analysis (Perrels & Juhanko, 2023). Avoided infrastructure damages due to flood damages or fluctuating water levels can also be considerable. In the future, more advanced methods could be applied to assess quantified avoided infrastructure damages and safety improvements using the LIE service.

Estimated BCR of the LIE service is satisfactory, at least after active development stage when production of the LIE service is relatively inexpensive. When impact of other information sources is considered as well, estimated BCR does not convince. However, only quantified avoided costs are included in the estimation and BCR is likely higher. Furthermore, if benefits other than avoided costs are added to the comparison, BCR is significantly higher. For instance, use of the LIE service and other sources in optimisation of hydroelectricity production creates notable economic gains ranging from couple of million euros to dozens of million euros for only one hydroelectric company (Arctic PASSION, 2024b). Aggregate monetary value obtained through lake ice observation and similar for all hydropower plants may hence be around 440 million to 4,4 billion euros. Besides direct economic impacts for the hydroelectricity, the LIE service generates also non-market impacts that are not avoided costs. For instance, time spent using the LIE service may have recreational value in itself as a small share of lake ice survey respondents stated that the reason for using the service is "general interest". Same was mentioned by the interviewee from the ice sea research, who said that the service can offer information that is "nice-to-know". As these benefits are not avoided costs, they are not investigated more in the thesis. Moreover, time spent in the service is quite short meaning that the benefits are likely minor (Arctic PASSION, 2024b).

Environmental gains using the service are most likely not significant when benefits for the academia are not considered. This is because although the LIE service may be used to plan the hydroelectric production in a way that influences the environment as little as possible, hydropower plant itself affects the environment negatively (Martínez-Gracia, 2020; Lähteenmäki et al., 2023). Hydropower plants can negatively affect provisioning and supporting ecosystem services of the river (Martínez-Gracia, 2020) and delay the migration of fish (Lähteenmäki et al., 2023). Moreover, monetisation of environmental values of the LIE services must be done with caution since while embedding welfare into market-based values allows for comprehensiveness, it cannot register all the dimensions of human life that affect well-being (Fleurbay, 2015). Namely, market-based measures such as income or wealth cannot capture the value of environment and ecosystems and other non-market values. As concluded by Fleaurbay (2015) "if life consisted only of market-related activities, one could imagine that income and wealth would appear as reasonable measures of advantage". Decision-makers should be made aware of limitations and conceptual foundations of CBA and non-market valuation techniques to achieve informed decision-making (Boardman et al., 2018; Nyborg, 2014).

6.2 Investment in climate services

As said, the wider economic impact of the LIE service is likely low. Nonetheless, absence of public funding of the LIE service would enable some savings in the short run. When counting in potential safety effects, higher – also tangible – costs are feasible in the longer run. As case studies often provide generalizable information (Flyvbjerg, 2006), results of the study could be used to assess aggregate value of similar services which again could be utilised to demonstrate the value to decision-makers and support justifying their financing. Aggregate value of small and local climate services could also be examined by applying macroeconomic modelling. Macroeconomic modelling is not conceivable for an individual climate service due to limited economic impact (Bosello, Delpiazzo & Dasgupta, 2018). Thus, the linkage between use of several small-scale climate service and wider economic perspective could be assessed by aggregating the benefits of several local climate services. Here other benefits and impacts than avoided costs should be taken into consideration as well. Moreover, avoided costs are highly context and location dependent which limits the validity of the results.

6.3 Adoption of the service

The number of users affects the level of avoided costs. Number of users has not increased significantly since its establishment. However, the service is quite new; it was first introduced in 2021. The full benefit of the service may not have materialized yet as also pointed out by Dewulf and Mamais (2022) in an assessment of socio-economic impact of the TARKKA service. As the service is developed further and the users learn the most efficient and beneficial way of using the service, avoided costs generated by climate services are likely to increase (Perrels, 2020). The LIE service may also have uses that have not yet been recognized and users that have not yet found the service. For instance, could the agricultural sector benefit using the service?

