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#HydrolinkMagazine

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DEEP LAKES

IAHR
AIRH
International Association
for Hydro-Environment
Engineering and Research

Hosted by
Spain Water and IWHR, China

IAHR.org

EDITORIAL

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Hydrolink editor

The present issue of Hydrolink focuses on the threats to deep lakes, resulting from climate change and increased nutrient loads from various human activities. The preparation of the four articles on lakes published in this issue was coordinated by the world renown limnologist Professor Jörg Imberger, who served as Guest Editor of this issue. This issue follows three very interesting webinar lectures by Professor Imberger organized by IAHR and recorded on video. The first was on averting the extinction of the world's freshwater aquatic fauna and flora[1], the second was on saving lakes from the impact of nutrient enrichment and global warming[2] and the most recent one, delivered on World Water Day 2021, was on improving water security through connecting with natureg[3]. The videos of all three lectures are available at the IAHR website (www.iahr.org).

In an article introducing the theme of this issue, Professor Imberger gives a brief overview of the interrelationship between the hydrodynamics and the biochemistry of lakes and its impact on aquatic ecology. He then goes on to explain how the continuous nutrient enrichment and to a lesser extent global warming can lead to the death of many lakes. Adaptive real-time management, supported by systems that combine data collection from key points in the lake and its watershed with self-correcting hydrodynamic and ecological models, offers an approach for saving lakes that are in danger. Placing the threats to lakes in a broader global context, Imberger makes a plea for respecting and protecting nature and all forms of life in it. This echoes the words of Sir David Attenborough who recently said to "just treat the natural world as though it is precious, which it is"[4].

The article by Clelia Marti takes a closer look at the cultural eutrophication of lakes, caused by the excess nutrient loading from human activities, and discusses the relative role of the two major nutrients, nitrogen and phosphorus. It then discusses how climate change can amplify the adverse impacts of eutrophication. Considering that the thermal structure of lakes affects nutrient cycling and the aquatic ecology, changes in temperature distribution due to global warming can have significant ecological consequences and threaten the survival of some species.

David Hamilton discusses several examples of the degradation of lakes resulting from eutrophication, manifested by the increased frequency of cyanobacterial harmful algal blooms, anoxia in the hypolimnion, and loss of biodiversity. In view of the bleak outlook for the ecologic health of many lakes, Hamilton stresses the urgency for interventions and management actions including the need for long-term monitoring and data collection to help understand the complex dynamics of these systems; addressing and regulating excess catchment nutrient loads; and identifying and prioritizing lakes in temperate areas which do not mix completely potentially resulting in severe ecological disruptions.

The fourth article on lakes, by Marco Pilotti and Giulia Valerio, presents an overview of the studies in Lake Iseo, a deep lake in Northern Italy facing serious environmental challenges. Work to understand hydrodynamic processes in the lake and their effect on water quality included a comprehensive data collection program with several stations providing continuous data over more than ten years and several special field campaigns. Based on these data and results from modeling of future conditions accounting for climate change, Pilotti and Valerio argue that a small increase in the water temperature of the lake will affect the thermal stability of the water column with consequences on the deep circulation process, expanding anoxia, promoting cyanobacteria blooms and having a detrimental effect on fisheries.

Finally, starting with this issue Hydrolink has a new look. We also start a new recurring feature, publishing in each issue the biography of a prominent woman in hydro-environment research and/or engineering. The first biography in this series is that of Valentina Samsonovna Istomina, one of the first women to receive a doctorate in hydraulics in the Soviet Union, and whose research included outstanding investigations on seepage in support of the design of hydraulic structures and large dams.

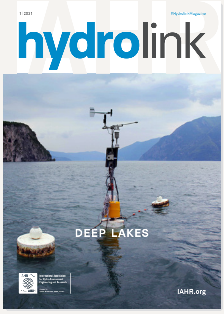
On behalf of the team that puts together the magazine, I would like to invite our readers to let us know if they have any suggestions on potential improvements to Hydrolink. We would also welcome any comments on the articles we publish. The themes of the next three issues are artificial intelligence and big data, offshore structures, and Africa. The themes of the 2022 issues have not been decided yet. We would welcome any suggestions for future themes that we should be focusing on next year.

1 | Improving Water Security by Connecting with Nature, Part 1. Averting the Extinction of the World's Freshwater Aquatic Fauna and Flora https://www.iahr.org/index/video/377

2 | A Design Strategy for Saving Lakes from the Impact of Nutrient Enrichment & Global Warming https://www.iahr.org/index/video/417

3 | Improved Water Security through Connecting with Nature https://www.iahr.org/en/lives/details?live_id=35

4 | BBC interview with Sir David Attenborough, 28 September 2020, https://www.bbc.com/news/av/science-environment-54319449



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Cover picture: Lake Diagnostic Station (LDS) moored in the lake at a point where it is 210 m deep, measuring the main thermal, radiative, and mechanical fluxes on the lake surface.

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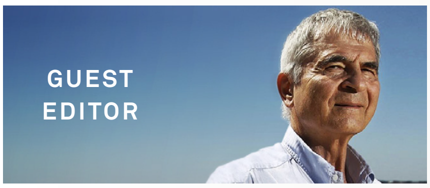

Jörg Imberger

Professor Imberger currently holds the following positions: Professor (Adjunct) RSMAS, University of Miami, Florida, USA; Visiting Professor University of Venice, Venice, Italy; Honorary Professor, Univ College London.

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Avoiding the impeding death of the global freshwater ecology: An opportunity to learn new engineering skills

By Jörg Imberger

Water is an essential requirement for human life and all of nature, yet the aggressive nature of human behaviour and the careless neglect of the externalities of our engineering designs is currently threatening world freshwater ecology. If we carry on with our business-as-usual behaviour, most freshwater life could become extinct in the next 30 years. Is this a major problem for humanity, or does it just mean that we then eat seawater fish rather than freshwater fish? Not at all: standing water bodies, natural and artificial, are enormously important for the human race. They provide water resources, recreation which is an essential element of human biology and psychology, as well as mechanisms for flood control and carbon sequestration in addition to their ecological value.

The first order impact of increases in nutrient loading in a lake is an increase in the surface layer primary production, so surface waters become more turbid, thus changing the light-capturing characteristics of the water column and hence the overall water column stability. This in turn has enormous consequences for the overall health of a lake. There is an urgent need to gain a detailed understanding of phytoplankton dynamics in general and of how phytoplankton respond to nutrients and light changes. Primary production therefore determines not only all lake food cycles, but also the overall lake hydrodynamics through its control of the water column stability, and in turn the flux path in the lake providing the nutrient gateway for the whole lake ecosystem. The stratification characteristics also determine the cascade of energy from basin-scale motions down to local turbulent patches where shear-driven turbulence finally dissipates the energies imparted to the lake by the meteorological forcing at the surface and by the inflows and outflows. The smallest scales of motion in these turbulent patches are about a hundred times larger than the size of the majority of phytoplankton, so the turbulence acts as an important agent for plankton colony formation and light access. Also, in shallow lakes an unproven hypothesis is that when bacteria seal the bottom sediments they prevent resuspension of sediments and clouding of the water column, so clearing the water for light to penetrate through the water column and enabling algal blooms are lethal to the rest of the food chain.

Consequently phytoplankton exercise a very important control over lake ecology as a whole. Adding more nutrients by increasing the loading from the catchment therefore changes not only the phytoplankton ecology but also the whole lake ecology, as well as the mixing regimes within the lake water column. As a result of supplying too much food via river loadings, phytoplankton dominate the whole lake ecology in the surface layer and rob all other organisms of oxygen in the hypolimnion, as well as increasing the water column stability and delaying the lake overturn. If this is allowed to continue so that the deoxygenated hypolimnion exceeds 80% of the lake volume, then at the next major overturn the whole lake would have an oxygen content of 1 mg L^{-1} or less all and life would be extinguished in the lake. Over the last half-century global warming has added to the problem by causing an increase in the incidence of longwave radiation, which is absorbed very close to the water surface.

The first reaction of a typical hydraulic or environmental engineer would be to say, as the German Government did, "Let's just cut the nutrient loading to the lakes". I understand that this thinking motivated Germany to spend over five billion euros on the clean-up of the Bodensee alone. This is counter-productive, because all the green matter in the water contains carbon, and about 5% of the total algal mass eventually settles to the bottom where it is included in the carbon dioxide emission budget, as it should be. Estimates in the literature suggest that freshwater lakes sequester about three times more carbon than all the oceans combined. If the freshwater clean-up action was to be included in the carbon emission budget of Germany, it would show a near-doubling of net emissions in the last ten years. Like people, lakes clearly have an optimum food uptake rate depending on the purpose of the lake management.

The objective of this issue of the Hydrolink magazine is to make the world's water engineers and managers aware of the possible disastrous consequences of the traditional business-as-usual approach to the aquatic health of the world's lakes. By explaining the particular consequences and the potential solutions it is hoped that engineers will take decisive action to care for their aquatic neighbourhoods. Following this explanation, the article by Clelia Marti describes the global nature of the problem, and David Hamilton's paper in this issue describes how the ecology of deep lakes is connected to lake stability. A concrete example of the threat to lakes is then described by Marco Pilotti and Giulia Valerio, who have done some pioneering work on Lake Iseo.

