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Research article

Costs and benefits of automated high-frequency environmental monitoring – The case of lake water management

Isabel Seifert-Dähnn [a,*], Ingvild Skumlien Furuseth [a], Godwin Kofi Vondolia [a], Gideon Gal [b], Elvira de Eyto [c], Eleanor Jennings [d], Don Pierson [e]

[a] *Norwegian Institute for Water Research, Gaustadalleén 21, 0349, Oslo, Norway*
[b] *The Yigal Allon Kinneret Limnological Laboratory, Israel Oceanographic & Limnological Research, PO Box 447, Migdal, Israel*
[c] *Marine Institute, Furnace, Newport, Co, Mayo, F28PF65, Ireland*
[d] *Centre for Freshwater and Environmental Studies, Dundalk Institute of Technology, Ireland*
[e] *Limnology Department, Institute of Ecology and Genetics, Uppsala University, Norbyvägen 18 D, 752 36, Uppsala, Sweden*

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ABSTRACT

Freshwater lakes are dynamic ecosystems and provide multiple ecosystem services to humans. Sudden changes in lake environmental conditions such as cyanobacterial blooms can negatively impact lake usage. Automated high-frequency monitoring (AHFM) systems allow the detection of short-lived extreme and unpredictable events and enable lake managers to take mitigation actions earlier than if basing decisions on conventional monitoring programmes. In this study a cost-benefit approach was used to compare the costs of implementing and running an AHFM system with its potential benefits for three case study lakes. It was shown that AHFM can help avoid human health impacts, lost recreation opportunities, and revenue losses for livestock, aquaculture and agriculture as well as reputational damages for drinking water treatment. Our results showed that the largest benefits of AHFM can be expected in prevention of human health impacts and reputational damages. The potential benefits of AHFM, however, do not always outweigh installation and operation costs. While for Lake Kinneret (Israel) over a 10-year period, the depreciated total benefits are higher than the depreciated total costs, this is not the case for Lough Gara (Ireland). For Lake Mälaren in Sweden it would depend on the configuration of the AHFM system, as well as on how the benefits are calculated. In general, the higher the frequency and severity of changes in lake environmental conditions associated with detrimental consequences for humans and the higher the number of lake users, the more likely it is that the application of an AHFM system is financially viable.

1. Introduction

Freshwater lakes are important providers of ecosystem services including drinking water and irrigation, flood attenuation, nutrient and carbon cycling, recreational services such as fishing, swimming, and boating, and also cultural and amenity services (Reynaud and Lanzanova, 2017; Schallenberg et al., 2013; Steinman et al., 2017). At the same time, lakes are exposed to multiple combined stressors derived from the exploitation of these services and from external forces such as climate change, pollution and habitat destruction (Gozlan et al., 2019; Ormerod et al., 2010). Thus, alterations in the biophysical and chemical conditions of the lake, termed here as lake environmental conditions (LEC), will have potential ecological, societal and socio-economic effects.

While some changes in LEC happen frequently and are part of the normal functioning of the ecosystem (such as daily or seasonal changes in temperature profile), there are also changes which happen suddenly or are unexpected. These include cyanobacterial blooms, occurrence of hypoxia and anoxia, episodic inputs of dissolved organic matter (DOM) and increases in turbidity (de Eyto et al., 2016; Jennings et al., 2012). How and if these alterations impact human lake usage and ecosystem service exploitation depend on whether they are detected at all, how early they are detected, and if there are possibilities to react i.e. to mitigate or avoid impacts. In addition, some LECs may not impact the whole lake, rather one isolated area. To make reasonable management decisions, monitoring data in sufficient temporal and spatial resolution to detect changes in LEC are necessary (Meinson et al., 2016).

Typically, the type of water use determines monitoring requirements

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* Corresponding author.
E-mail address: Isabel.seifert@niva.no (I. Seifert-Dähnn).

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and intervals. National regulations specify which physio-chemical and biological variables must be monitored, and when and at which interval the monitoring should occur. For example, monitoring requirements for European water bodies used for bathing are defined in Annex IV of the EU Bathing Water Directive from 2006 (EU Bathing Water Directive, 2006). Sampling is required before the bathing season and then at least 4 times throughout the season with intervals not exceeding a month. In case of short-term pollution, additional samples are required to confirm a return to baseline conditions. Similarly, operational monitoring for the Water Framework Directive (EU Water Framewok Directive, 2000) is required at time intervals of one month up to 3 years.

