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Critical Review

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Automatic High Frequency Monitoring for Improved Lake and Reservoir Management

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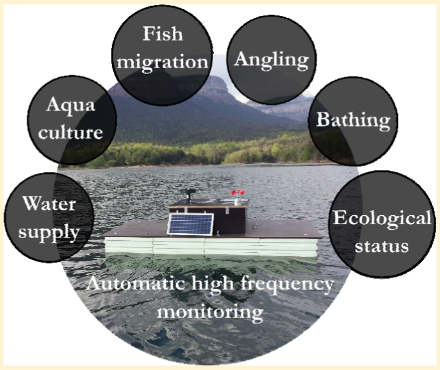
ABSTRACT: Recent technological developments have increased the number of variables being monitored in lakes and reservoirs using automatic high frequency monitoring (AHFM). However, design of AHFM systems and posterior data handling and interpretation are currently being developed on a site-by-site and issue-by-issue basis with minimal standardization of protocols or knowledge sharing. As a result, many deployments become short-lived or underutilized, and many new scientific developments that are potentially useful for water management and environmental legislation remain underexplored. This Critical Review bridges scientific uses of AHFM with their applications by providing an overview of the current AHFM capabilities, together with examples of successful applications. We review the use of AHFM for maximizing the provision of ecosystem services supplied by lakes and reservoirs (consumptive and non consumptive uses, food production, and recreation), and for reporting lake status in the EU Water Framework Directive. We also highlight critical issues to enhance the application of AHFM, and suggest the establishment of appropriate networks to facilitate knowledge sharing and technological transfer between potential users. Finally, we give advice on how modern sensor technology can successfully be applied on a larger scale to the management of lakes and reservoirs and maximize the ecosystem services they provide.



INTRODUCTION

Lakes and reservoirs provide a large number of ecosystem services including provision of fresh water and food, water purification, and recreation, among others.[1] Because of their location at the crossroads of material exports from watersheds, they also function as sentinels of changes in climate, anthropogenic forcing, and land use.[2] In acknowledgment of their important biogeochemical function and high value for society, government agencies and private companies around the world have adopted different strategies to monitor and understand anthropogenic and climate induced long-term changes in lake and reservoir water quality.[3] To assess the ecological status of water bodies and evaluate proper remediation plans, responsible agencies typically apply monitoring schemes based on weekly to monthly sampling of relevant chemical, biological, and physical variables. Over the years, this has provided a wealth of data essential for understanding long-term lake ecosystem responses and dynamics; these monitoring data can eventually lead to decision making.[4]

Despite the usefulness of traditional monitoring programs, the discrete nature of sampling also results in vital knowledge gaps related to short-lived, extreme episodic, or unpredictable events, and in general to any process with a characteristic temporal scale shorter than the sampling frequency.[5] Indeed, the Nyquist–Shannon sampling theorem implies that the sampling frequency should be at least twice the highest frequency contained in the signal (i.e., the Nyquist frequency). An inadequate sampling rate results in the phenomenon known as aliasing, in which power at frequencies higher than the Nyquist frequency is interpreted as appearing at lower frequencies, not only resulting in a loss of information about the system, but also distorting the information obtained. Thus, when measuring ecological variables in lakes, the sampling frequency of the time-series obtained is critical for capturing and understanding patterns of temporal evolution in these variables[6] and to avoid misleading interpretations.

The inadequate sampling problem is particularly prevalent for most biogeochemical processes which are driven by microorganisms, since they often have generation times of hours to days, far too short for a monthly or biweekly sampling scheme. Remarkably, short-term biogeochemical processes determine lake-wide processes, behavior, and response to external forcing. For instance, calculation of lake productivity and phytoplankton biomass needs to take into account strong diel and day-to-day changes.[7] Eutrophication management is typically based on long-term monitoring schemes, but a high frequency sampling can provide a unique insight into the relationship between phytoplankton biomass and external and internal nutrient loads.[8,9] Moreover, low frequency sampling is inadequate for identifying potential threats, such as short-lived blooms of cyanobacteria[10] and the fast water quality shifts promoted by sudden floods in reservoirs.[11] These limitations may compromise our ability to understand how aquatic systems respond to, and recover from short-term perturbations,[12,13] and make clear the importance of new measurable variables and an enhanced temporal sampling resolution for extended periods of time. Nonetheless, limited sampling locations in spatially heterogeneous aquatic ecosystems may fail to identify micro and mesoscale perturbations crucial for the understanding of processes affecting water quality, like phytoplankton patchiness.[14] The use of automatic high frequency monitoring (AHFM), that is, any monitoring program collecting data at frequencies sufficient to capture the phenomena of interest by autonomous equipment in one or more sampling stations, makes it possible to overcome some of these limitations.

Although scientific and applied uses of AHFM in lakes find their roots well into the 1960s, recent technological developments have increased the number of variables and aquatic systems being monitored using AHFM. Sensor technology has evolved during the past 20 years from probes focusing on variables related to the physical environment (e.g., water temperature, conductivity, ambient light, turbidity) to probes that can be used to monitor the chemical environment (e.g., dissolved oxygen, pH, photosynthetic pigments), to finally beginning to target biological entities (e.g., phytoplankton functional groups estimated from in situ recorded spectrofluorometry and flow-cytometry data[15]). These developments offer an unprecedented range of monitoring targets for management. Furthermore, improvements in both sensor and data infrastructure technologies during the past decade have increased the robustness and reliability of the information generated, and make the formerly restrictive technological challenge of data storage and communication much simpler.[16]

These technological developments allow for in-depth monitoring of key parameters in aquatic systems using instrumented platforms to provide real-time data to scientists, managers, and local end-users via wireless technology. In parallel, new methods and technologies for data processing and interpretation allow the mining of data to perform sophisticated numerical analyses (e.g., ref 17). Indeed, many AHFM systems have successfully been deployed across the globe and provide researchers with a wealth of information on changes in water quality, the physical environment, and carbon and nutrient cycling in response to anthropogenic and climatic drivers.[18] Science networks like Networking Lake Observatories in Europe (NETLAKE; www.dkit.ie/netlake) and the Global Lake Ecological Observatory Network (GLEON; www.gleon.org) strive to coordinate efforts of hundreds of research teams boosting data and knowledge sharing at a global scale.[19,20]

In contrast with these ongoing efforts,[21,22] outside the scientific arena design of AHFM systems and posterior data handling and interpretation is currently being developed on a site-by-site and issue-by-issue basis without standardization of protocols or knowledge sharing for adaptation to particular needs. This poses a tremendous challenge for environmental agencies and private companies willing to apply AHFM, because they lack a clear roadmap of AHFM capabilities which details the different technological choices and options for data handling, modeling, and interpretation. As a result, many deployments become short-lived or underutilized. For the same reason, many new scientific developments in AHFM which could be useful for water resource management and influential in environmental legislation remain underexplored.