The flux paths in deep lakes and the impact of human behaviour

Increasing turbidity of surface waters causes shortwave solar energy to be captured closer to the free surface, making the surface layer thinner and warmer, so the water column as a whole becomes more stable. Further, the increased algal concentration in the surface layer causes more organic material to sink into the hypolimnion after a two-day delay. The dead algae sinking into the hypolimnion are food for the bacteria, but oxygen is needed for the consumption of the carbon, so the dissolved oxygen in the deep hypolimnion waters is rapidly depleted. This triggers a further feedback mechanism, the lower oxygen concentration in the hypolimnion aiding the release of nutrients stored in the sediments. Most lakes in the world have existed for a long time, and in the past have supported a healthy ecosystem, the bottom sediment layers functioning as sinks for the nutrients coming down the catchments in the inflowing rivers. As the river nutrient loads increase, the lake's trophic values rise above oligotrophic levels and the sediments become sources of nutrients rather than sinks. This feedback mechanism can easily double or treble the total net nutrient loading into the lake water volume. Internal wave seiching then also sets up a benthic boundary layer that transports the nutrients from the dark, deep inflow impacted waters into the base of the surface layer, where they support yet faster algal growth, completing the feedback. The net effect of this combined biochemistry and hydrodynamics is to physically increase the volume of the hypolimnetic low oxygen water in the lake by raising the level at which the oxygen level begins to decrease rapidly.

As a result, further feedback mechanisms are triggered. First, the rise of the no- or low- oxygen level increases the area of sediments exposed to this low-oxygen water, so the nutrient flux from the sediments increases proportionally. Second, the stratification increases the benthic boundary flux strength and causes it to become more separated from the general hypolimnetic circulation, so the nutrients are pumped more efficiently from the sediments into the benthic boundary layer and then directly into the base of the surface layer, bypassing the dilution associated with being mixed throughout the metalimnion and the hypolimnion volumes. Third, the increased stability renders the water column more resistant to a complete overturn and of course the longer the hypolimnetic water remains in this very low oxygen state, the more nutrients are pumped out of the sediments into the surface layer where they feed primary production, and the entire scenario starts again.

The net impact of all these changes to a lake may be estimated from an order of magnitude calculation of the effect of an increase in the turbidity closer to the water surface. Suppose we consider a lake with an average depth H, a surface area A_s and a surface layer depth h. Further, suppose we consider a lake with vertical sides in order to simplify the calculations and assume the algal and yellow substances are uniformly distributed over the surface layer with an associated Secchi depth of h_{sd}. This simplification allows us to write a heat absorption equation as follows:

$$Q_s = Q_o e^{k\,(z-\frac{H}{2})}$$

where k is the extinction coefficient and Q_o is the shortwave radiation entering the surface of the lake. Here the vertical coordinate z is taken as the upward vertical distance from the mid-depth of the lake basin, which is, for this simple lake configuration, also the centre of gravity. The rate of increase of temperature, due to this radiation, follows directly from the 'heat' budget and reads:

$$\frac{d\theta}{dt} = \frac{kQ_o}{C_p\rho_o}\, e^{-k\frac{H}{2}} e^{kz}$$

where C_p is the specific heat of water and ρ_o is the base water density. The rate of change of potential energy, PE_s, due to the shortwave radiation, relative to the mid depth, is then given by:

$$\frac{D(PE_s)}{dt} = P_o R$$

where,

$$PE_s = A_s \int_{-H/2}^{H/2} gz\ d\rho\, dz$$

$$P_o = \frac{g\alpha Q_o H A_s}{2C_p}$$

$$R = 1 - \frac{1}{\varphi} + e^{-2\varphi}\left(\frac{1}{\varphi} + 1\right)$$

and $$\varphi = \frac{kH}{2} = 1.7\,\frac{H}{2h_{sd}}$$

where it is assumed that the extinction coefficient is given to a good approximation by:

$$k = \frac{1.7}{h_{sd}}$$

and where $\alpha = 2.1 \times 10^{-4}$ °C^{-1} is the coefficient of thermal expansion and the specific heat of water $C_p = 4.2 \times 10^3$ Jkg^{-1} °C^{-1}. The impact of nutrient enrichment can thus be estimated by comparing the rate of gain of potential energy for water column turbidity characterised by a Secchi depth corresponding to the trophic status with the rate for an oligotrophic (h_{sd} = 8 m) water column. Let us assume that Lake Iseo, discussed in the article by Pilotti and Valerio, provides values typical of large lakes in mid-latitudes. Suppose the average annual incoming net solar radiation is Q_o = 200 W m^{-2}, the basin surface A_s = 65 km^2, the surface layer thickness h = 15 m and the average depth H = 124 m. The Secchi depth, h_{sd}, in Lake Iseo changed from a value of 8 m between 1965 and 1980 to 4 m in 2015[1]. Substitution of the above values into the various equations yields an estimate for the change in the rate of change of potential energy due to the penetration of solar radiation, as shown in Table 1 which also accounts for the effect of global warming. Clearly when the water is very transparent, so that h_{sd} > H, the radiation will reach the lake bottom, heating the lake bottom, causing natural convection to uniformly heat the lake from the bottom.

Global greenhouse gases absorb the outgoing longwave radiation and thus, as the name implies, warm the whole earth at a rate of about 2 °C per 100 years under the business-as-usual scenario. The warmer atmosphere in turn then radiates back a little more longwave radiation, increasing the incoming longwave radiation impacting the lake water surface. The global average increase from 1950 to the present was about 5 to 6 Wm^{-2} [3] which is absorbed at the surface of the lake. Hence in the simplest of terms, global warming again leads to an increase in water column stability, putting further pressure on the lake overturn mechanisms. An estimate of the

i	Secchi Depth, h_{sd}	φ	R	$\frac{D(PE_s)}{dt} = P_o R_i + P_o^{GW}$	$P_o R_{i+1} - P_o R_i$	State
	m			W	W	
0	>>H	0		11,860		Transparent
1	62	1.7	0.4648	195,615	183,755	Clear Water
2	8	13.2	0.9242	377,236	181,621	Oligotrophic
3	4	26.4	0.9621	392,220	14,984	Mesotrophic
4	0.5	210.8	0.9953	405,345	13,125	Eutrophic
5	0	∞	1.0000	407,203	1,858	Extreme Pollution

Table 1 | Rate of increase of potential energy as a function of the lake trophic state with Po = 395,343 W

impact of this change may again be obtained by calculating the rate of change of potential energy now compared to that in 1950, assuming that the incoming shortwave radiation stayed approximately constant and the longwave average radiation increased by say 6 Wm^{-2}, in the 60 years between 1950 and 2010. If it is assumed that all this extra longwave energy is absorbed in the top 1 cm of the water column (R=1), then the rate of change of potential energy resulting from this radiation increase would lead to rate of potential energy increase P_o^{GW}= 11,860 W.

Consider a typical overturn event in a lake approximated by Lake Iseo. Every year the lake stratifies in the summer months and begins to cool in the autumn until a major cold storm event causes the whole water column to overturn. To gain an understanding of the effect of the increased potential energy, consider our sample lake. At the end of the summer the stratification may be approximated by a two-layer system[2]. The surface layer is, say, 15 m thick at 25°C (density = 996.79 kg m^{-3}) and the water underneath is uniform at 6 ºC (density 999.9 kg m^{-3}) , leading to a density difference of Δρ = 3.11 kg m^{-3}. The total potential energy associated with such a density change can be calculated from the following equation:

$$PE = A_s\, h\, g\, \Delta\rho((H-h)/2)$$

which gives 1.62 x 10^{12} J.

An overturn event is a combination of surface cooling and wind mixing. Suppose that 85% of this potential energy is removed by cooling, leaving 2.43 x 10^{11} J for every year the overturn is delayed, to be mixed by the wind. Again, by way of example, suppose that the water surface shear velocity is:

$$u_* = \left(C_D \frac{\rho_a}{\rho_o}\right)^{1/2} U_w$$

where the drag coefficient C_D ~10^{-3} is assumed to be constant, the air density ρ_a = 1 kg m^{-3}, the reference water density ρ_o = 1000 kg m^{-3}, and the wind speed is constant and uniform and has a duration of 2 weeks (T = 1.21 x 10^{6}s) then the wind strength, U_w, necessary to impart this amount of energy is given by the balance:

$$\rho_o u_*^3 A_s T = \rho_o \left(C_D \frac{\rho_a}{\rho_o}\right)^{3/2} U_w^3\, A_s T =$$

$$= 65\, T U_w^3 = 2.43\, x\, 10^{11}$$

implying a wind strength U_w = 14.57 m s^{-1} (52.5 km hr^{-1}).

If the potential energy of the water column had been increased by one year's radiation being absorbed by a eutrophic lake plus global warming impact, rather than an oligotrophic lake and no global warming impact, then the additional energy that must be mixed by the wind would have been 1.89 x 10^{11} J (from 0.15 x 39,969 x 3600 x 24 x 365). This needs to be added to the potential energy, increasing the wind speed needed for complete mixing to 17.64 m s^{-1} (63.5 km hr^{-1}). A ten-year delay between overturns would require a two-week wind event with a wind speed of around 30.04 m s^{-1} (108 km hr^{-1}).

This illustrates the fact that nutrient enrichment and to a lesser extent global warming have very detrimental impacts on large lakes such as Lake Iseo. Global warming is also known to increase the weather extremes, so a scenario of a number of mild weather years, when there is no lake overturn, followed by a severe weather year is clearly a recipe for disaster. The stability keeps getting strengthened during the calm years, prolonging the period between overturns, with associated increase volume of the no-oxygen water in the form of the hypolimnion.