Targeted marketing to people who need lake ice extent information in recreation (e.g. canoeists and fishermen) could promote wider adoption of the service. For instance, if even half of the over 5000 Finnish trek skaters (Suomen retkiluistelijat, 2024) are reached, avoided costs may increase. Results showed that at least some trek skaters use the service at present. Furthermore, Dewulf and Mamais (2022) note that use of satellite data is in its early stage in Finland and as the level of its use increases, so do benefits. They estimate that benefits of using satellite data in Finland will grow considerably in the next five to ten years. Dewulf and Mamais (2022) suggested that evaluation of satellite data should be carried out in five years at earliest. Although the thesis focuses only on the avoided costs of the LIE service, it marks the halfway point of the timeline they set up and may advance prospective evaluations. Results will also be utilised in economic evaluation of the LIE service that is performed in the Arctic PASSION project.

6.4 Uncertainties and limitations

While behaviour of the user is the most important factor in economic evaluation of climate services, it is also the main source of uncertainties. Especially the number of users who have avoided travel costs by using the service are difficult to estimate. It may be that the estimated number of avoided trips is either nearly not as high, or higher than estimated. Since the time period of lake and river ice accumulation and break-off is quite short, only a couple of months in the spring and in the autumn, number of avoided trips may be lower. On the other hand, as third of the survey respondents stated that they use the service almost every day, the number of avoided trips can also be higher. Both alternatives are addressed in sensitivity analysis which shows that especially number of avoided trips per user affects the results significantly. Further evaluation is required to assess the accurate number of avoided travel expenses.

Cooperation with other fields of research such as information behaviour could benefit the analysis as economic framework is limited in addressing the complexity of human behaviour as also argued by Flyvbjerg and Bester (2021). In microeconomic theory on which CBA is based on, it is assumed that people are rational and aim to maximise their welfare through consumption. Rationality in the context of microeconomic theory means that people are able to rank their preferences, are aware of other sets of alternatives and choose an alternative that is the most favourable for them. (Osborne & Rubinstein, 2020.) Nevertheless, estimating the value of the information provided by climate services may indicate the importance of the information on decision-making which again may help recognise the benefits that are most likely to influence one's behaviour.

Besides the complexity to assess influence of information on human behaviour, using several climate services complicates the analysis. Multiple information sources are used and they are used to complement each other (Arctic PASSION, 2024b). Therefore, avoided costs that occur due to the decision may not have been achieved by using just one of the services. Also, the significance of the sources is most likely not distributed evenly between information sources albeit it is assumed in the analysis. Namely, it is likely that some sources are relied on more than others. This is most likely the case in the LIE service as the interviewee from sea ice research and survey respondents pointed out that the spatial resolution may not suffice. In addition, the information that the service produces is not available when it is cloudy or dark, or when size of a lake is small (Heinilä et al., 2021). Contribution of the LIE service to avoided costs was assessed through sensitivity analysis which showed that it significantly affects the level of avoided costs.

Assumptions used in estimation of quantified avoided costs increase uncertainty of the results. Exact lengths of the leisure trips to the lake are not known nor is the number of people going to the lake and their exact annual incomes and working hours. Share of recreational users is also uncertain due to various reasons. For example, several users may be behind the same IP-address. (Donner, 2022.) Same applies to assumptions on average trip length to summer cottage, median salary, and cost of using a car per kilometre. Assumption that cost of recreational avoided trip consists of trip to the site and back may also cause biases as plans can be changed after one finds that recreational activity is not plausible due to the lake ice conditions. It is also uncertain whether every hydroelectricity company use the service and that every ELY centre and hydroelectric company do the same number of in-situ monitoring trips. Factors such as geographical location is likely to influence the need for in-situ monitoring. Exclusion of avoided drone costs may also cause uncertainties. Impact of drone use to avoided costs was excluded from the analysis as drone use cannot be fully avoided, and their costs are for the most part fixed.