In this Critical Review, we want to bridge the gap between the current scientific uses of AHFM and the use of AHFM for lake and reservoir management, by describing examples of successful applications. We also highlight critical issues to be solved to enhance the application of AHFM and suggest the establishment of appropriate networks to facilitate knowledge sharing and technological transfer between potential users. Finally, we give advice on how modern sensor technology can successfully be applied on a larger scale to optimize the management of lakes and reservoirs to make the most from the ecosystem services they provide.

■ STATE OF THE ART IN AHFM

AHFM is not just an alternative to traditional monitoring but a powerful tool to tailor monitoring to the fundamental spatial and temporal scales of ecological processes that maintain ecosystem services of societal interest. AHFM extends the scales of observations to provide a useful basis for theory and model developments,[23,24] improving our understanding of lake responses to short- and long-term perturbations[25] and thus enhancing our predictive capacity, for example, for management and planning remediation actions. AHFM incorporates recent developments in sensor applications in earth system sciences, in which AHFM networks are already a standard research tool.[26] The fast progress of microelectronics and data infrastructure technologies during the past decade, particularly wireless data transfer and networking, has boosted capturing lake environmental data at unprecedented temporal and spatial scales.[19] Sensors, logging, and communication equipment are more robust and reliable, and require less power supply and maintenance. In parallel, great progress has been achieved in automation of data analysis and archiving. Moreover, sensor technology has moved from measuring easily detectable variables sometimes considered as proxies of other compounds (e.g., oxygen concentration for reduced substances), to directly target the variables of interest (e.g., sulfide and metal concentrations).

We define three broad categories of sensors used in AHFM that roughly correspond to advances in sensor technology:[27] (1) sensors devoted to physical measurements, the most developed technology, targeting temperature, irradiance, turbidity, water level, and hydrodynamics; (2) sensors measuring a wide range of inorganic and organic molecules, including toxins; and (3) sensors identifying and enumerating aquatic biota (plankton and benthic organisms, and fish) or their activity (e.g., primary production), the least advanced technologies in which large improvements are still possible. All in all, many variables currently monitored for water resources management are already under the umbrella of AHFM (Table 1). The rise of ion-selective electrodes, UV-absorbance, fluorescence, and biochip probes has boosted the application of AHFM for a broad range of chemicals and biological variables and processes, including some emerging micropollutants. Regarding micropollutants, sensors and biosensors offer some advantages for online environmental analysis when compared to conventional analytical techniques. Most probes are relatively inexpensive and simple to use and they are easily miniaturized and portable, permitting their use as working on-site field devices.[28] Despite efforts during the last 20 years, however, only a limited number of commercial devices are available that can be directly applied for on-site determination of pollutants. While full automation is already possible for probes based on optical properties (absorbance and fluorescence), this is still difficult for ion-selective electrodes and biochips. Main challenges are low limits of detection required for micropollutants, sensor maintenance requirements, and lack of rugged sensors needed for long-term unattended deployments. Similarly, some measurements (e.g., cyanotoxins) are ready for laboratory deployments where water is pumped toward the sensor, but are still a challenge to deploy off-shore using buoys or platforms.[29] Among technologies devoted to quantify aquatic biota, only applications for phytoplankton communities and presence of enteric bacteria are convincing, though they still require highly specialized equipment and well-trained personnel.

■ AHFM FOR MAXIMIZING THE PROVISION OF ECOSYSTEM SERVICES SUPPLIED BY LAKES AND RESERVOIRS

Lake and reservoir water monitoring has always sought to guarantee and maximize the provision of water-related ecosystem services, through the examination of particular variables directly or indirectly related to the processes sustaining such services. The following is an overview of applications of AHFM supporting water resources management, with selected examples, and potential applications in areas where recent technical developments open the door to the use of AHFM for assisting decision making.

Provision of Freshwater and Water Purification. The provisioning of clean water for human activities (drinking water, agricultural, and industrial) is a principal ecosystem service provided by freshwaters, and it attracts most of the applications and developments of AHFM in inland waters. AHFM systems can assist in managing the provisioning of clean water in several ways (Table 2). In water supply schemes, AHFM has been used to avoid the withdrawal of water rich in nutrients, sediment, metals and organic matter during floods[11,25] or from anoxic layers;[30] the detection of organic matter, the presence of which

Table 1. Variables That Can Be Measured for Water Resources Management in Lakes and Reservoirs and Their Relationship with AHFM[a]

variable	target	used for lake management	most common sensors	potential for AHFM
		physical measurements		
water level/discharge	resource availability dam safety and flood threat residence time groundwater level	very common	pressure transducer acoustic doppler	fully developed
water velocity/direction	hydrodynamics	rare	acoustic doppler	fully developed
temperature	thermal stratification and mixing ice phenology habitat assessment chemical rates biological rates (e.g., food intake in fish)	very common	thermistor heat flow sensors	fully developed
transparency/irradiance	eutrophication and restoration assessment prediction of phytoplankton and macrophyte blooms	very common	radiometer	fully developed
suspended solids	water quality assessment sedimentation, accretion, and sediment resuspension phytoplankton bloom prediction	very common	nephelometer	fully developed
		chemical measurements		
pH/redox potential	carbon chemistry eutrophication and restoration assessment acidification redox state fish protection	very common	glass electrode	fully developed
conductivity	water quality assessment tracing water masses evaporation	very common	potentiometer	fully developed
dissolved oxygen	eutrophication and restoration assessment proxy of redox state habitat assessment biological activity (e.g., food intake in fish)	very common	optode/electrochemical electrode	fully developed
nitrate	eutrophication and restoration assessment prediction of phytoplankton and macrophyte blooms biological activity human health protection	very common	UV absorption	fully developed
other dissolved gases (CO_2, CH_4, N_2O, etc.)	greenhouse gases microbial processes, e.g., methanogenesis and denitrification	very common	IR absorption spectrometry laser-based detection mass-spectrometry	challenging
ammonium/ammonia	eutrophication and restoration assessment prediction of phytoplankton blooms biological activity fish protection	very common	ion-selective electrode	challenging
total phosphorus	eutrophication and restoration assessment prediction of phytoplankton and macrophyte blooms	very common	online analyzer (colorimetric)	extremely difficult
soluble reactive phosphorus	eutrophication and restoration assessment prediction of phytoplankton blooms	very common	miniaturized analyzer (colorimetric)	challenging
reactive silica	eutrophication and restoration assessment prediction of diatom blooms	rare	not available	not applicable
major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-})	water quality assessment	common	ion-selective electrode	challenging
sulfate	water quality assessment	common	not available	not applicable