As explained in the article by Pilotti and Valerio, by way of a concrete example, in the 1950s Lake Iseo completely overturned annually or biennially with minimum hypolimnetic oxygen concentration dropping to about 4 mg L^{-1} in about 50% of the lake volume. This has changed to a situation where oxygen levels at a 200 m depth dropped to zero in 2010, five years after the last complete overturning in 2005. The lake still has not overturned and currently the hypolimnion volume has an average oxygen concentration of around 2 mg L^{-1} and occupies about 90% of the lake volume. Should an abrupt overturn occur at any time, then all the water in the lake, including the epilimnion would reach an oxygen concentration low of approximately 2.5 mg L^{-1}, a value at which no aquatic life can exist. The devastation would be catastrophic!

The ecology of many lakes is largely endemic, so once it has been suffocated that is the end of all species in these lakes.

Can this disastrous situation be avoided? About ten years ago I had a conversation with a very enthusiastic young water treatment engineer who told me about the submerged impellers he had used to mix water tanks in a treatment plant. Lakes are huge compared to treatment water tanks, so I did not make the connection until a few years later, when we showed[1] that a 2 m diameter Flygt mixing impeller generates a jet with a mean velocity of about 0.9 ms^{-1}, a volumen flux of 4.2 m^3s^{-1} leading to kinetic energy flux equal to $Q\rho u^2$ = 3,402 W into the water body. Numerical simulations showed that the momentum from the impeller is sufficient to penetrate down to about 200 m. Hence, to first order N such impellers mounted in the surface layer, pointing downwards, could introduce sufficient mixing energy $N\varepsilon Q\rho\, u^2$ to eliminate the extra potential energy, $\Delta(PE_s)$, per second (14,900 W) from the change of turbidity and global warming, where:

$$N = \frac{14{,}900}{\varepsilon Q\rho\, u^2} \sim 22$$

and where ε is the mixing efficiency of the impeller assumed to be 0.2. This result suggests that a maximum of 22 impellers, could be a solution to staving off the pending disaster in large deep lakes discussed above. Motivated by this calculation, we carried out a series of numerical simulations and found that by moving vertically the downward-pointing impellers on a daily basis, so that they were always located at the depth of the thermocline, the efficiency could be greatly increased[1]. We found that five Flygt impellers were sufficient to arrest the degradation due to the increased trophic level and global warming in the very large Lake Iseo. More work is needed to find the position of impellers for optimum efficiency.

Recently considerable progress has been made in establishing lake data bases containing both in situ and ad hoc data of both physical and ecological state variables as well as time-series data from satellite remote sensing of the surface area, the surface water temperature and even water surface roughness. An example of such a database is, HydroLAKES. The National Oceanic and Atmospheric Administration (NOAA) also has also made publicly-available data from a global weather model that runs both in real-time and forecast modes under the assumption of three future scenarios (lower greenhouse emissions, business- as-usual, and higher emissions), making it possible to set up real-time and forecast simulations of any lake of interest. The authors of this Hydrolink issue are conscious of the vast expertise residing in the IAHR organisation and the objective of this article is to raise the awareness of the problem within the IAHR community in the hope that members will take an interest in their local lake environments and if there is a potential problem, they persevere at finding a way to avoid this massive killing of the earth's freshwater aquatic life by the aggressive lifestyle of humans.

A completely new field of engineering has emerged recently, pioneered by physical limnologists. Adaptive Real-Time Management Systems (ARMS) are coupled high resolution numerical models that can simulate the environmental state variables in any particular domain. However, care must be taken to choose the right models and the operators should not be afraid to change models if they do not predict what is being measured. The systems should also contain several critical real-time measuring points, where state variable data are collected in real time for model validation. Such applications have four further components:

- They contain algorithms that trigger calls to action to the relevant administrators by sending out action emails to the persons responsible for managing certain control functions in the domain.

- Administrative staff can insert into the simulations any proposed domain changes, such as land clearing, building of new canals, dredging, more boat traffic, higher nutrient loading etc., in order to simulate the likely impact of proposed developments under the three future atmospheric scenarios. This can alleviate unexpected disasters and also allow a lake administration to levy impact charges on proposed developments.

- New self-learning systems are becoming available that use AI algorithms to autocorrect model calibration coefficients or even automatically modify the simulation codes in order to make the simulations more accurate.

- Data from the simulations can be made available to the general public via smart phone access, with the capability for all stakeholders to upload their responses to what is happening to their favourite water bodies and for managers of the domains to bring any predicted, non-supporting water quality conditions under control before they become an issue. Such output would raise awareness among all the stakeholders and hopefully improve awareness and understanding of local environments in order to act in the more considered way to protect it.

Experience with such a sophisticated system in Western Australia has been extremely positive. Millennials who are more proficient at accessing websites than their parents quickly learned about their physical environment and uploaded their reactions on a daily basis. Naturally, parents being proud of their children's uploads, also started to take ownership of their local environment and it was only a matter of three years before over a hundred junior schools and high schools were using the system as a teaching tool. The objective of such a management system is to involve all stakeholders and make everyone aware of the consequences of their actions with respect to the liveability of their local neighbourhood, as well as the global environment. The most powerful tool to get humans to do what is good for their "home" in the long-term is to make sure that they take ownership.

With this focus, such models could predict the probability of a devastating lake overturn and its ecological consequences. The public would react quickly and urge lake administrators to avoid the disaster. An example of such a public concern occurred in Paraguay, when the community around Paraguay's icon tourist attraction, Lake Ypacarai, woke up one morning in 2012 to the totally unexpected sight a huge number of dead fish on the shore of the

Figure 1 | Dead fish on the shores of Lake Ypacarai close to Asunción, the capital of Paraguay, following a blue-green algal bloom. Photo: AFP/GETTY IMAGES

lake and the lake water a solid green colour emitting a terrible stench (Figure 1). In that case there had been no predictions so the impact was even more devastating, to the extent that the economy of Paraguay was affected, the whole country suffering economically. By rendering the model predictions on a virtual reality platform, the general public would be able to go for a walk via the virtual reality goggles along the shores of their favourite lake as it might look months or even years into the future and then and compare the stroll along the shore of their lake with that of walking along lakes in other countries. This would immediately provide public support for the administrators to take action should a disaster be threatening. The management would then also be able to test various alleviation measures and obtain cost efficiency predictions, as well as time-management system study plans. The adaptive approach flexibly accommodates changes and provides a range of solutions.

Clearly, if all the lakes in the database were managed using an adaptive approach then the world would be a much safer place for the freshwater ecology. Further, by setting up all data and information in a real-time system with outputs available on the web, the managers for one lake could learn very easily from the experiences of everybody else. Further, there would be many side benefits of such systems being rolled out around the world for all to share, raising the awareness of the public of its own impact on nature in general! The emperor's words would be heard (Fig. 2).

Figure 2 | "People, Your wasteful lifestyle is unsustainable and will lead to your and our extinction in the near future unless you adopt a more holistic management approach that will teach your people to behave more sustainably and account for the fact that technology has given humans a reach and action that now extend all over the world. Management must recognise that every stakeholder must be kept informed of the implications of their actions and the externalities their actions. Humans must also be taught, at an early age the services nature provides humans, so that they show greater respect towards us."

The fundamental knowledge of limnological processes is available to set up what has been suggested. In environmentally responsible societies the mixing impeller solution could be used as a temporary solution until catchment nutrient loading strategies took effect. In others, what is outlined in this issue would provide a vehicle for the community to learn how to live more sustainably with respect for their local environment. Managing a water body is the same as managing our food intake: with no food you die and with too much food you die, and the optimum good health diet depends on a person's lifestyle. A water body is much the same. First, the stakeholders need to define a quantitative vision to assess whether their water body and its environment has a problem and the extent of the problem when seen from the perspective of their vision. Second, they must develop a strategy that will ensure that their vision is achieved on the expected time scale. Such a strategy should include adjustments to the nutrient loading, so as to optimize the ecological health of the fauna and flora in the lake, the rate of carbon sequestration, all embedded in the overall vision of the community in which the water body is located.

Our hope in preparing this Hydrolink issue is that it will make water engineers around the world aware of the threat to their water bodies, providing an incentive to start setting up a real-time management system for their local lake in the form of a gateway to nature for the community they live in. Further, the technology pioneered by physical limnologists offers engineers new design strategies applicable to many other fields of engineering. Engineers coming on board will automatically develop a competitive advantage in their other problem-solving activities.

Lastly, by projecting the underwater life in their lake into every home in the world via a virtual reality technology the community will start taking ownership, the engineers will better understand possible externalities of their designs, and aquatic life will have a future! Lakes need our help, but in return they offer humans a way to develop a new lifestyle where we are confronted with the consequence and externalities of our actions, a more sustainable lifestyle that will ensure that the future of the human race is more secure in this finite world we live in!

Conclusions

According to the HydroLAKES database there are over 1.4 million lakes scattered around the world that have a full surface area that is greater than 10 ha. About one million of these lakes are deeper than the seasonal thermocline, hence the severity of the problem cannot be exaggerated.

First, about 80% of all species in lakes are endemic to a particular lake as discussed in the article in this issue by Clelia Marti. Thus, the loss, should such a suffocation disaster occur, would be simple enormous.

So, by IAHR members taking an interest in their local lakes they can learn and then make their colleagues in other fields of engineering aware of the importance of identifying and then quantifying the impact of all possible externalities of a design.