Even though there is no doubt about the usefulness of conventional monitoring programs, short-lived, extreme and unpredictable events with a temporal scale shorter than the sampling frequency of a traditional monitoring program can frequently go undetected (Marce et al., 2016). Automatic high-frequency monitoring (AHFM) with temporal resolution ranging down to the sub-minute level (Meinson et al., 2016) can help to overcome this problem (Rode et al., 2016). In the last decade profiling buoys equipped with high-frequency sensors have been increasingly deployed in limnology to document temporal and vertical lake dynamics (Brentrup et al., 2016). Currently high-frequency monitoring is not a requirement in most water monitoring, but the revision of the Drinking Water Directive recommends online monitoring for waterworks producing more than 10.000 m^3/day (EU Drinking Water Directive Annexes 1-6, 2018).

High-frequency monitoring can improve the response of drinking-water treatment plants to changes in raw water quality (Ruberg et al., 2008). AHFM can help provide a more realistic picture of nutrient loadings and sources in comparison to spot samples (van Geer et al., 2016). Furthermore, high-frequency monitoring can be used to optimize the management of recreational activities for lakes that are prone to harmful algal blooms (Tran Khac et al., 2018). If the monitoring system is automated, additional cost-savings in comparison to manual sampling can be expected (McBride and Rose, 2018; Trevathan and Johnstone, 2018). Despite its potential usefulness in water management, it is often difficult for water managers to decide if an implementation of an AHFM system is cost-effective. Will the benefit or value of having data at higher temporal (and eventually spatial) resolution outweigh the investment and maintenance costs? In this article, we adopt a cost-benefit approach to assess the costs for implementing, running and maintaining AHFM systems deployed in freshwater lakes on profiling buoys. At three case study lakes we compare the costs to potential benefits that can arise by having additional and more timely information. To our knowledge this is the first quantitative analysis of the costs and benefits of deploying AHFM in lake management.

2. Description of methods and case study lakes

2.1. Conceptual framework

Sudden changes in LEC often challenge lake users and water managers as they require fast execution of mitigation measures to avoid negative consequences. The point of departure of our conceptual framework (Fig. 1) is, that mitigation actions can be carried out earlier due to the availability of new information (in case of changes in LEC which remain undetected by conventional monitoring) or information that becomes available earlier when AHFM is deployed. The first step is to assess the contribution that the additional information gained by using AHFM makes to improved decision making. Secondly, the welfare gain (benefit) associated with the improved decision making is assessed (Bouma et al., 2009). In the third step the welfare gain of the additional information is compared to the costs needed to obtain this information. When the welfare gain is larger than the costs, then it is financially viable to establish the AHFM system.

2.2. Cost assessment of AHFM

For the assessment of costs associated with the implementation and operation of AHFM equipment it is necessary to define which kind of changes in LEC are relevant to monitor and what kind of sensors have to be used. Marcé et al. (2016) provide a good overview of what sensors are deployed in AHFM and what changes in LEC can be monitored with them. For our analysis we took as point of departure that AHFM was not yet implemented in our case study lakes. The introduction of AHFM equipment is in reality often a gradual shift i.e. more and more sensors are mounted over time. Some variables, for which the sensor technology for AHFM is fully developed (see Table 1 in Marcé et al., 2016), can be measured continuously, while at the same time other variables have to be monitored in parallel by manual sampling.

Cost estimates for equipment were compiled with help of expert judgement as well as data available through the NETLAKE Cost Action (Laas et al., 2016). In addition to the investment costs we also take into account costs for deploying the system as well as yearly maintenance costs. For Sweden this includes the removal and winter-storage of the AHFM system, and its redeployment in spring after the ice has gone. All costs are given in USD for the year 2018. It should be noted that the cost estimates present average values. Many suppliers offer price estimates only upon request (Trevathan and Johnstone, 2018). A detailed list of the cost-data can be found in the supplementary data 1. The lifetime of an AHFM system and its components depends on the quality of its components as well as on its exposure to storms or other harsh conditions. For Irish conditions, it was estimated that after three years the