Table 1. continued

variable	target	used for lake management	most common sensors	potential for AHFM
	chemical measurements			
sulfide	eutrophication and restoration assessment water quality assessment	common	ion-selective electrode	challenging
alkalinity	water quality assessment	common	ion-selective electrode	challenging
organic matter	water quality assessment formation of disinfection byproducts	common	UV absorption and fluorescence spectroscopy	fully developed
chlorophyll-*a*	eutrophication and restoration assessment water quality assessment	very common	fluorescence spectroscopy	fully developed
phycocyanin/phycoerythrin (cyanobacteria)	eutrophication and restoration assessment water quality assessment harmful cyanobacteria blooms detection	common	fluorescence spectroscopy	fully developed
other photosynthetic pigments	eutrophication and restoration assessment water quality assessment	rare	fluorescence spectroscopy	fully developed
cyanobacterial scum formation	water quality assessment harmful cyanobacteria blooms detection	rare	fixed cameras	challenging
cyanotoxins	harmful cyanobacteria blooms detection	rare	biochips with immunologic or hybridization technologies	extremely difficult
metals (Al, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Zn), F, and CN	water quality assessment human health protection	common	ion-selective electrode	challenging
hydrocarbons	water quality assessment human health protection	common	fluorescence spectroscopy	fully developed
micropollutants (antibiotics, pesticides, endocrine disruptors, etc.)	emerging contaminants detection human health protection	common	biochips with immunologic technology or fiber optic interferometry	extremely difficult
	enumeration/activity of biota			
phytoplankton[b]	water quality and habitat assessment eutrophication and restoration assessment harmful algal blooms detection biodiversity indexes	rare	flow-cytometry and automated image identification	challenging
zooplankton	water quality assessment biodiversity indexes	rare	flow-cytometry (for small zooplankton) and automated image identification	not applicable
macroinvertebrates	eutrophication and restoration assessment water quality assessment biodiversity indexes	common	automated image identification	not applicable
fish	water quality assessment fisheries biodiversity indexes	common	hydro-acoustics or underwater cameras	challenging
macrophytes	eutrophication and restoration assessment water quality assessment biodiversity indexes	rare	terrestrial or airborne imagery (ROV mapping, drones)	challenging
E. coli and other enteric bacteria	water quality assessment human health protection	very common	biochips with immunologic or hybridization technologies	challenging

[a] The table details the variables, the relevant processes that they target, whether this variable is usually used to make management decisions, the most common sensors used for in situ measurements, and whether AHFM is potentially applicable. "Fully developed" means that the measurement is possible and easily applicable in terms of sensor technology and deployment in unattended conditions (power consumption, measurement stability, data storage, etc.). "Challenging" means that it is still possible but some difficulties exist (e.g., high power consumption, weak calibration stability, etc.). "Very difficult" applies for sensors that have been used in some circumstances with very complex, expensive, or time-consuming deployments and maintenance. This table only considers underwater measurements. ROV is remotely operated vehicle. [b] We do not consider the measurement of photosynthetic pigments as a surrogate for cell density.

leads to formation of disinfection byproducts during chlorination;[31] and the identification and prediction of harmful cyanobacterial blooms.[10] The information delivered by AHFM is used in different ways to assist management: it may be used to prompt grab sampling for confirmation of a threat, to switch to alternative unpolluted sources, to trigger an in situ remediation action (e.g., application of hydrogen peroxide for algal bloom control[32] or to change the intake depth in reservoirs with several withdrawal structures). Another advantage of AHFM is its lower susceptibility for sampling errors due to spatial heterogeneity.

Table 2. Selection of Ecosystem Services from Lakes and Reservoirs, Management Issues and Threats That Compromise Their Provision, and Variables That Can Be Measured by AHFM to Assist Planning and Decision Making

ecosystem services	management issues	associated threats	target for AHFM	relevant refs
provision of freshwater and water purification	flash flooding and erosion	clogging of filters and pipes in intake structures	water level	82, 30, 83
		sedimentation and reservoir filling	water velocity and direction	
		increased treatment costs for water supply	turbidity	
	start and end of ice season	obstruction of intakes	temperature	39, 84, 38
		loss of vehicles/accident	in situ cameras	
	watershed impacts on water quality	increased nutrients, organic matter, and microbial pollution	light, transparency	36
		increased treatment costs for water supply	pigments	
			organic matter	
			enteric bacteria	
			water level	
			discharge	
			nutrients, cDOM, pollutants	
	effects of water temperature on water quality	disinfection byproducts during chlorination	temperature	85
		secondary metabolites following phytoplankton blooms	organic matter	
			photosynthetic pigments	
	oxygen depletion, presence of reduced substances	increased treatment costs	oxygen	86
		odor compounds	pH/redox	
		enhanced internal loading	nitrogen forms	
			dissolved phosphorus	
			sulfide	
			metals	
	location of optimum layers to withdraw drinking water	withdrawal of low quality water leading to increased costs at treatment	temperature	87
			oxygen	
			pH/redox	
			nitrogen forms	
			dissolved phosphorus	
			photosynthetic pigments	
			cyanobacteria biomass	
			turbidity	
			organic matter	
			sulfide	
			metals	
	early warning systems for unpredictable and short-lived events	harmful algal blooms	irradiance	88, 89
		anoxia and metals	chlorophyll *a*	
			specific phytoplankton pigments (e.g., phycocyanine)	
			temperature	
			pH/redox	
			nutrients	
			organic matter	
	target grab sampling (algal blooms, anoxic layers, spills)	missing of relevant health threats	micropollutants	30
		increasing monitoring costs with unfocused sampling	metals	
			cyanobacterial pigments	
			hydrocarbons	
			enteric bacteria	
			dissolved oxygen	
			organic matter	
provision of food	flash flooding, turbine releases	fish kills	turbidity	this study
		fish escapes from ponds	water level	
			hydro-dynamics	
	oxygen depletion, reduced substances	fish kills	oxygen	43, 44
		bioaccumulation of metals	pH/redox	
			nitrogen forms	
			sulfide	
			metals	
	optimization of stock and landing	suboptimal growth conditions	temperature	42
			oxygen	
			pH/redox	

Table 2. continued

ecosystem services	management issues	associated threats	target for AHFM	relevant refs
recreation	angling	suboptimal fishing conditions	water temperature weather conditions	this study
	microbial contamination	human health	enteric bacteria virus particles	[51]

While classical water sampling fails to realistically asses the ecosystem state if a phenomenon occurs with high spatial patchiness (e.g., a cyanobacterial bloom), AHFM provides more reliable information by calculating time-averaged values, which minimize the noise induced by spatial heterogeneities.[33] Applying AHFM on moving platforms (e.g., unmanned boats) allows for the detection of horizontal distribution patterns at scales never achievable by means of conventional sampling.[18] However, in large systems a single AHFM system may fail detecting a particular event, e.g. a phytoplankton bloom localized far from the AHFM system. Therefore, decision on how many sampling stations and their location is paramount for a successful AHFM application in a large system, which will depend on the management target (e.g., bloom detection) and previous knowledge of the system (common location and spatial heterogeneity of blooms).