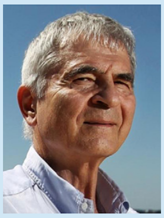
Engineers, no matter in which field they are working, rarely take into consideration the externalities of their designs. In the past, rivers and lakes had very low nutrient concentrations, but then people had no cars that pollute the atmosphere with carbon and did not waste 50% of the food they harvested. If we are to avoid a global disaster, then we cannot concentrate on a few simple priorities, but we must embed our solutions into a global picture. The world is now finite!

Further, the management of lakes offers a great opportunity to teach the world of engineering that strategies must adjust to the fact that the humans now have global reach and action. Simple 5-year, 10-year or even 20-year plans are no longer the way to manage the environment. There are four main reasons for this:

- Static plans are very rarely adhered to because strong, rich individuals always get their way, so any plan quickly becomes obsolete.
- Technology is changing much faster than the environment can heal itself so in, say, ten year's time the impact of humans on a lake and their vision for a lake will probably be very different, and it would be pure luck if today's "Plan" had foreseen those changes.
- The information overload that people have to cope with these days is simply too large for them to take a deeper interest in their local environment.
- Social media has become so ubiquitous that "truth" is now defined as something that is repeated often enough, which means that a static plan becomes irrelevant almost overnight.

I would like to close on a personal note. I think many IAHR readers will have heard of me, so may I appeal to you all, please try to take notice and help the bugs, the fish and the shrubs in your local neighbourhood. Nature provides a nice environment for your children to grow up in.

Make nature your religion and remember the very famous quote from my friend, John Watling: "if insects became extinct the world would collapse, if humans became extinct the world would flourish".



GUEST EDITOR

Jörg Imberger

Professor Imberger currently holds the following positions: Professor (Adjunct) RSMAS, University of Miami, Florida, USA; Visiting Professor University of Venice, Venice, Italy; Honorary Professor, Univ College London. He is a Board Member of the following Companies: WeatherTec-Services Pty Ltd; Airwater Pty Ltd; Quobba Propellers Pty Ltd. Jörg Imberger received his PhD from UCB at 28 years of age and became Australia's youngest full professor at 35. His research interest are in environmental engineering as applied to rivers, lakes, estuaries and coastal seas. Recent foci also include strategies for sustaining functionality of aquatic systems in a changing world. He is a Fellow of 10 International Academies and the recipient of 30 major honours including the Onassis International Prize, the Stockholm Water Prize and Member of the Order of Australia. He has published 5 books, with two further in preparation, contributed to 19 books and has published 275 journals papers. Google Scholar credits him with 23,873 citations and an h-Index of 70.

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A global problem: trends in nutrient loadings of lakes with climate change and increasing human developments

By Clelia Luisa Marti

Lake ecosystems are resources providing many valuable services. Some (like food, drinking water, energy production, flood damage reduction, navigation, recreation and tourism) are directly valued by the human population while others (such as aquatic wildlife habitat, biodiversity hotspots, conservation of endangered species) have positive environmental impacts that benefit us indirectly[1]. The ecosystem benefits provided by lakes are variable, depending on their underlying ecology and on their location, because lakes are intimately connected with their surrounding landscape and human communities[2].

Lake ecosystems around the world are being exposed to environmental changes having origins both anthropogenic (inputs of excess nutrients, harmful algal blooms, overexploitation of water and food resources, emerging organic pollutants, etc.) and climatic (global warming, changes in precipitation patterns and amounts). Changes occur in the physics, biology and chemistry of lakes, as well as in interactions between their internal compartments and their connectivity with the surrounding landscape. These changes are predicted to intensify in the future, threatening the functioning of the ecosystems and the services they provide on both local and global scales, and causing unprecedented world-wide concerns[2, 3]. Some anticipated impacts are likely to be similar across different lake ecosystems, while others may be system-specific[4].

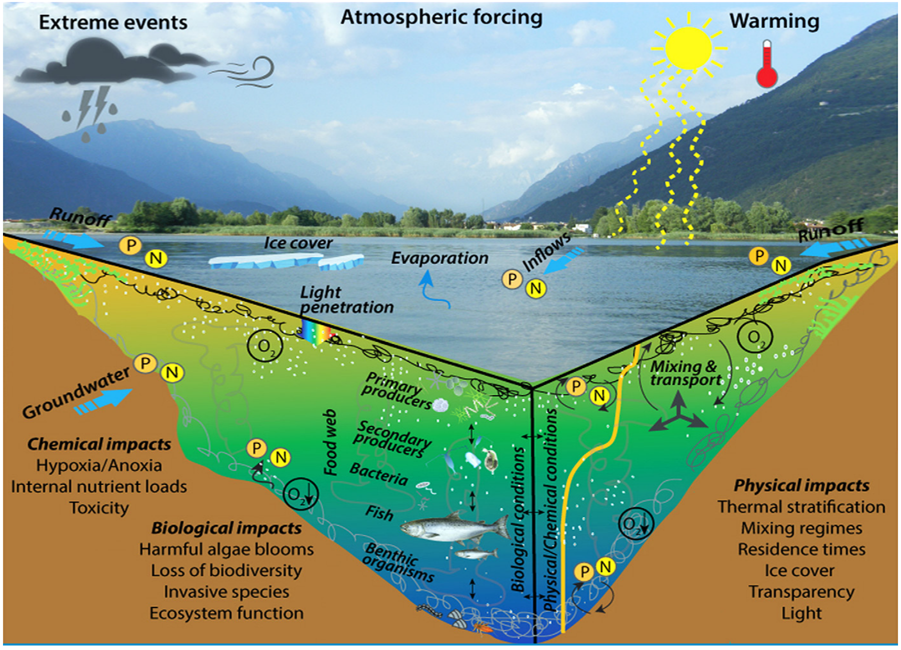

Figure 1 | Schematic showing the major impacts of global warming and increased nutrient loading on lakes.

Intensive research efforts over past decades have provided alarming evidence worldwide of resource depletion (particularly water and food), increasing water temperatures, reduction in polar ice cover, depletion of oxygen in deep waters, fragmentation and destruction of habitats and ecosystems, loss of biodiversity and accelerating pollution, among others[1, 3, 5, 6, 7, 8, 9, 10, 11, 12, 13]. Furthermore, long-term monitoring datasets together with increasing in situ real-time high resolution monitoring data and numerical modelling (i.e., ranging from land-use and climate models to hydrodynamics, biogeochemical and physiological models) have played a key role in quantifying this degradation and increasing our knowledge and understanding of the possible impacts on lake ecosystems[14]. Continued efforts are therefore required to focus on how long-term and emerging threats (including micropollutants and microplastics) will interact and how lake ecosystems will respond. Prediction of these effects will be critical to resource management, to public understanding of changes that have already begun, and to establishing lake restoration and adaptive management strategies for protecting and sustaining lake ecosystems. Increased nutrient loading and climate change are the most widespread stressors having strong impacts on the lake ecosystem environment[13, 15, 16] (Figure 1). A description of the main impacts and trends is summarized below. Increased nutrient loadings as a result of agricultural, urban and industrial development of catchments and lake shoreline areas is, as in the past, a key cause of this 'cultural eutrophication'[16].

In spite of extensive research since the 1960's, cultural eutrophication remains a major concern worldwide[15] and has emerged as an increasingly important issue in the context of protection of water resources for future generations[17]. Cultural eutrophication may lead to many drastic lake ecosystem changes[15, 16]:

- Decrease in water transparency.
- Increased incidence of oxygen depletion (anoxic events < 0.5 mg/L or hypoxia < 2 mg/L).
- Overgrowth of phytoplankton.
- Accumulation of organic matter and a large recyclable sediment phosphorus (P) pool.
- Loss of biodiversity and rapid homogenization of biotic assemblages.

Figure 2 | HAB in Burlington Bay, Lake Champlain (Vermont, USA).

It has been known for many decades that eutrophication fuels excessive plant and algal growth, including harmful algal blooms (HABs). These blooms may produce noxious toxins and high water turbidity, cause fish kills due to hypoxia/anoxia, food-web alterations and impair important ecosystem services such as water supplies for human consumption, agriculture, irrigation, aquaculture, and fisheries, as well as recreational and aesthetic values (Figure 2). There is a vast literature on this topic[13, 14, 15, 16].

Historically, cultural eutrophication has been associated with an oversupply of P[16]. However, nitrogen (N) loading from anthropogenic sources has increased at alarming rates and has been shown to be directly implicated in water quality degradation and eutrophication[16, 18]. More than 40% of lakes are eutrophic and affected by algal blooms. Between 1900 and 1950 surpluses of P and N in agricultural soils increased by nearly eight-fold and two-fold, respectively, and by around four-fold for both nutrients between 1950 and 2000. Despite enhanced efficiency of nutrient recovery, surpluses are projected to increase further to 2050[19]. Between 2010 and 2050, the number of inhabitants connected to a sewage system will have increased by 2 to 4 billion people and nutrient discharge to surface water will have increased by 10% to 70% despite a 10% to 40% increase in nutrient removal in future wastewater treatment facilities[20]. A portion of these additional nutrients inevitably enters the aquatic ecosystems and such increases are and will be stressing aquatic resources in the future.