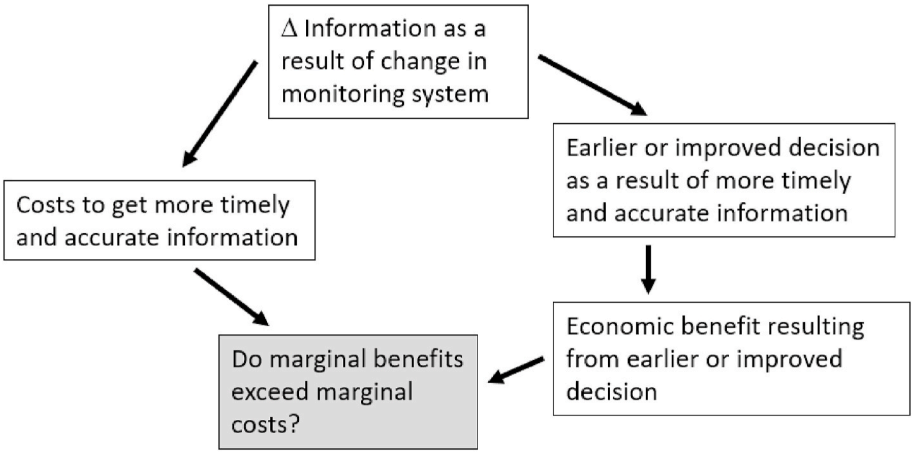

Fig. 1. Conceptual framework to assess the economic benefit of information (adapted after Bouma et al. (2009)).

complete AHFM system has to be overhauled. In Sweden this time span was considered to be on average 3–5 years. In Israel the currently installed system has already been running for 9 years with some sensor replacements, and every fifth year a dry docking of the deployed raft to undertake some metal and painting maintenance.

Based on this information we assumed the following streams of investment:

- Ireland: Initial investment, overhauling every 3rd year with 50% of initial investment sum
- Israel: Initial investment, overhauling every 5th year with 10% of initial investment
- Sweden: Initial investment, overhauling every 4th year in winter with 50% of initial investment

For all case-study lakes the depreciated costs, which converts all future costs into present terms, were calculated by summarizing all costs accruing over a period of 10 years with a discount rate of 4%. This discount rate was chosen as it represents an average social discount rate for Sweden and Ireland as estimated by Florio and Sirtori (2013) and falls also in the range of social discount rates presented by Kazlauskienė (2015) and discount rates for health evaluation studies by Attema et al. (2018).

2.3. Benefit assessment of AHFM

2.3.1. Assessing the economic benefit of AHFM

In comparison with conventional monitoring, often done weekly, monthly or even more seldom, AHFM operates in sub-daily time intervals. Thus, it allows the detection of changes in LEC, which would remain undetected by using conventional monitoring intervals. It also allows the detection of these changes earlier than with conventional monitoring. So, the main benefit of AHFM is an information gain or an information and time gain i.e. lake water managers can react earlier if the information of changes in LEC is earlier available. To assess the benefits of derived by AHFM in monetary terms, we assume that negative consequences of changes in LEC are either completely avoided (e.g. reputational damage/decreased trust) or that knowing earlier about a change in LEC would trigger earlier responses by the water managers. Thus, one of the most significant benefits of AHFM is the avoidance of damages. It can be calculated for each type of change in LEC as shown in Equation (1). For a more detailed description of the variables in the equation, we refer to the supplementary data 2.

$$Benefit\ of\ AHFM\ (change\ in\ LEC) = Sum\ (\ r * s * i * t * Avoided\ damages * p) \tag{1}$$

with.

- *r* refers to the reliability of the AHFM system to detect changes in LEC.
- *s* refers to the spatial coverage of the AHFM system to detect changes in LEC.
- *i* refers to the number of incidences per year of a certain change in LEC.
- *t* is the average time (here given as number of days) during which damage would occur when no AHFM is in place.
- *Avoided damages* refer to damages that would occur when no AHFM is in place. There might be several different avoided damages linked to one type of change in LEC (see column 2 in Table 1).
- *p* refers to the number of people affected by potential damages

The total benefit of AHFM is then the sum of all the individual benefits. Benefits were depreciated using the same time period and discount rate as for the costs. To compare benefits with costs the benefit-cost ration (BCR) was calculated by Equation (2). If the BCR is larger than 1, i.e. benefits are larger than costs, then a project is considered financially viable from an economic point of view.