Remarkably, AHFM solutions are flexible enough for assisting water supply management in a range of settings. On one hand, AHFM can assist very large companies or agencies supplying water for large regions or cities, like the complex network of AHFM systems deployed in 18 water supply reservoirs in Sardinia (Italy) by the Ente Acque della Sardegna (ENAS, http://www.enas.sardegna.it/il-sistema-idrico-multisettoriale.html), including profiling buoys with multiparameter probes, and data transmissions systems for online data acquisition and system configuration. The information is used by ENAS to identify the optimal depth for water withdrawal and as a warning system for development of algal blooms. On the other hand, AHFM can also assist communities running very small schemes, like the small rural Group Water Schemes in Ireland, where approximately 6% of population is supplied through them. These community-owed schemes are managed by voluntary committees, and those relying on resources stored in small lakes have started using AHFM to manage their resource, like in the Milltown Lake, the drinking water source for the Churchill and Oram Group Water Scheme (GWS) (http://www.mestech.ie/2011/12/water-quality-sensor-deployment-at-milltown-lake-december-2011/). This system is collecting real-time environmental and water quality data from the lake, in order to identify the various land uses and human activities that have caused water quality impairment episodes in the past.

AHFM is also used to evaluate the importance of the terrestrial-aquatic link for water quality in lakes and reservoirs, offering a monitoring tool that provides environmental variables in sufficiently high frequency. Recently, the increase in dissolved organic matter in numerous freshwater systems in Europe and North America[34] raised awareness about the relationship between terrestrial organic matter and generation of disinfection byproducts during drinking water production.[35] Since high organic matter pulses usually go along with flood events, classical low frequency sampling fails in capturing such dynamics and AHFM is required to monitor the fluxes on a shorter time scale. AHFM systems in drinking water reservoirs are becoming more frequent for real-time control of the problems associated with flooding events, when water with high dissolved organic matter[36] (Figure 1) or suspended solids content[37] can reach water treatment facilities increasing the cost of treatment.

Finally, although not related to water purification, AHFM with a range of temperature sensors permits accurately calculating the timing of ice formation and ice-out.[38] Thus, AHFM is useful for the assessment of, for example, winter transportation and also helps to prevent ice related incidents, such as ice jams and obstructions for power plants,[39] as well as extensive shoreline and property damage in exceptionally cold winters.[40]

Provision of Food. Aquaculture in ponds, lakes, and reservoirs is present in many countries where freshwater fish are a valued food source. AHFM in aquaculture is common practice, because accurate control of dissolved oxygen and temperature conditions is needed to avoid stress, overfeeding, disease, and mortality of the fish. For instance, the high short-term variability showed by dissolved oxygen concentration and pH in fish ponds precludes an accurate assessment of the effects of the low-oxygen periods on fish growth unless measurements are taken at high frequency.[41] Similarly, for maximizing fish yields, parameters such as dissolved oxygen, temperature, salinity, turbidity, pH level, and ammonia should be obtained at high frequency.[42,43] For example, three AHFM stations in the 228 ha fishpond Dehtář, located in South Bohemia (Czech Republic), give managers real time information on dissolved oxygen and water temperature for mitigating the effects of hypoxic periods (Figure 2A). The AHFM information is particularly important during summer fish stocking, feeding and harvesting allowing managers to avoid mass mortalities. AHFM is also valuable to assess the changes in habitat conditions for fish.[44]

The migration of diadromous fish through man-made barriers such as dams and hydropower stations is also an important issue for fisheries managers. More than one-third of freshwater fish species in Europe are threatened by human activity and in over 40% of these cases, structures impeding the flow (dams, thresholds, etc.) are the leading cause of ecological disturbance.[45] When the main fish passage channels are through hydropower turbines, significant mortalities can result (up to 27% for salmon smolts leaving the Loire catchment[46]). One way to minimize mortalities is to turn off hydropower turbines during certain conditions, which are favorable to fish movement.[47−49] In the Burrishoole catchment, west of Ireland, the autumn migration of silver eel and the spring migration of salmon and sea trout smolts are reliably predicted using AHFM information about discharge and water temperature (Figure 2B). Real-time assessment of these variables, along with moon phase therefore allows an informed decision about turbine operation and relative risk of continued operation.

Recreation. Angling is one of the main recreational services provided by lakes and reservoirs around the world, and can be a significant source of revenue to local and national economies. Angling supports an important tourism sector. A tangible example of the benefits of AHFM to angling is in the use of real time weather and lake conditions in informing prospective

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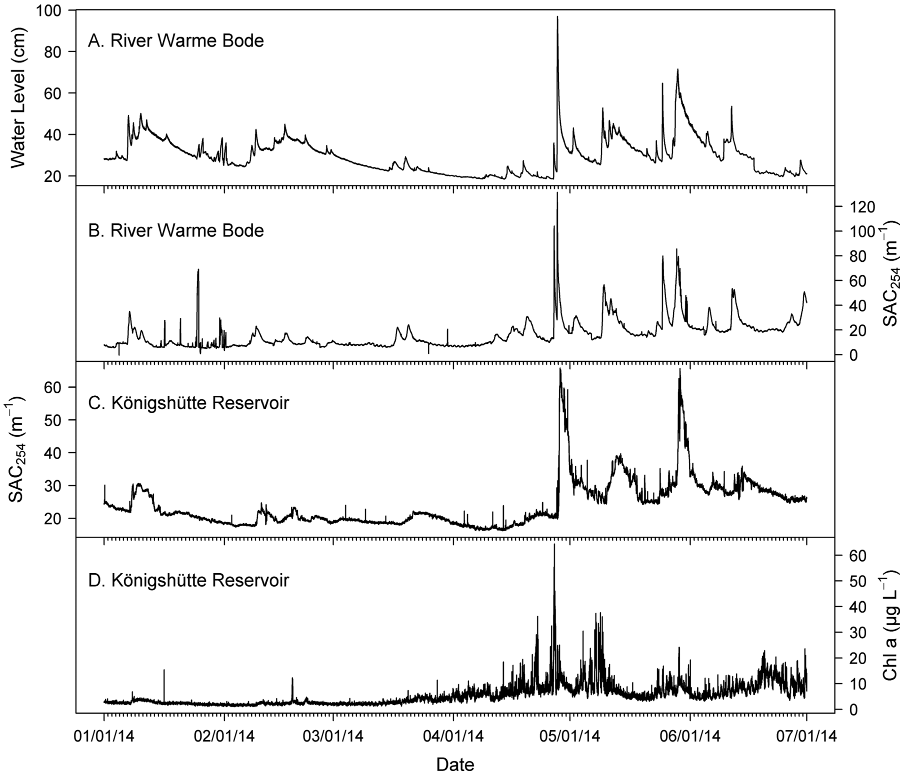