Reduction of P load inputs to aquatic ecosystems has generally been advocated as a key eutrophication mitigation step based on the assumption that P universally limits HABs[15, 16]. Phosphorus accumulates in both the water column and sediments, as there are no gaseous forms facilitating P escape from aquatic ecosystems, other than phosphine (phosphane) and diphosphane, which are occasionally generated in “marsh gas” from stagnant waters. Phosphorus mainly leaves aquatic systems by flushing or ending up in the sediments leading to a legacy of P supply supporting persistent internal loadings (which are regularly activated by resuspension of bottom sediments, as well as effective P regeneration from the sediments). These “legacy nutrients” provide a positive feedback loop supporting HABs, so even if P inputs are reduced, reversing the harmful effects of eutrophication can take a substantial period of time, especially in large lake ecosystems with long water residence times. Reduction of P has decreased HABs in many lakes but has been unsuccessful in others[16, 21]. Nitrogen can leave an aquatic ecosystem as a gas (e.g., N_2, N_2O, NO, NH_3), but some N also ends up in solution leaving a legacy in water bodies. Annual rates of denitrification often exceed rates of N_2 fixation especially in bloom-prone eutrophic systems. Therefore, chronic limitation of N is maintained, and external N inputs play a critical role in supporting eutrophication and sustaining HABs. Recent studies have shown that combined P and N enrichment rather than N or P alone often stimulates HABs more, indicating that the dynamics of both nutrients are important for their control. As a result, external loads of both P and N need to be constrained in order to impose more nutrient-limited conditions, so as to mitigate the HABs problem in light of global agricultural, urban and industrial expansion, and climate change[16, 18].

Significant progress has been made in developing and implementing management strategies to minimize the effects of cultural eutrophication since the 1960s. The reduction of external nutrient loading has proved to be one of the most effective measures for sustainable control of HABs. However internal loading of legacy nutrients from the sediments enriched by years of high nutrient inputs often causes a delayed response in water-quality improvements following reduced external nutrient loading. In-lake methods of HAB control (mechanical mixing, hydraulic or pneumatic pumping, floating covers, biological control, chemical control, sediment removal) represent a final fallback position, sometimes necessary to prevent the negative impacts of severe HABs but mostly failing to address the root cause of nutrient over-supply. These approaches are generally expensive and have been successful in small (< 50 ha) ecosystems, but not in large lakes[18].

Climate change has been identified as one of the most important issues facing humanity today and has already had an impact on the structure, function, and ecosystem services provided by lakes[1,3]. A substantial body of research demonstrates the responses of lakes to climate change[6] including increases in surface water temperature[5], reduction in ice cover[8], altered stratification and mixing regimes[7], and increases in evaporation rates[22].

Deep lakes, which tend to be large in surface area, are more likely to lose ice cover in a warming climate than shallow lakes at similar latitudes[8]. Similarly, the average *surface water* temperatures of large, deep lakes have often been found to be rising at rates as high as 1.0 °C per decade and these rates are projected to increase in the future[5]. On the other hand, *deep water* temperatures have shown little change on average[23]. It is predicted that higher latitude lakes will tend to become more like lower latitude lakes[24]. The warming rates seem to vary widely among lakes[5], and even spatially across large lakes[25]. Interactions with other stressors can also lead to negative consequences[16,26]. For example, changes in precipitation patterns and amounts, runoff, evaporation, and water usage have contributed to shifts in seasonal water levels in some lakes, whereas historically low or high water levels in others, leading to changes in water quantity and quality. Factors varying feedback from large lakes to the atmosphere have also been identified, such as increasing regional air temperatures[3].

Changes in the thermal structure of lakes affect their ecological function, including key processes like nutrient cycling and depletion of deep-water dissolved oxygen[7,9,10]. During the stable stratified period, increases in the strength or duration of thermal stratification isolate the cool, deeper waters by reducing vertical mixing, with profound implications for nutrient and oxygen availability, food-web structure and habitat[11]. These deeper waters are the sources of important thermally dependent biogeochemical processes, such as P release from anoxic sediments and methane production[27] and they offer critical habitats for many temperature-sensitive aquatic organisms. There is increasing concern about the loss of cold-water fish species, such as salmonids[28].

Besides the extent of the stratified season, the maximal depth of convective mixing in winter (the "winter mixing depth") also plays a key role in oxygen renewal, nutrient upwelling and primary productivity in deep lakes. Deep lakes have considerable quantities of nutrients stored in the deep hypolimnion. These can increase productivity when penetrative convective events or strong winds allow mixing with the euphotic zone. For example, in Lake Constance (Bodensee) that borders Germany, Austria and Switzerland and Lake Garda in Italy, nutrient availability in their upper layers depends to a substantial degree on the winter mixing depth[10,29,30]. Given ongoing climate warming, the increase in both autumn stratification and winter temperatures will continue to reduce the winter mixing depth resulting in reduced nutrient availability in the spring, which is often the limiting factor for primary production. Recent studies have reported decreased upwelling of nutrient rich deep-water with potential impacts on primary productivity in deep lakes[29], so shallower winter mixing will lead to a reduction of algal growth ("climate warming-induced oligotrophication"). However, changes in nutrient availability may also cause shifts in phytoplankton communities, which in turn affect nutrient budgets[10]. The mixing depth affects oxygen replenishment during winter-spring turnover. In some Italian lakes (e.g., Magiore, Como, Garda) a decrease in deep-water oxygen content has been reported and in others (e.g., Lugano and Iseo) there is an increase in the extent of anoxic conditions as a result of climate change[9]. Such conditions may adversely impact the habitat of benthic organisms[31], enhance the internal P cycling[32] and limit fish habitats[12].

In particular critical conditions, such as those experienced by anoxic lakes, there is potential for the whole water column to be oxygen-depleted, resulting in death of all aerobic organisms as an effect of full lake turnover[9].

Furthermore, climate change has altered the horizontal temperature structure in some lakes by warming offshore surface water more rapidly than shallower nearshore waters[25]. This change has implications for lake organisms, given that temperatures above a particular threshold are lethal to some species[12]. This is important for colder water species in a warming climate. The seasonal timing of population development for organisms within lakes is being affected by changes in the growing season length within lakes[12]. Climate change has led to phenological shifts within and among trophic levels, which might cause a mismatch between prey and predator with wide-ranging consequences in reproductive success, survival and growth, especially when the warming rate is seasonally heterogeneous, thereby ultimately affecting lake ecosystem structure and function[33].

Climate change is also expected to amplify the adverse impacts of eutrophication in the future and further degrade lake ecosystem health and the services provided by them[1,13]. The combination of rising temperatures with higher nutrient loading is linked to HAB magnitudes, frequency, distribution and duration and can also enhance the toxicity of HABs[16]. Climate change has altered the duration, magnitude, and frequency of extreme events, including flooding, droughts, forest fires, and heatwaves[26], with significant environmental impacts on both terrestrial and aquatic ecosystems reducing ecological resilience. Excessive episodic rainfall events (Figure 3) followed by extensive summer droughts can promote large nutrient pulses followed by lengthy residence times, and enable the development and proliferation of HABs[16]. Climate change is fueling wildfires leading to nutrient loading due to increased sediment movement from catchments, especially when followed by extensive rainfall and flooding. This has been the case in California and recently in eastern and southern Australia[14,34].

Figure 3 | High intensity storm over the catchment of Lake Argyle (Western Australia, Australia).

In addition to augmenting P inputs associated with the mobilization of sediments, deforestation also triggers N loadings, as seen in the shift in the Laurentian Great Lakes nitrogen cycle[35]. Thus changes in these climatic drivers will need to be integrated into the development of nutrient input reductions that will effectively maintain HABs potentials below specific nutrient loading thresholds for individual lake ecosystems[16].

Key uncertainties remain about how climate change will affect lake ecosystems: continued research efforts and long-term assessment will be required to fully understand and predict future changes and effects on humanity.

Lake Constance is an example of successful management of eutrophication. Total phosphorus (TP) concentrations have now decreased by an order of magnitude to levels (6-8 μg/L) typical of those prior to the massive eutrophication that occurred from the 1950s to the 1970s [36]. Until quite recently, phytoplankton and zooplankton populations responded as predicted and extirpated species reappeared. Conversely, species that increased with eutrophication declined [37], and blooms of cyanobacteria also decreased [36]. Overall productivity decreased, which probably contributed to reduced growth and standing stock biomass of whitefish, the most commercially important fish species in Lake Constance, threatening the sustainability of fishery resources in the lake [38]. Recently, massive changes affecting multiple tropic levels of the pelagic food chain have been observed in Lake Constance. Most remarkably, the invasive sticklebacks, a littoral fish present in Lake Constance since the 1950s, changed its habitat and is now the dominant fish species in the pelagic zone [39], the habitat of the originally dominant whitefish. Its growth, and also (possibly due to stickleback predation on eggs and larval fish) recruitment, declined [39]. The zooplankton community has changed due to the overall increased predation pressure in the pelagic zone. Moreover, despite TP concentrations below 10 μg/L, the abundance of the cyanobacterium *Planktothrix rubescens* recently increased. Although lake managers have successfully combated the eutrophication problem in Lake Constance, the extent to what food web structure modifications due to the massive stickleback invasion of the pelagic zone and/or climate warming are causing these changing environmental conditions is currently unclear; thus likely to alter the ecosystem services that this lake provides[3].

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Her main research is focused on improving the scientific understanding of transport and mixing processes in SWS and the interplay between these processes and the biogeochemistry of the environment using high-level process fieldwork and data analysis, numerical modelling and mathematical scaling.