Table 1
Affected water uses and damages (in bold) triggered by changes in LEC and potential mitigation actions.

Sudden changes in LEC	Affected water uses and triggered damages	Potential mitigation actions
High non-algal DOM episode	Drinking water for human consumption → non-fulfilment of treatment targets → **human health impact, reputational damage/ decreased trust**	Additional treatment or temporary use of another drinking water source
Non-harmful algal bloom	Recreation (with and without water contact) → disgust, aesthetic misperception → **lost recreation** opportunity	Inform lake users about the conditions of the lake, prohibit or limit lake use
	Drinking water for human consumption → non-fulfilment of treatment targets → **human health impact, reputational damage/ decreased trust**	Additional treatment or temporary use of another drinking water source
Harmful algal bloom	Recreation with water contact → **human health impact** → **lost recreation** opportunity	Inform lake users about the conditions of the lake, prohibit or limit lake use
	Recreation without water contact → disgust, aesthetic misperception → **lost recreation** opportunity	Inform lake users about the conditions of the lake, prohibit or limit lake use
	Drinking water for animals → **dead or damaged wild animals, cattle and pets**	Prevent animals from drinking the water i.e. by setting up fences
	Drinking water for human consumption → non-fulfilment of treatment targets → **human health impact, reputational damage/ decreased trust**	Additional treatment or temporary use of alternative drinking water source
	Commercial fishing and aquaculture & recreational angling → fish dying → **lost revenue, lost recreation opportunity** → bioaccumulation → lowered product quality → **lost revenue,** human **health impact**	Only limited mitigation actions possible at fish-farm level (eventually moving the cages), precautionary advice against food consumption
	Agriculture irrigation → bioaccumulation in food → **lost revenue**	Additional treatment (washing, cooking) before consumption (for low concentrations of cyanotoxins)
Shift from stratified to mixed lake conditions	Drinking water for human consumption → increased risk for microbial contamination of water → **human health** impact	Changes in drinking-water treatment, increased monitoring intervals

$$Benefit - cost\ ratio = \frac{Discounted\ total\ benefits}{Discounted\ total\ costs} \tag{2}$$

2.3.2. Assessment of avoided damages

As depicted in Table 1, there are at least six categories of damages triggered by changes in LEC, which can be potentially avoided by AHFM due to the earlier detection and execution of mitigation actions: human health impacts; lost recreation opportunity; dead or damaged wild animals, cattle and pets; reputational damage; and lost revenue from commercial fishing, aquaculture and agriculture. Detailed information about the data used and assumptions made for the assessment of avoided damages for each damage category can be found in the supplementary data 1 and 2.

To quantify the avoided costs due to those damages, it is necessary to define indicators which represent them (Table 2, second column). Information about damage costs were obtained from previous studies (Table 2, last column). Preference was given to reviews or meta-studies summarizing avoided damage costs from several countries or studies. To take into account the heterogeneity of values in time and space, we normalized the data by using national GDP deflator indices (adjustment over time), national income per capita (adjustment between study and policy site) and purchasing power parity (currency conversion) as described by Brander (2013). National GDP deflator indices and income per capita are available from the World Bank[1] while purchasing power parity (PPP) is available from the OECD[2]. Income elasticity for willingness to pay for environmental goods usually lies between 0.1 and 0.6 (Baumgärtner et al., 2016). For this study it was chosen to be 0.5. For non-sparkling bottled water we used an income elasticity of 0.051 (Zheng et al., 2015) as we consider the markets in our case study countries to be similar to the US. Health costs in different countries were adjusted using income per capita (European Commission, 2018). All damage costs were converted to 2018-USD. As we could not find reliable data for the health impacts after long-term sub-acute exposure, impact on wild animals, livestock and pets as well as the lost revenue from commercial fishing, aquaculture and agriculture, we had to omit them in our assessment.

Table 2
Indicators for avoided damage costs due to changes in LEC.