Figure 1. Monitoring the impact of watershed processes on reservoirs. Data from the first half of 2014 in Königshütte Reservoir (Harz Mountains, Germany) and its main tributary. The upper two panels show (A) water level and (B) UV absorbance at 254 nm (specific absorbance coefficient, SAC_{254}) in the major inflow into the system (river Warme Bode). The lower two panels show (C) SAC_{254} and (D) chlorophyll *a* concentration in Königshütte Reservoir. Note that the spectral absorbance at 254 nm is used as a proxy for DOC. The panels show how the inflowing storms drive not only the dynamics of the dissolved organic matter in the reservoir, but also internal processes like primary producers biomass expressed as chlorophyll *a* (for details see ref 36.).

anglers about fishing conditions. For example, successful fly fishing for salmon is enhanced by a cloudy sky and moderate wind. Online access to AHFM is a valuable tool in attracting anglers to areas where they can check in advance whether weather, river, and lake conditions are likely to be favorable (e.g., Figure 2C). Other popular angling fish species across Europe include common carp (*Cyprinus carpio*), pike (*Esox lucius*), pike-perch (*Stizostedion lucioperca*) and wels (*Silurus glanis*). Common carp and wels are more likely to be caught during or after rainfall events.[50] Simple AHFM stations including automatic weather and water quality stations providing online data can be particularly useful when the data are presented in a user-friendly fashion, offering anglers and fisheries managers a real time picture of whether conditions are good for fishing.

Another recreational activity that may potentially benefit from AHFM is bathing. Currently, inland bathing water quality in the European Union (EU), and many other countries around the world, is formally assessed using microbiological parameters (e.g., intestinal enterococci and *E. coli* concentrations). Indeed, AHFM is already a reliable method among the many proposed for microbiological determinations related to the EU Bathing Water Directive.[51] In contrast, although Article 8 of the EU Bathing Water Directive (EC 2006) does mention that appropriate monitoring should be carried out to enable timely identification of cyanobacterial health risks, it provides no formal guidelines on how this should be carried out.[52] The main element of cyanobacterial monitoring is visual inspection of cyanobacterial blooms or scum in bathing water, determination of cyanobacterial cell numbers or biovolume, and measurements of microcystin concentrations.[53] However, AHFM of cyanobacterial pigments[54] and even cyanotoxin concentration[29] is already possible, and some applications for cyanobacterial risk management at bathing sites already exist (Figure 3). Considering the time scales involved in scum formation and breakdown (hours) and cyanobacterial bloom development (days), and the time and expertise demanding microscopic examination of plankton samples, the potential of AHFM for cyanobacterial risk management in bathing should be further explored.

■ AHFM FOR EVALUATING THE ECOLOGICAL STATUS ACCORDING TO THE WFD

The evidence that human well-being depends to a great extent on services provided by freshwater ecosystems prompted a myriad of environmental policies related to the monitoring and protection of lakes and reservoirs. The US Clean Water Act (CWA) and the more recent EU Water Framework Directive (WFD) are examples of environmental policies applied to a large number of water bodies across vast regions. Since these policies may enforce the implementation of remediation actions in systems subject to impairment of water quality or ecosystem health, agencies need a sound understanding of the processes that regulate the dynamics of aquatic ecosystems at the appropriate scale.

The WFD allows EU Member States to tailor their monitoring according to the conditions and variability within their own waters.[55] The key requirement is that member states must adopt monitoring frequencies which are adequate to achieve an acceptable level of confidence and precision which should be reported in the River Basin Management Plans. The WFD, however, provides