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The ecology of large lakes and the connection with thermal stability

By David P. Hamilton

Eutrophication and the resulting degradation of large lakes is usually pervasive and long-lasting. Symptoms of degradation are manifested as increased frequency of cyanobacterial harmful algal blooms (CyanoHABs), anoxia of bottom waters, reduced complexity of food webs and the attendant loss of biodiversity. Its causes – mostly from elevated external and internal loads of nutrients (phosphorus [P] and nitrogen [N]) – have been described for many decades [29, 6]. Other global environmental problems, such as synthetic pesticide disruption of food chains and destruction of the ozone layer by chlorofluorocarbons, were also described many years ago but have been at least partly remediated by coordinated global responses following scientific identification of their causal factors. Controls on nutrients still remain a 'tragedy of the commons'; despite progress in addressing point sources, diffuse nutrient emissions remain a major problem and are dispersed among a few main actors who continue to impact the broader benefits provided by lakes, their services and their role as refugia for biota [9].

Phosphorus and nitrogen

Lakes, at the base of the hydrological landscape and representing some 87% of liquid surface freshwater on Earth, are sentinels that reflect the extent of anthropogenic perturbations in their catchments and climate change [1,33]. Many of these perturbations are associated with the disruption of biogeochemical cycles, where humans have magnified nutrient fluxes into and out of lake catchments, as well as reducing the resilience of the system to withstand these perturbations. The 'Green Revolution' of the 1960s markedly increased agricultural food production and averted potentially dire food shortages, but it was also a precursor to massive inefficiencies of phosphorus retention on the landscape, generating diffuse runoff from erosion and losses of P from excess P in the soils of intensive agricultural systems. Estimates of this inefficiency vary among studies, from 5 to 33% depending on assumptions made in P balance calculations [17]. The Green Revolution was also made possible by the Haber Bosch process of artificially synthesizing inorganic N, resulting in dramatic increases in crop production and reduced reliance on recycled forms of N. Nowadays, N from anthropogenic sources dominates the global N cycle and synthetic applications of N continue to be lost to the environment at an accelerating rate [7].

We are now developing rich databases of lake responses to global change [18] and they are also irrefutably pointing to the synergistic challenges arising from increases in temperature of surface waters [20], including heat waves [35], and nutrient additions leading to eutrophication [13].

The Green Revolution in agriculture in the 1960s quickly led to green lakes – "The Algal Bowl" described by Vallentyne [31] – that subsequently led to development of policies for P management in North America (primarily P control in detergents, led by the late D. W. Schindler) to avert the impending environmental disaster from eutrophication described by Vallentyne. Increasingly, nitrogen, as well as phosphorus, has been recognised as a causative agent of eutrophication in aquatic systems. For example, nitrogen additions have been linked to CyanoHABs, including increased CyanoHAB toxicity [12], even though some cyanobacterial taxa are diazotrophic and can 'fix' atmospheric N, loss of submerged macrophyte communities that act as stabilizing agents for lake primary productivity [21], and eutrophication of downstream estuaries and coastal systems where nitrogen is the primary limiting nutrient for algal productivity [23]. A dual strategy, involving control of both N and P, is now recognised as critical for restoring the health of aquatic systems impacted by eutrophication [5,9].

Anthropogenic atmospheric pollution is another form of diffuse pollution which particularly affects oligotrophic lakes and extends to continental scale. Even the most remote lakes at high latitude or elevated altitude in the northern hemisphere have not been spared from eutrophication as a result of emissions of nitrous oxide from anthropogenic sources [2], with this form of N also a potent greenhouse gas. Current rates of atmospheric P deposition are estimated to be 1.4 times higher than pre-industrial levels [3], with land use practices, particularly fires and tropical deforestation, and desertification associated with climate change, identified as increasing soil dust emissions and ultimately leading to greater dry deposition of P. Oligotrophic lakes in the Southern Hemisphere have been identified as being especially vulnerable to increased P deposition.

Nutrients, hydronymamics, eutrophication and climate change

There are 1,709 lakes of area >100 km^2 on Earth and while these represent only 0.2% of the total number of lakes greater than 0.1 km^2, they account for more than 90% of the surface area and volume of water contained in lakes globally. While lakes may be regarded as sentinels for the way that they respond to external stimuli, i.e., catchment hydrological and nutrient loads and climatic variables,

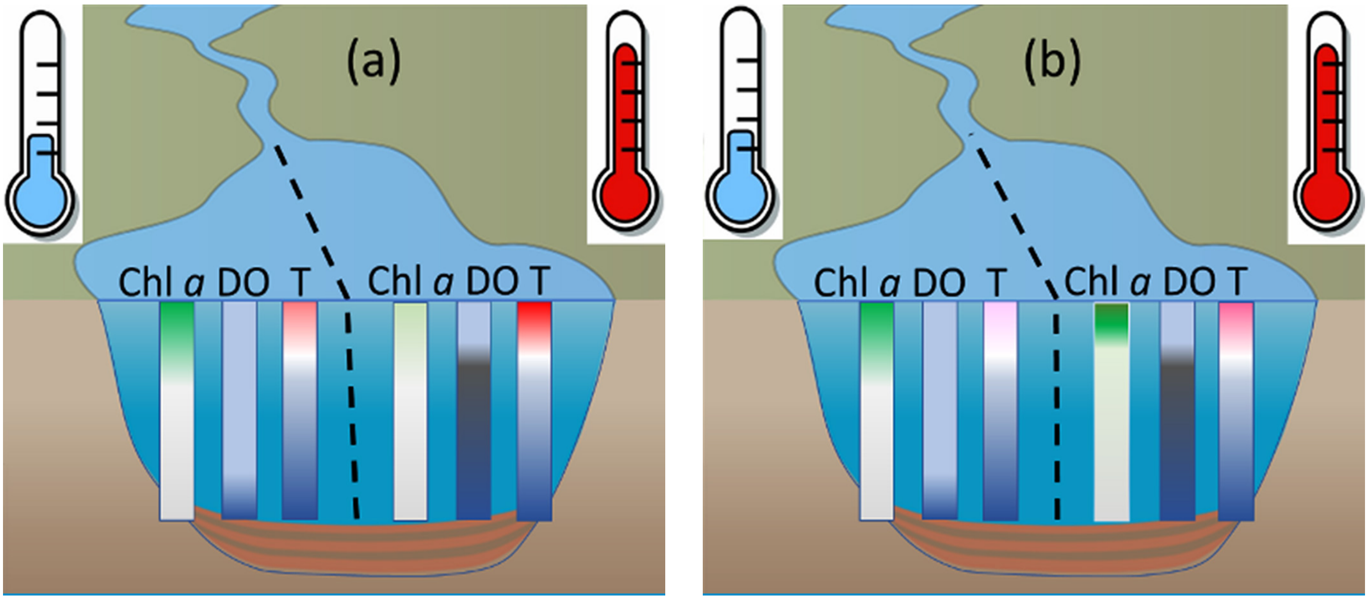

Figure 1 | Conceptual model of changes in water column (vertical bar) chlorophyll *a* (Chl *a*), dissolved oxygen (DO) and water temperature (T) under a 'baseline' (e.g., 1990s, blue thermometer, left-hand side of each panel) and a future climate (e.g., 2080s, red thermometer, right-hand side) for deep lakes in (a) tropical/sub-tropical and (b) temperate climates. Vertical coloured bars scale from low (bottom) to high (top) values. Baseline and future climates are separated by a dashed line in each panel.

this paradigm simplifies the reality of complex lags and feedbacks[28]. Lake Baikal in Siberia, the world's deepest lake (maximum depth >1,600 m), which was thought to be highly resistant to eutrophication and climate change because of its enormous volume and thermal inertia, has shown an increase (as of 2005) in average water temperature of 1.21 °C since 1946 and chlorophyll *a* of 300% since 1979, while cladoceran grazers have increased 335% since 1946[10]. A recent extended drought (2001-17) has strongly limited silica loads to Lake Baikal and may preempt an important shift in phytoplankton composition, from the dominant silica-dependent diatoms (mostly *Aulacoseira* spp.) to filamentous green algae and cyanobacteria more commonly associated with eutrophic waterbodies[30].

The case of Lake Baikal contrasts with that of Lake Tanganyika, the world's second deepest lake (maximum depth 1,471 m) spanning four countries on the African continent. Algal biomass and primary production in Lake Tanganyika have declined with increases in water column stability as surface waters warm more rapidly than bottom waters and renewal of nutrients from intermittent partial mixing events is reduced[19, 32]. These changes have major implications for Lake Tanganyika's fishery – 60% of regional animal protein is consumed from the lake – as they are associated with loss of oxygenated habitat and reduced fish production, as well as overfishing of the dwindling fishery resource[4].

The difference between the response to climate warming of Lake Baikal and Lake Tanganyika can be explained mostly by the equation of state, which dictates that water column stability increases more rapidly with increasing temperature in the warmer tropical waters of Lake Tanganyika than in colder Lake Baikal, reinforcing continuous stratification and reduced primary productivity in the deep tropical lakes (see Figure 1). In deep coldwater lakes the major change will be an extended ice-free growing season (e.g., Lake Baikal, Figure 2). These lakes are mostly dimictic (i.e., with two cycles of water column mixing annually), with model projections indicating that around one-quarter will be ice-free by 2080-2100 and one-sixth will become monomictic (i.e., with only one cycle of water column mixing annually)[34] dramatically affecting the balance of winter and summer productivity. In temperate regions where there are many deep lakes that are monomictic, lake mixing regimes can be expected to be much more variable in the future. For example, of 100 monomictic lakes across the world that were selected for model simulations, about one-quarter may shift to being permanently stratified[34] or more specifically, meromictic (i.e., partial water column mixing on an annual basis; see the case of Lake Iseo in the article by Pilotti and Valerio, in this issue). Indeed, we do not need to cite model projections to demonstrate how rapidly deep temperate lakes across the world are changing[24], including from monomictic to meromictic regimes; recent years of rapid warming and/or meromixis have been reported for lakes Tahoe in California, USA[25]; Biwa in Japan[11]; Iseo in Italy[15]; and Taupō in New Zealand[8].