Impact/Damage category	Indicators for avoided damage costs	Data sources
Human health impact – acute exposure	Societal costs of being ill (medical treatment & lost productivity) due to - Acute exposure to harmful algal blooms (HAB) - Bacteriological infections	European Commission (2018) Kouakou and Poder (2019) Bacteriological infections are not assessed.
Human health impact – long-term sub-acute exposure	Societal costs of being ill (medical treatment & lost productivity) due to - Incomplete removal of cyanotoxins - Formation of disinfection by-products during periods of elevated DOM levels	Not assessed as there is still insufficient evidence on the effect of long-term sub-acute exposure.
Recreation opportunity (in and on the lake & along the lake shore)	Value of ecosystem services - value of swimming - value of recreational fishing - value of recreation without water contact (boating, sightseeing, other non- specified recreation)	Reynaud and Lanzanova (2017)
Dead or damaged wild animals, livestock and pets	Lost revenue due to dead livestock	Not assessed, due to lack of information.
Lost revenue from commercial fishing, aquaculture and agriculture	Lost revenue of products: - aquaculture products - agricultural products	Not assessed, due to lack of information.
Reputational damage/loss of confidence/ decreased trust in tap water	Increased spending for bottled water (during period of reduced trust in drinking water supplier)	European Commission (2018) Morris et al. (2016)

For the assessment of acute exposure to cyanotoxins, we adopted the approach of Kouakou and Poder (2019) and assumed a mild (scenario 1) and a more severe (scenario 2) exposure scenario. For the reputational damage category, we distinguished based on historic observations also two scenarios: one covering a short-term sharp increase in bottled water consumption (scenario A) and the other longer lasting, but with a less pronounced increase (scenario B). A detailed explanation of these scenarios can be found in supplementary data 2.

2.4. *Description of case-study lakes*

For this study we selected three lakes in three countries, which differ in size, their hydro-morphological conditions, the changes in LEC they experience as well as in their number of lake users and in their lake usage (Table 3). The aim was to find contrasting examples of lakes where lake managers had expressed an interest to apply AHFM or AHFM is already applied. More details about the case-study lakes can be found in the supplementary material 1 and 2.

3. Results and discussion

3.1. *Cost of deploying AHFM in lakes*

The installation of an AHFM requires some basic equipment encompassing the platform or buoy itself, but also a power supply, data loggers and weather protection for the equipment. A meteorological station may be needed, when there is no other station close by. A profiling winch system is optional but facilitates measurements at

Table 3
Characteristics of the case-study lakes. NR = not relevant.

	Lough Gara (Ireland)	Lake Kinneret (Israel)	Lake Mälaren (Sweden)
Lake surface area	11.96 km^2	169 km^2	1140 km^2
Average depth	shallow	25.6 m	12.8 m
Lake geometry	3 main basins	one main basin	several basins and bays
Water residence time	18 days in summer	>7 years	2.8 years on average, but large variations between the basins
Mixing regime	polymictic	monomictic	dimictic
Changes in LEC			
• HABs	✓	✓	✓
• Not harmful algal blooms	✓	✓	✓
• High non-algae DOM episodes	✓	NR	✓
• Hypoxia and Anoxia	NR	✓	NR
• High nutrient events	✓	NR	✓
Yearly number of lake visitors	4490	2 500 000	1700 000
Lake usage			
• Drinking water provision	✓	✓	✓
• Irrigation water abstraction	NR	✓	✓
• Commercial fishing	NR	✓	✓
• Bathing/ Swimming	✓	✓	✓
• Recreational angling	✓	✓	✓
• Recreation without water-contact	✓	✓	✓

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[1] https://databank.worldbank.org/source/world-development-indicators.

[2] https://data.oecd.org/conversion/purchasing-power-parities-ppp.htm.

different depths, which enables better monitoring of depth-dependent processes and water quality threats such as buoyant cyanobacteria which often have an unequal vertical distribution. The most economical AHFM system using a self-constructed buoy, without meteorological station or winch system and with the cheapest sensors deployed, but capable of detecting lake mixing, non-harmful and harmful algal blooms, high non-algae DOM episodes, high nutrient events and hypoxia costs about 15 kUSD. An expensive version with similar but expensive sensors would be 51 kUSD. If in addition a meteorological station is needed and a profiling winch system installed, the costs will amount to 41 kUSD for the cheap version and 109 kUSD for the expensive version, respectively.