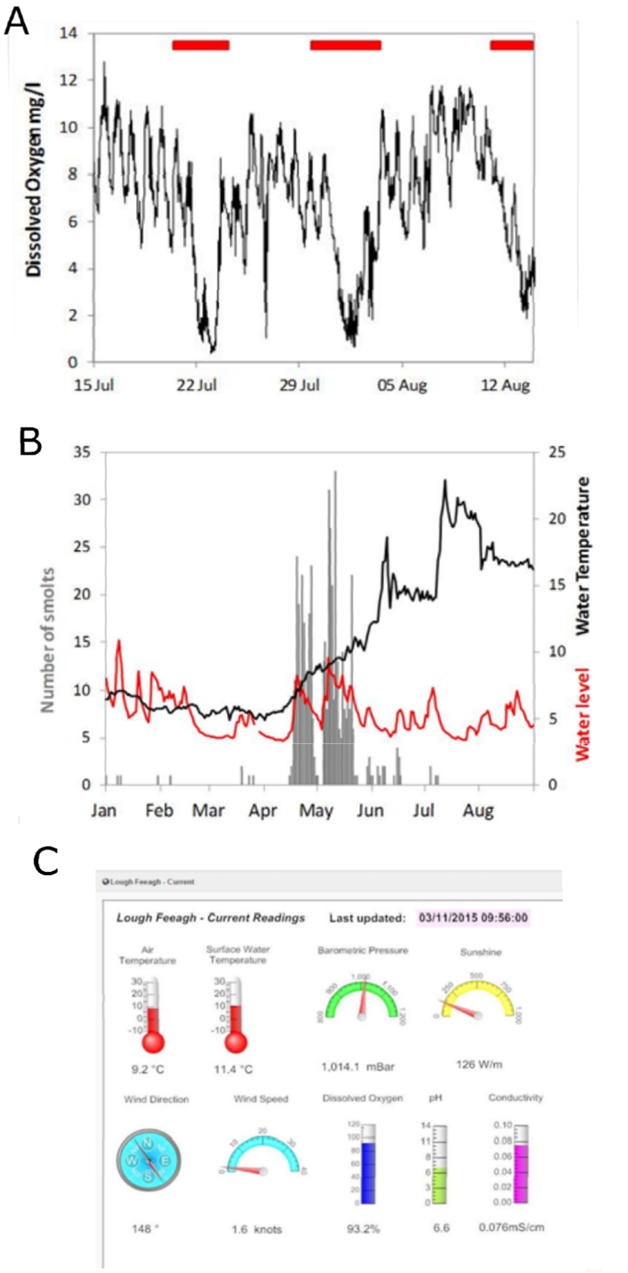

Figure 2. Selected examples on the use of AHFM in lakes and reservoirs for the protection of provision of food and recreation. (A) Characterizing periods of hypoxia (red bars) in a valuable aquaculture site to avoid mass mortalities (unpublished data from COST project FISH-POND2014). In this panel three periods of hypoxia developing fast in a fish pond detected by AHFM, which allowed to mitigate the impacts by timing fish harvesting and stocking to avoid mass mortalities. (B) Using high resolution monitoring of water level (red line) and temperature (black line) to predict movements of migratory sea trout (gray bars).[90] The rising temperatures favors migration of the trout smolts, and the use of AHFM provides information to managers as to when these conditions are approaching, allowing an informed decision about turbine operation. (C) Providing real time data on weather and lake conditions to inform anglers on fishing prospects (image taken with permission from http://burrishoole.marine.ie). Many species are particularly sensitive to both weather and surface water conditions like temperature and oxygen levels.

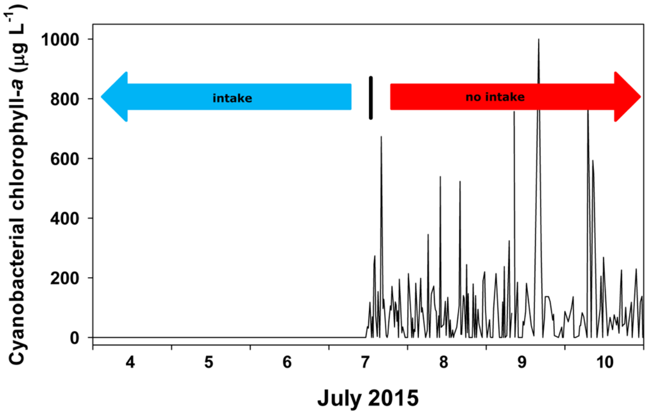

Figure 3. Water Authority Brabantse Delta (The Netherlands) installed an AHFM station near the water intake of Lake Binnenschelde, which was designated an official bathing site. The relatively high water level of Lake Binnenschelde is maintained by the intake of water from the adjacent Lake Volkerak, which is prone to cyanobacterial blooms. To prevent the intake of high concentrations of cyanobacteria into Lake Binnenschelde, the water quality including cyanobacterial chlorophyll-*a* of Lake Volkerak is monitored every 15 min by sensors attached to a buoy. A protocol is used for management decisions and water intake is stopped when cyanobacterial chlorophyll-a concentrations exceed 75 μg L^{-1} at three consecutive measurements. The figure shows an example of a sudden apparition of cyanobacteria in the intake that prompted the decision of stopping the intake from Lake Volkerak.

only minimum monitoring frequencies for all quality elements, for example, 4 times a year for nutrient and oxygen levels; 2 times a year for phytoplankton; and once every three years for aquatic flora (macrophytes, microphytobenthos).

Most countries have higher sampling frequencies than the suggested minimum: for chlorophyll *a* and phytoplankton community sampling, frequencies vary from once during the summer to monthly sampling throughout the year, the most common sampling frequency being 4−6 times/year. On the other hand, confidence and precision of ecological status assessment based on pigments or phytoplankton community information are largely unknown in most assessment systems. This raises the question whether this sampling frequency is adequate enough to provide reliable estimates of ecological status. Although the among-system variability for a large population of lakes can be adequately assessed with at least 3 samplings in the summer months for at least 3 or 4 years,[56] several studies have shown high temporal variability in chlorophyll data for single systems, meaning that frequent sampling is necessary to ensure sufficient accuracy.[57,58] Pomati et al.[59] in a study of Lake Zurich showed that AHFM correctly captured the rise and fall of a cyanobacterial bloom, whereas routine 14 day interval monitoring gave a false impression of a stable phytoplankton community. For individual lakes, the risk of misclassification in terms of ecological status is high with fewer than 15 phytoplankton community samples per summer period.[60] Nonetheless, the confounding effects of low sampling frequency are not restricted to phytoplankton. Assessments of ecological status based on other variables, particularly dissolved oxygen concentration, can also be misleading unless AHFM is applied.[61] In fact, ecological assessment using AHFM of chlorophyll *a* and cyanobacterial pigments is already in use in some countries.[10]

It should be noted that AHFM data cannot fully substitute traditional monitoring data, as the different national assessment systems for ecological status include metrics requiring a full taxonomic analysis. Still, it has been shown that the final outcomes of all assessment systems have significant correlations with chlorophyll-*a*[62] and cyanobacteria biomass.[63] Therefore, simple metrics acquired by AHFM have great potential as efficient proxies of a full community level assessment.

Additionally, in the context of the WFD, AHFM can be used for the following: (i) Establish reference conditions based on existing high status water bodies. As a high status is the anchor point for the classification of the ecological status, a higher level of confidence and precision is needed, which could be ensured by a higher sampling frequency. AHFM can be used to acquire this very sensitive data. (ii) Monitor lakes exhibiting high and unpredictable variability, for example, shallow lakes with frequent shifts between clear water and turbid states, impacted by many factors such as climate and top-down control of trophic cascades,[64] or fluctuating between good and moderate ecological status (fluctuating around the suggested management target) Again, AHFM systems deployed in those particular systems can help identifying all the variability in, for instance, oxygen and chlorophyll *a* levels. The final ecological assessment would be much more tied to the real state of the system. (iii) Monitor lakes recovering from eutrophication. Remediation measures may have the most pronounced effects on water quality outside the summer periods,[64,65] the focal season for most WFD monitoring programs. Also, remediation measures are usually expensive, and a good understanding of the new water quality trajectories and the process behind the observed changes are paramount to tailor the remediation technology to the system, and to disentangle the effects of the remediation action from other confounding factors (e.g., climatic variability). AHFM can help extending the sampling to the whole year and acquiring valuable information on lake dynamics to tailor the remediation measures to lake response.