There are grave concerns for the ecological status of lakes that become meromictic. The monimolimnion (deepest water layer) is likely to become permanently devoid of dissolved oxygen. The intermittent annual cycle of incomplete deep mixing will transport anoxic deep water, with high levels of phosphate and ammonium, into the surface mixed layer, fuelling productivity and increasing the likelihood of CyanoHABs, with the possibility of fish kills also, depending on the volume of water involved and the mass of unoxidized organic matter. Overall, the advent of meromixis is likely to result in lakes transitioning from net deep-water nutrient sinks to sources[15] as a result of redox-driven phosphorus release from sedimenting organic matter, metal cations and bottom sediments, and the buildup of ammonium caused by the loss of

Figure 2 | Lake Baikal (showing Olkhon Island). The lake is already showing a strong response to climate warming and ice cover duration will be strongly impacted. Photo: Sergey Pesterev.

oxidised conditions that would otherwise support nitrification. Under highly anoxic conditions, methane is produced as the final product of organic matter breakdown and, with deep mixing, methane from bottom waters is brought into surface waters and escapes to the atmosphere[27]. The result will be an increase in the greenhouse gas warming potential of these lakes compared to lakes where bottom waters remain well oxygenated and CO_2 rather than methane is the dominant source of carbon contributed to the atmosphere (see the article by Imberger in this issue).

Invasive species

Climate change and eutrophication are just two of the stressors impacting lakes across the globe. Invasive species are another, as demonstrated by Li *et al.*[16] who showed how non-indigenous molluscs (zebra mussels [*Dreissena polymorpha*] and quagga mussels [*Dreissena rostriformis*]) now regulate the phosphorus cycle at whole-system scale in the Laurentian Great Lakes of North America, which collectively represent more than 20% of Earth's surface freshwater. The introduction in the 1950s of Nile perch (*Lates niloticus*) into Lake Victoria had major negative socio-economic outcomes by causing widespread decimation and the extinction of numerous endemic cichlid species that were integral to the protein intake and livelihood of local communities. Numerous African deep lakes, and many lakes globally, are affected by incursions of invasive weeds that proliferate in shallow waters (e.g., water hyacinth [*Eichhornia crassipes*]) and disrupt aquatic food webs. Rapid proliferation of aquaculture pens for fish production in developing areas (e.g., Indonesia) is also severely disrupting large lakes and has in some cases caused major economic losses of farmed fish, driven by overcrowding of fish pens and anoxia[26].

Some of the interactions of eutrophication and invasive species are complex and not usually well-predicted. For example, the recovery of Lake Constance from eutrophication over the past ~ 30 years, mostly through stringent phosphorus controls, was once heralded as a major success but views are mixed; a small littoral fish, the stickleback (*Gasterosteus aculeatus*) has proliferated and may be a cause of declining commercial fishery yields, while the deep-living toxic CyanoHABs species, *Planktothrix rubescens,* has also increased as water clarity has improved[13].

The message in these examples is that we cannot separate many of the stressors acting on lakes; they operate concurrently and aquatic communities that experience rapid or abrupt change (e.g., as a result of change in mixing regime) may be severely impacted and not necessarily resemble the communities associated with an earlier baseline or reference state. Moreover, many of the species incursions in deep lakes where impacts were expected to be isolated mostly to shallow littoral areas of greatest human interaction, exert whole-lake impacts, as demonstrated for the example of mollusc incursions in the Laurentian Great Lakes.

Future management of deep lakes in an era of chance

Jeppesen *et al.*[14] provide case studies for 35 lakes to indicate that re-oligotrophication may take ~ 5-35 years, but we can expect the higher limit of this range to be more accurate for deep lakes. Osgood[22] has suggested that the combination of near-saturation levels of P in lake catchment soils and internal P loading may make it almost impossible to restore lakes in a decade or two using catchment best management practices alone. These reviews suggest that deliberative interventions and/or preventative management actions are required to avert rapid decline in ecological state of large lakes under the multiple stressors of changes in climate change and trophic status, and invasive species.

Some priorities for action are considered below:

1 | Ensure that lake monitoring programs provide uninterrupted long-term time series data and process information that are essential to understand the complex interactions and spatio-temporal dynamics of external and internal nutrient loads, climate and lake food webs, as well as for documenting successful lake restoration case studies.

2 | Address excess catchment nutrient loads as a priority, ensuring that diffuse nutrient pollution is adequately quantified and regulated so that future generations are not burdened by enormous catchment clean-up costs.

3 | Identify and prioritize management of lakes in temperate areas where meromixis may cause severe ecological disruption. In such cases consider enhancing natural processes by artificial mixing at critical times (i.e., in the period of weakest stratification) to achieve full water column mixing and penetration of oxygen throughout the water column, and avert the associated severe impacts of loss of habitat of aerobic organisms and CyanoHABs.

4 | Treat large lakes as sentinels for, and integrators of, human activities – both beneficial and detrimental.

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LAKE ISEO
A PARADIGMATIC CASE

By Marco Pilotti and Giulia Valerio

Lake Iseo is a deep Italian lake located in the prealpine area of east-central Lombardy which well represents the features and dynamics of other large lakes located south of the Alps. With a surface area of 60.9 km² and a maximum depth of 256 m, it is characterized by steep banks and a large island that separates its central part from an eastern 100 m deep channel (see Figure 1). The lake drains a wide, strongly inhabited, 1,800 km² mountain catchment, also sharing the largest Italian glacier.

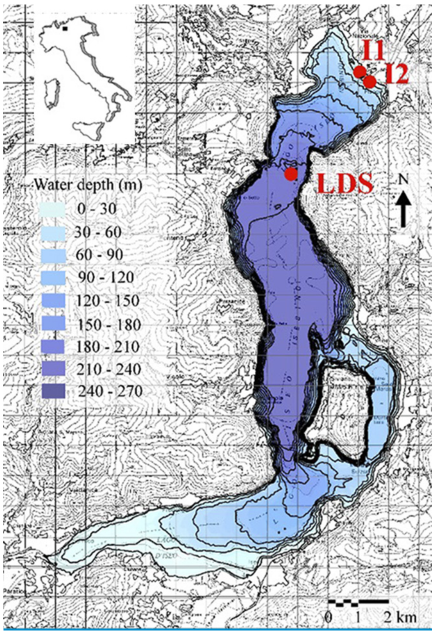

Figure 1 | Bathymetry and location of Lake Iseo. Symbols are defined in the text.

Figure 2 | Floating Piers connecting mainland, Montesola and San Paolo Island.

Accordingly, the lake is challenged by climate change both through the strengthening of its stability caused by temperature rise and from the weakening of the intrusion process of the cold waters of its main tributary. Lake Iseo gained international notoriety to lay-people in 2016 thanks to the extraordinary work of Land Art known as Floating Piers (see Figure 2), by the conceptual artist Christo, connecting two islands in the lake to the mainland.

Another reason that makes the Iseo lake paradigmatic is its response to 60 years of sprawling urban growth in its watershed. In the first scientific investigation of this lake, two biologists Bonomi and Gerletti[1] documented that Lake Iseo was oligomictic and that its 5.75 °C hypolimnetic waters had 70% of oxygen saturation and 22 µg/l of $[PO_4]^{3-}$ at its deepest point.

At the first signs of what they perceived as an incipient enrichment process, Bonomi and Gerletti[1] virtually called for the involvement of the community of hydraulic engineers, suggesting that any firm conclusion on the future evolution of the lake should be based primarily on the comprehension of its hydrodynamics. However, during the following 45 years nobody investigated the dynamics of this relatively small lake, which is in the shadow of the larger, more famous and less endangered Lake Como and Lake Garda. The lake is now locked in 15 years long meromictic-condition, with a bottom temperature of 6.7 °C, anoxic water with total phosphorus concentration above 100 µg/l under 100 m of depth.

Eventually, 15 years ago the challenge proposed by Bonomi and Gerletti was taken and a first detailed measurement campaign was set-up. After that a first seasonal campaign, the vertical thermal profile of the lake showed evidence of internal wave activity. In spring 2010, with the support of the Centre for Water Research led by Jörg Imberger, a Lake Diagnostic System (LDS)[2] was moored in the northern part of the lake at a point where the lake is 210 m deep (see Figure 1), measuring the main thermal, radiative, and mechanical fluxes on the lake surface.

Figure 3 | LDS station: its location is shown in Figure 1.

This floating station consisted of a set of sensors located 2.5 m above the water level for the measurement of wind speed and direction, net total and incoming short-wave radiation, air temperature and relative humidity. The temperature of the first 50 m of the water column was monitored with 0.01 °C accuracy by a submerged thermistor chain, initially equipped with 21 measuring points from 0.25 to 49.75 m depth, which was extended up to 156 m depth in 2014. During the summer of 2011, an analogous thermistor chain monitored the temperature profile in the southern basin with 16 sensors located between 4 and 36 m of depth. In the following years two additional wind stations, also measuring atmospheric pressure, were installed to account for the spatial variability of the wind field around the lake. Temperature and conductivity loggers were also installed to measure water temperature and conductivity of the two main tributaries to the lake.