For our case studies we asked experts to provide estimates of the costs of their existing AHFM system or a system which might be deployed at the case study sites. For each lake the system was assumed equipped with a meteorological station, sensors for basic monitoring, and sensors needed to observe the changes in LEC, which are prevalent in each lake. At Lake Mälaren (Sweden), a system capable of monitoring lake mixing, algal blooms, harmful algal blooms, high non-algae DOM episodes and the consequences of high nutrient events at different depths would be required. A buoy with a profiling winch enabling measurements at different depths would satisfy these requirements. Lough Gara (Ireland) would need the same sensors, but due to its shallow depth no profiling winch would be needed. In Lake Kinneret (Israel) the monitoring of high non-algal DOM episodes and high nutrient events is not necessary, but a profiling winch would be needed.

The initial investment costs for the AHFM system for Lake Gara are much lower than for the other lakes as a winch-system is not needed (Table 4). Overhauling the system every 3rd year, however, increases the costs, so that the depreciated costs for Lough Gara are higher than for the system required for Lake Kinneret in Israel. The most expensive is the system required for Lake Mälaren. Even though the initial investment is the highest single payment in the cash flow series, the required maintenance and overhauling costs dominate the cost-picture for Lough Gara and Lake Mälaren over a 10-year period. These costs are lower for Lake Kinneret due to less harsh environmental conditions in winter, but they still comprise more than 50% of the total costs of the expensive version of the AHFM system. Not considered in our cost-assessment is the time needed for sensor calibration, regular scheduled visits to check if the equipment is working properly as well as unscheduled visits to resolve eventual problems. These costs vary from site-to-site and year-to-year and will increase the depreciated costs further.

Table 4

Cost-estimates for deployment of one AHFM unit on a buoy in the three case-study lakes. Initial investment costs and depreciated total costs are given for a cheap AHFM system version as well as an expensive version. The depreciated costs are calculated for a period of 10 years at a discount rate of 4%. All costs are in 2018-USD.

Cost-types	System components	Approx. Costs
Lough Gara (Ireland)		
Initial investment with deployment	Fixed depth system with multiprobe sondes on a raft	17–54 kUSD
General annual maintenance		5 kUSD
50% Re-investment each 3rd year		8–27 kUSD
Depreciated total costs		84–166 kUSD
Lake Kinneret (Israel)		
Initial investment with deployment	Profiling system with sensor package and meteorological station on a raft	36–104 kUSD
General annual maintenance		5 kUSD
10% Re-investment each 5th year	Dry docking, metals and painting works	4–11 kUSD
Depreciated total costs		86–164 kUSD
Lake Mälaren (Sweden)		
Initial investment with deployment	Profiling system with multiprobe sondes on a raft	42–110 kUSD
General annual maintenance		6 kUSD
Winter-storage and re-deployment		1 kUSD
50% Re-investment each 4th year		21–55 kUSD
Depreciated total costs		140–262 kUSD

The selection of cheap instead of expensive sensors can reduce the depreciated cost by close to 50%. As sensor technology improves and standard sensors become cheaper in the future, we can expect that the initial investment costs as well as costs for sensors replacement will drop, but probably not the costs involving manual work. When considering the deployment of AHFM, it would be reasonable to compare the manual work required for AHFM with manual work necessary for conventional monitoring routines. This was not assessed in this study. For simplification we considered in our study the deployment of only one AHFM unit in each lake. Complex lake geometries with several basins and lake users spread over several locations can require more than one AHFM unit to assure appropriate monitoring of all sites of interest. This means that the costs would increase accordingly and make AHFM less or not economically profitable.

3.2. *Benefits of AHFM in lakes*

Based on the environmental conditions of each lake and the number of lake users, the benefit of AHFM was calculated for each case study lake (Table 5). Avoided damages due to mild HAB exposure (scenario 1), loss of recreation opportunities, and the short-lived decreased trust in drinking-water treatment (scenario A) were summarized to a “low” yearly avoided-damages estimate, while HAB exposure to scum (scenario 2), loss of recreation opportunities and the long-lasting decreased trust in drinking-water treatment (scenario B) were aggregated to a “high” yearly avoided-damages estimate. For both sums the depreciated benefits were calculated.