■ ENHANCING THE APPLICATION OF AHFM FOR MANAGEMENT PURPOSES

Application of AHFM in the applied arena is still hampered by several factors. From a technical point of view, we still have a limited or no choice of robust and low-maintenance sensors for dissolved phosphorus, ammonium/ammonia, sulfide, micro-contaminants, bacterial enumeration, cyanobacteria/cyanotoxins, and biota in general. Also, most ion-selective electrodes are far from being the robust, minimum-maintenance sensors needed for a convenient AHFM system, although the spread of AHFM systems will probably encourage technology developers to cover this emerging market in the future. Nonetheless, there is a severe limitation in precision common to virtually all available chemical probes. For instance, most nitrate sensors cannot detect any nitrate in the epilimnion of many lakes during summer when nutrient concentration falls to low levels. Also, fluorescence measurements are gaining momentum, but there are large species to species and environmental-induced variations in the fluorescence emitted per unit chlorophyll,[66] which limits the use of fluorescence for applications asking for very precise measurements of pigments. The significance of fluorescence measurements for organic matter quality assessment is still controversial too,[67] which, does not compromise the use of CDOM sensors for general assessments of the quantity of organic matter in a system, but asks for caution when trying to use this information for characterization of the organic carbon pool. Whether AHFM-technologies will finally turn into a standard tool in water quality monitoring and management depends on how well we can overcome these technical limitations and, of course, on economic aspects. As soon as the deployment, maintenance, and quality control of AHFM-technologies become more affordable than classical monitoring strategies (mainly because reduction of personnel costs), they will successfully conquer the area of governmental and industrial water resources management.

With the advances made during the past decade, infrastructure technologies for data collection, transmission, and storage are no longer the main limitation for AHFM. Although in some geosciences the bottleneck of data acquisition systems is indeed the transmission and storage of the information generated by thousands of very inexpensive sensors,[68] this would seldom be the case in AHFM systems devoted to water resources management. In our opinion, the "data deluge" that an AHFM system can stream into a company or public agency information system shifts the bottleneck to the analysis and interpretation of the information. From our experience, many AHFM systems devoted to water resources management become short-lived or underutilized because managers lack the time or expertise to cope with the huge quantity of data being stored in their computers. We refer to this as the *Syndrome of the Gigabyte* and the main symptoms are huge amounts of data stored on a hard disk without any quality check or use, coming from an AHFM without proper maintenance.

The *Syndrome of the Gigabyte* is frequently related to an unfocused objective, that is, the AHFM system was deployed as a "water quality sentinel" measuring a dozen or more variables without a clear management target. Defining a clear objective can help both designing the simplest AHFM system that fits the requirements, and defining appropriate descriptors or summaries of the data that can then be used by personnel with minimum training. For instance, we have found water supply companies deploying costly and high-maintenance AHFM systems with profiling capability for several variables in a lake or reservoir. Many of these AHFM systems have been eventually dismantled after numerous failures of the profiling equipment, and because the personnel in charge of analyzing the data and making decisions simply could not handle the amount of data collected. In most occasions, a simpler AHFM system with oxygen and temperature sensors deployed at fixed depths coincident with the intake structures would have been the best choice.

However, in some applications the collection of many variables is justified and the integration of this information helps to solve highly demanding problems, for example, a water treatment cost analysis with strong trade-offs between variables or an Early Warning System (EWS) for phytoplankton blooms. In those situations, an appropriate protocol for data handling and interpretation by nonspecialist personnel must be viewed as an integral and fundamental part of the AHFM system. Data-driven Decision Support Systems (DSS) and EWS are powerful tools that make the most of a AHFM system,[69] because they make the final user blind to data handling and processing and therefore most time is invested in interpretation of the different outputs and decision making. These tools usually combine data from sensor networks and complex modeling and statistical analyses in ad hoc software, and their development is one of the ways of collaboration between research and management applications of AHFM (e.g., refs 70 and 71). A promising future development in building such DSS and EWS is the use of standardized scientific workflow systems (e.g., *Kepler*, *Taverna*, *Pegasus*) that may help bringing homogeneity and transferability across AHFM applications.[72] Presently, it is very difficult to share different tools (codes, algorithms, models, etc.) between water quality DSS and EWS because of their differing programming architecture, which should be one of the top research priorities for the following years.

AHFM may also assist water quality management through the identification and prediction of the impacts of climatic extreme events on lakes, in particular storms and heat waves.[13] Understanding the impact of these events is important because of the negative effects they can have on the ecosystem services that lakes provide.[73] Storms with high rainfall, for example, are typically associated with inflow of large loads of dissolved organic matter,[74] while toxic cyanobacterial blooms can form during heat waves.[75] Both high levels of organic matter and the occurrence of algal blooms can lead to substantial costs for water managers and mitigation of their effects will be a pressing need into the future. For example, an extreme event in the US in 2011 (Hurricane Irene) not only had huge effects on water column mixing in a New York drinking water reservoir[25] but was also responsible for 43% of the total annual DOM loading.[76] High DOM levels in water can result in formation of disinfection byproducts (DBPs), such as trihalomethanes (THMs), when water supplies are chlorinated. Large storm events can also lead to accelerated rates of erosion that in turn greatly increase streamwater suspended particulate material levels along with the particulate material loading to recipient water bodies. These can be monitored by AHFM using optical turbidity, which is a proxy for suspended particulate material but which is in itself also a regulated water quality variable (Figure 4). Exploring the occurrence and the effects of these events requires monitoring that captures the event itself (which may occur over hours), as well as the ensuing impact (which can be months or years). AHFM arises as a fundamental tool to identify and predict the impact of extreme events on lakes, which are now becoming more frequent, a trend that has been linked to directional climate change and is projected to continue.[77]

The interaction between researchers and managers is paramount for current and future applications of AHFM in lakes and reservoirs and works in both directions: management issues are a rich source of hypotheses and challenges for scientists,[4] while managers can benefit from scientific tools that inform them about the fundamental drivers of water quality and processes controlling other ecosystem services. It is urgent that well-established scientific networks focused on AHFM (e.g., GLEON and NETLAKE) build up appropriate forums piping scientific knowledge to management issues, and informing researchers about the relevant problems managers face. Also, these forums must involve a rich diversity of industries and public agencies applying or willing to apply AHFM, and should create transparent and confident mechanisms for boosting knowledge sharing between companies while preserving business confidentially in the often socially and politically sensitive water resources sector.