As a limitation of the study, the small sample size reduces the external validity of the results. It is not feasible to draw credible conclusions to cover all the professional users based on the sample size of one ELY centre and one hydroelectric company. Same applies in recreation, larger sample size would have been beneficial. In addition, interviews from Finnish border guard and emergency services would have benefitted the analysis and reduced the uncertainty related to the safety improvement of the service. Due to time restrictions, this was not done in the thesis.

7 Conclusions

Planning of efficient and timely climate change adaptation measures requires high quality data in both global and local scales. As climate change affects the Arctic regions the most (Rantanen et al., 2022), information provided by climate services in the Arctic may prove to be valuable. However, increasing budget pressure may affect the attractiveness of investment in climate services (e.g. Leviäkangas & Hautala, 2009). Communicating the economic impacts of climate services to decision-makers may promote their uptake as it may be challenging to discern the economic effects using a climate service. Especially avoided costs can be difficult to observe, which could also be seen in the study. Connection between information provided by climate services, actions of the users and economic outcome of the actions is highly difficult to assess.

Quantified avoided costs using the LIE service are not significant from the wider economic perspective as the service is quite local and niche; lake ice information does not benefit everyone. Nevertheless, only avoided travel expenses are included in the quantified estimation of avoided costs. When qualitatively assessed avoided costs are considered, value of the service increases. This underlines the importance of including values that are difficult to quantify into economic evaluation. As policy makers often prefer quantified values (Nurmi, 2019), efforts to quantify and monetise all values are required. In the case of the LIE service, especially understanding the contribution of the service on avoided flood losses, infrastructure damage and mortalities is needed.

Results are highly uncertain. Most uncertain factors affecting avoided costs regard recreation and safety improvements. Especially uncertainty of safety improvements is necessary to address as change in estimated level of safety improvements influence the results considerably. In the future these uncertainties could be assessed more thoroughly. Uncertainty related to the number of avoided trips could be investigated with cooperation with scientists from the field of information behaviour and ex post assessment on the avoided costs of the LIE service should be carried out to both address the uncertainties and to ensure the functionality of the economic assessment (Perrels, 2020a).

Addressing uncertainties of the avoided cost estimation may support materialisation of total benefit potential of the LIE service. Other than economic evaluation measures are also required to materialise the full potential of the service. Potential user groups should be made aware of the LIE service and shown how to best utilise it. Targets of development are also important to address to ensure that the service meets the needs of its users. However, in the case of the LIE service targets of development have been considered and improvements have been made based on feedback of the users (Arctic PASSION, 2024b). Other measures that could be taken to promote uptake of the LIE service include assessing their impact on wider economic landscape by aggregating their value. Results could be used to support justifying investment in climate services.

While understanding all impacts of the LIE service is necessary to justify its financing, importance of its value for research should be emphasised. Timeframe for climate change adaptation measures is short, and some of the potential impacts are irreversible and unknown. Better information on the lake ice extent may help understand expected changes of the warming climate on a local scale. Furthermore, relevance of information provided by the LIE service may increase in the future as climate change proceeds.

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Appendices

Interview questions

ELY-centre

Discussion (via email) was built on previous interview.

- In which ways does the LIE service save working time?
- How much working time in-situ monitoring takes annually, and how extensively in-situ monitoring is done (km)?
- Can you estimate the need for in-situ monitoring trips without information on lake ice conditions?

Energy sector

Discussions were built on previous interview.

Via email.

- Can you estimate the need for in-situ monitoring trips without information on lake ice conditions?
- What is the need for in-situ monitoring despite information provided by the LIE service and similar services?
- How extensively ice conditions are monitored? What are the distances to the sites that are being monitored (km)?

In an online meeting. Previous interview was looked through briefly.

- Has the use of the service changed since last interview? Do you have anything to add?
- How many people are required in in-situ monitoring trips?
- How much do you use drone in these in-situ monitoring trips? What is the annual cost of drones?

Sea ice researcher

- What are the most important indicators to look for when assessing the safety of lake ice?
- How important is extent of lake ice cover on safety?
- How does information on lake ice influence actions of people utilising the ice?
- Do you know other users that need information on the extent of lake ice?