For all cases the losses in recreation opportunities was much lower than the other avoided damages. Societal costs of illness related to exposure to HAB scums were the highest avoided-damage costs in all lakes, followed by the long-term decrease in trust in drinking-water treatment. Lake Kinneret showed the highest avoided damages of all lakes. This is due to the high number of lake visitors and that there are on average two events of toxic cyanobacteria bloom each year. Lake Kinneret also showed the largest avoided-damage costs from decreased trust in drinking-water treatment even though the number of people supplied with drinking water is higher for Lake Mälaren, than for lake Kinneret. This is because the current per capita consumption of bottled water in Israel is already much higher than in Sweden and Ireland, so small increases of 5 and 10%, respectively, result in large amounts of additionally consumed bottled water.

3.3. *Comparison of costs and benefits of AHFM in lakes*

To compare depreciated costs and depreciated benefits of an AHFM system in each lake, four benefit-cost ratios were calculated (Table 6). The low benefit estimate was divided by the cost for an expensive AHFM system (low/expensive) and a cheap AHFM system (low/cheap), and the high benefit estimate was divided by the costs for an expensive system (high/expensive) and a cheap system (high/cheap). The high benefit estimates for Lake Kinneret and Lake Mälaren showed positive benefit-cost ratios, and the benefits already outweighed the costs from the first year. For Lake Kinneret in the most optimistic case i.e. low costs for the AHFM system, but high potential benefits, the benefits outweighed the costs by a factor of 162 (Table 6). While for Lake Mälaren under the low benefit scenarios the benefits will never exceed the low or the high

Table 5

Avoided-damage costs due to deployment of AHFM in the three case-study lakes. The depreciated benefit is calculated for a period of 10 years at a discount rate of 4%. All avoided damage costs are in 2018-USD.

Category of avoided damage	Avoided-damage costs
Lough Gara (Ireland)	
Health damage HAB mild exposure (scenario 1)	35 USD per year
Health damage HAB, exposure to scum (scenario 2)	3600 USD per year
Loss of recreation opportunity – bathing	3 USD per year
Loss of recreation opportunity – recreational angling	0.04 USD per year
Short-lived decreased trust in drinking-water treatment (scenario A)	55 USD per year
Long-lasting decreased trust in drinking-water treatment (scenario A)	673 USD per year
Sum of yearly avoided damages (low estimate)	93 USD per year
Sum of yearly avoided damages (high estimate)	4277 USD per year
Depreciated benefit, low estimate	1 kUSD
Depreciated benefit, high estimate	39 kUSD
Lake Kinneret (Israel)	
Health damage HAB mild exposure (scenario 1)	13 384 USD per year
Health damage HAB, exposure to scum (scenario 2)	1 391 268 USD per year
Loss of recreation opportunity – bathing	398 USD per year
Loss of recreation opportunity – recreational angling	9 USD per year
Short-lived decreased trust in drinking-water treatment (scenario A)	11 508 USD per year
Long-lasting decreased trust in drinking-water treatment (scenario A)	140 009 USD per year
Sum of yearly avoided damages (low estimate)	25 298 USD per year
Sum of yearly avoided damages (high estimate)	1 531 684 USD per year
Depreciated benefit, low estimate	230 kUSD
Depreciated benefit, high estimate	13 955 kUSD
Lake Mälaren (Sweden)	
Health damage HAB mild exposure (scenario 1)	1790 USD per year
Health damage HAB, exposure to scum (scenario 2)	186 031 USD per year
Loss of recreation opportunity – bathing	40 USD per year
Loss of recreation opportunity – recreational angling	1,5 USD per year
Short-lived decreased trust in drinking-water treatment (scenario A)	4447 USD per year
Long-lasting decreased trust in drinking-water treatment (scenario A)	54 106 USD per year
Sum of yearly avoided damages (low estimate)	6278 USD per year
Sum of yearly avoided damages (high estimate)	240 178 USD per year
Depreciated benefit, low estimate	57 kUSD
Depreciated benefit, high estimate	2188 kUSD

cost estimates, at Lake Kinneret the break-even point considering the cheap cost estimate would already be reached after one year (Fig. 2). After four years Lake Kinneret would also reach break-even for the expensive cost estimate. For Lough Gara the benefits never outweigh the costs from a pure economic point of view.

As we were not able to quantify all the previously identified damage resulting from changes in LEC (see Table 2), the benefits of AHFM might be larger than the estimates presented here. Health costs of bacteriological infections, long-term health effects of exposure to lower doses of cyanotoxins and disinfection by-products, lost revenues from fisheries, aquaculture and agricultural products as well as environmental costs of bottled water were not considered in this assessment. Further, the assumptions made on the number of lake users can be regarded as rather conservative estimates, especially for Lake Mälaren. On the other hand, we have to acknowledge that other assumptions we made, especially on damage costs are uncertain. They are based on a limited number of studies, often from other countries than those where our case-study lakes are located.