Our experience during the NETLAKE project (COST Action ES1201) suggests that the best mechanism for this knowledge sharing is engaging in common research and innovation projects in a codevelopment framework. Codevelopment is a methodology for creating partnerships that seeks maximizing profits for companies, expanding markets and shorten time to them, and enhancing innovation and flexibility of research.[78] In our context, codevelopment means that scientists benefit of direct user design advice while still retaining full intellectual property and control over research, whereas end-users become directly involved in the culture of research. What often comes out is a compromise between what the end-user really wants and what the researcher thinks he or she wants. In our opinion, the best results would be achieved when clear management goals are assisted by a combination of AHFM and ecosystem models in integrative tools that also take into account user impact models (e.g., how lake water quality impact the treatment process for water supply) (Figure 5). To be effective, codevelopment frameworks and meetings should be implemented by external experts, which also helps building the necessary mutual trust between industrial and research partners.

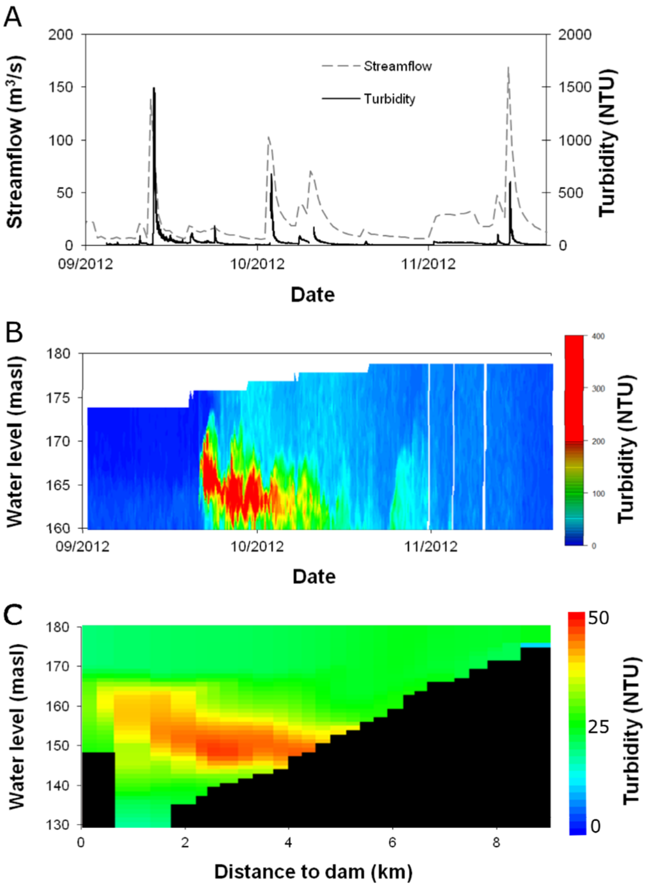

Figure 4. AHFM data collected during the late summer−early winter of 2012 from Ashokan Reservoir (USA), part of the New York City (NYC) water supply. (A) AHFM data of the major inflow to the reservoir, showing how large storms can lead to orders of magnitude increases in streamwater turbidity levels. (B) Turbidity isopleths calculated from an automated profiling system,[91] moored midbasin in the reservoir. Distinct increases in reservoir turbidity correspond to the timing of storm events. It can also be seen how the turbidity sinks downward between events, and with the seasonal deepening of the thermoclime. NYC water supply managers use such AHFM data in near real time to support decisions on reservoir operations (ie water source and withdrawal rates), and the NYC water supply modeling group use these data to supply model initial conditions and verify model performance.[92] (C) An example of a model simulation which predicts the depth and the turbidity plume associated with the 30 Oct 2012 storm event. Information collected by AHFM can improve model based predictions.

The implementation of lake and reservoir AHFM in local and regional policies is still very limited, yet long-term AHFM deployments may add to global strategic planning of using lake ecosystem services. This vividly contrasts with the status of other in situ monitoring networks related to Earth System Sciences (e.g., ground-based weather stations, ocean buoys and floats or air quality monitoring networks) which are already fully integrated into large and policy-influential data infrastructures like the EU Copernicus program or the European Environmental Agency EIONET. This is particularly true for the lessons learned from ocean observatories: to the best of our knowledge we do not know about any existing formal forum for knowledge and

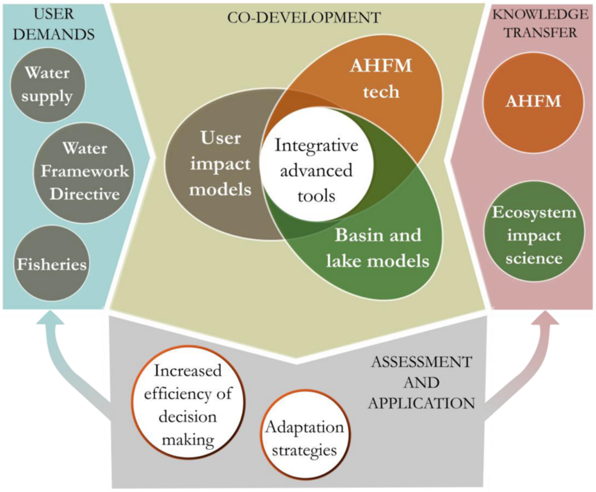

Figure 5. Codevelopment research framework to enhance the application of AHFM for management purposes. Codevelopment is a strategy to define common scientific and management goals in a research or innovation project. In this way, managers are "scientifically empowered", whereas researchers shorten the path of innovation to markets. In the case of AHFM, user demands related to increased efficiency of decision making or definition of adaptation strategies for the maximization of ecosystem services are best supported by projects merging AHFM, ecosystem models, and ad hoc user impact models into integrative modeling tools.

technological exchange between the ocean and freshwater community concerning AHFM. In our opinion, the inclusion of freshwater observatories in such global networks would force both ocean and lake researchers to step toward common technological and data handling standards, and this should be a top priority for lake researchers in the upcoming years.

The inclusion of lake AHFM in those large-scale infrastructures asks for a clear definition of processes operating at the high temporal resolution that is at the core of the application of AHFM and which are relevant for reporting water quality status. In addition, lake and reservoir AHFM may also provide adequate information to calibrate relevant global satellite observations[79] and complement other in situ observations networks (e.g., terrestrial CO_2 eddy covariance towers) monitoring global changes.[80] Now that the role of inland waters on global biogeochemical cycles is becoming clearer[81] and that one of the draft UN Sustainable Development Goals is to ensure availability and sustainable management of water for all, it is time for freshwater researchers to firmly demonstrate the relevance of incorporating lake AHFM as an additional tool in Earth System Sciences and management.

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Notes

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