Not included in our assessment of benefits are intangible values like the value of AHFM-data for research. It increases our understanding of sub-daily dynamics in lake ecosystems to inform better lake management. Other intangible benefits might be case-specific. For Israel, for example, the water transfer from Lake Kinneret to the Kingdom of Jordan has political significance and the ability to inform the neighbouring state about any changes in water quality might be of uttermost importance in times of fragile political stability. In Ireland AHFM might help to adapt drinking-water treatment to avoid excessive levels of disinfection by-products in drinking water. This was the reason that in 2018 the European Commission opened an infringement case against Ireland for not fulfilling its obligations under the Drinking Water Directive.

4. Conclusions

To our knowledge this article is the first attempt to quantify the benefits of AHFM in lakes. Our study has shown how costs and benefits of an AHFM system can be estimated and compared to give an indication if the deployment of such a system is warranted from an economic point of view. Even though the results here are only valid for the chosen case-study lakes and can only give an indication if the installation of an AHFM is warranted from an economic point of view, lake managers for other lakes can easily adopt and refine the approach used in this study. In general, the more often and severely a lake is affected by changes in LEC with detrimental consequences for humans and the higher the number of lake users, the more likely it is that the benefit-cost ratio is above one. There may, however, be other criteria than purely economic considerations to decide to install an AHFM system. In future studies the presented approach could be improved by using local site-specific data on avoided damages, include avoided damages which were not quantified in this study, and by refining the cost data.

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Author statement

Isabel Seifert-Dähnn: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization; Ingvild Skumlien Furuseth: Methodology, Investigation; Godwin Kofi Vondolia: Methodology, Writing – review & editing;

Table 6

Comparison of depreciated costs and benefits of an AHFM system. All depreciated values are given in 2018-USD for 10 years with an interest rate of 4%. Benefit cost-ratios were calculated for all combinations of low and high benefit estimates with cheap and expensive AHFM systems.

	Depreciated costs of AHFM (one AHFM unit deployed) [USD]	Depreciated benefits of AHFM (avoided damage costs) [USD]	Benefit-cost ratios (low/expensive, low/cheap, high/expensive, high/cheap)
Lough Gara	84–166	1–39	<1/< 1/< 1/< 1
Lake Kinneret	86–164	230 - 13 955	1.4/2.7/85/162
Lake Mälaren	140–262	57 - 2188	<1/< 1/8/16

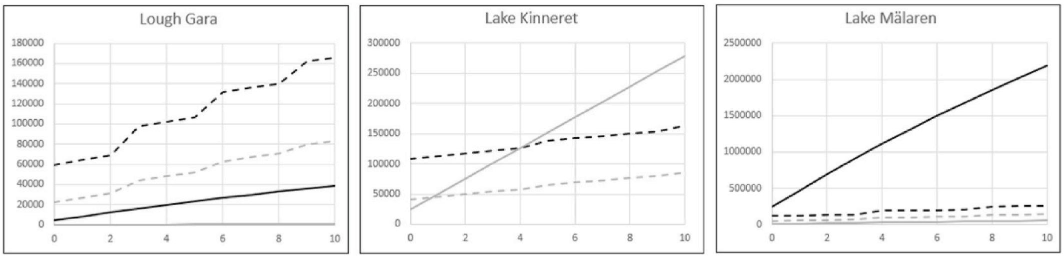

Fig. 2. Stream of depreciated costs and benefits for the three lakes. The x-axis shows the time in years, while the y-axis shows accumulated depreciated benefits and costs in USD. Continuous lines show depreciated benefits, dashed lines depreciated costs. The black lines represent the expensive cost and the high benefit estimates, the grey lines the cheap cost and low benefits estimates. For Lake Kinneret the high benefit estimate is not displayed as it is much larger than the other estimates already from year 1.

Gideon Gal: Investigation, Writing – review & editing; Elvira de Eyto: Investigation, Writing – review & editing; Eleanor Jennings: Investigation, Writing – review & editing; Don Pierson: Investigation, Writing – review & editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.112108.

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