This network of limnological stations has provided a continuous data set for 10 years that, integrated with several field campaigns in the lake, has shed light on the main hydrodynamic processes and their effects on water quality. Eventually, most of these measurements, along with a data set of the group led by Dr Garibaldi of Milano Bicocca University, were organised in a comprehensive data set that allows the interseasonal lake thermal evolution to be modeled over a 17-year period and to be compared with the field data collected on a monthly basis at 13 depths. The data set was made available to the scientific community[3] for testing the capability of models to reproduce the dynamics of deep oligomictic lakes.

The measured data have shown a distinctive meromictic behaviour of the lake, where density stratification resists deep mixing. Superimposed to the seasonal thermal stratification, a permanent so-called chemical stratification is present, with the deeper water being about 25 mg/l denser due to the dissolved compounds.

As shown by the conductivity profile of Figure 4, the maximum chemical gradient is located around 100 m ("chemocline") and determines a physical separation ("meromixis") between the seasonally circulating water mass, mixolimnion, and the lower monimolimnion, the deep part of the lake that never mixes with the layers above. The vertical profiles reported in Figure 4 clearly show how the chemocline prevents the oxygenated and colder waters to penetrate in the monimolimnion in the winter. Consequently, the stagnant monimolimnion is permanently anoxic and accumulates dissolved and particulate substances that settle from the upper layers and that are released by the sediments. This further stabilizes the stratification and increases the phosphorous storage in the monimolimnion. This condition will worsen under the effects of climate change. By means of a 1D model, we studied the evolution of the multi-annual thermal dynamics of Lake Iseo for the period 2012–2050, by coupling a lake model with the results of a long-term hydrologic model[4]. An overall average increase in the lake water temperature of 0.012 °C/year and a reinforced Schmidt thermal stability of the water column in the winter up to 800 J/m^2 were predicted. Both these effects will further hinder the deep circulation process, which is vital for the oxygenation of deep water, expand anoxia, promote cyanobacteria blooms and deteriorate the quality of fisheries.

A fundamental ecological consequence of the meromixis is that it modulates the nutrient dynamics in the lake. The field campaign aimed at measuring fluxes and pools of phosphorous in Lake Iseo[5] showed that at least 55% of the settled phosphorous is rapidly released by the sediments

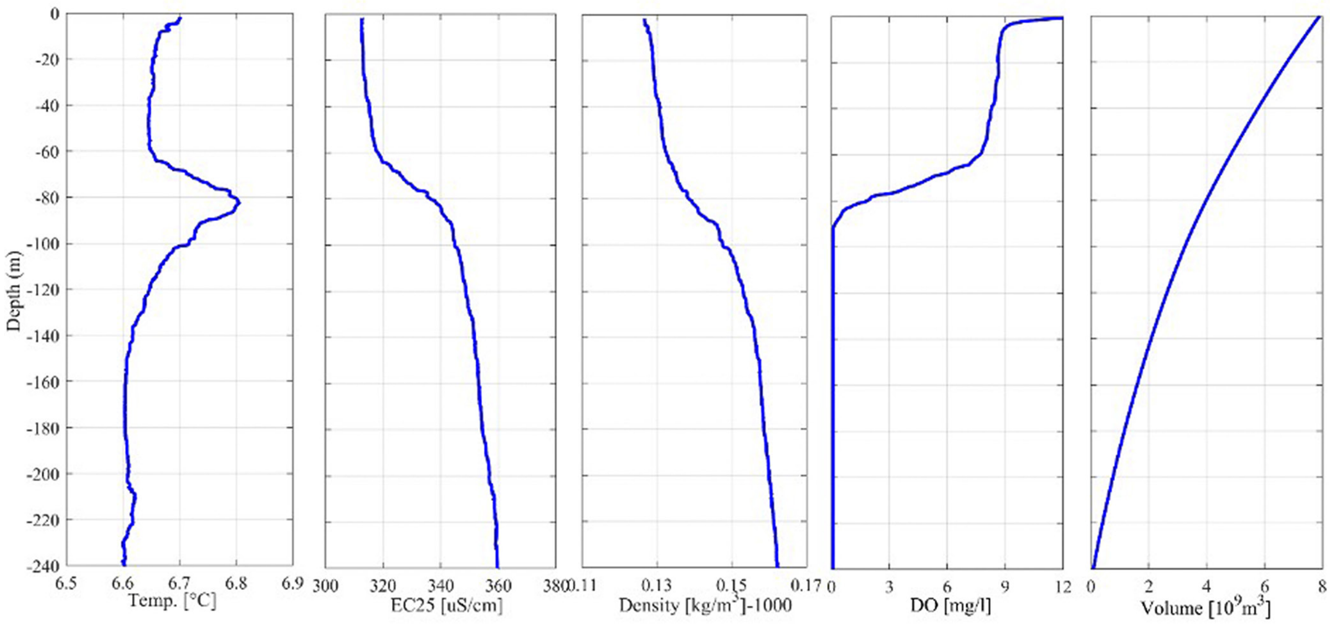

Figure 4 | Vertical profiles of temperature, conductivity normalized at 25 °C, density and dissolved oxygen collected in Lake Iseo on February 2017. The rightmost curve quantifies the volume of waters present below a given depth.

to bottom waters isolated from flushing, promoting at the same time oligotrophication of the surfaces waters and deep-water eutrophication. At present, the monimolimnion retains 45% of the lake waters with 76% of the lake phosphorous. Accordingly, a dangerous paradox is occurring in Lake Iseo, with the upper layer improving its level of quality that may eventually lead to possible advantages in term of recreation use of the surface waters, while the largest portion of the lake volume, invisible to people, is worsening in quality, accumulating nutrients and consuming oxygen. However, re-oligotrophication of surface waters might have a severe, long-term impact on a lake ecosystem. A reduction in internal phosphorous recycling affects the algal community composition and promotes the proliferation of cyanobacteria benefiting from deep light penetration. In less productive systems with elevated cyanobacterial densities, the quantity and quality of food available to fish both decline. At the same time fish habitats shrink due to increasing anoxia and temperature. Finally, a major concern lies in the future effects of an exceptional deep circulation, which might be driven by a particularly windy and cold winter, which could trigger pulse introduction of phosphorus to the euphotic zone. After a full circulation, the entire water column of the lake would be homogenized, reaching a concentration of about 76 μg/l of phosphorous and low level of dissolved oxygen that could threaten the whole aquatic ecosystem in the lake with asphyxiation. Pulse phosphorous introduction to the euphotic zone can trigger mass phytoplankton growth followed by hypoxia and fish kills.

Lake Iseo is also the Italian lake where internal waves have been most carefully investigated. Mixing in a deep lake is governed by internal waves and without mixing in its different forms a lake would be a pool of still water. In a simple but explicative example, Hutchinson[6] showed that a perfectly undisturbed lake with a uniform initial oxygen concentration of 11 mg/l and a constant concentration of 12.6 mg/l at the upper boundary in equilibrium with the atmosphere, under the action of molecular diffusion only would take 638 years to rise its concentration to 11.4 mg/l at 10 m depth. A similar concept was later implicitly shown by Vollenweider[7] who, in his seminal paper on lake eutrophication, observed that it is the interplay of the water renewal process and nutrient loads that determines a lake trophic status. Accordingly, internal wave studies pave the way to the understanding of the redistribution of pollutants and, most importantly, to the mass and energy exchange between the shallower layers of the lake, the widening monimolimnion, the benthic boundary layer and the bottom.

The summer data measured at the LDS station in the northern part of Lake Iseo show the prevalence of basin-scale internal wave of vertical and horizontal modes 1 (V1H1), superimposed on which were occasional higher vertical modes (V2H1) and higher horizontal modes (V1H5) trapped by the main island[8]. The occurrence of these motions was interpreted as forcing by the wind components with similar horizontal structures and with energies at frequencies near the natural oscillations of the excited modes. The modifications of the wind field by the topography was also investigated, showing in particular the excitation of an anticyclonic wave trapped around the island. Also, occasional internal nonlinear waves induced by storm events were observed[9] showing that around 15% of the total potential energy contained in the basin scale internal waves was transferred to nonlinear internal waves in response to moderate forcing, so emphasising the relevance of nonhydrostatic effects for accurate modelling of ecological processes in this and other deep large lakes.

The basin-scale internal wave motions were able to explain the large fluctuations observed at the depth of the chemocline (having an amplitude of up to 20 m and periods ranging from 1 to 4 days), determining alternating redox conditions in about 3% of the sediment area[10].

The study of internal waves demands a careful representation of their primary driver, that is the wind field, whose spatial distribution in lake Iseo is reconstructed using direct measurements at 4 stations. This local information can be greatly enhanced by coupling the wind field simulated by a high resolution atmospheric model with a 3D lake model[11].

Another relevant momentum and mixing source in a lake are its tributaries, whose mouth is located in the northern part of the basin (I1 and I2 in Figure 1 and 5). They are also an important source of nutrients and oxygen to the lake, so the path of inflowing currents has fundamental implications on its dynamics. Field observations[12] evidenced the presence of a laterally falling plunge region with little mixing, an underflow region with substantial mixing, and finally an intrusion. In the years following these observations, the role of intrusion was also explored with respect to the Earth rotation[13]. A rotating vertically distorted physical model of the northern part of this lake, respecting both Froude and Rossby similarity, was set-up. By exploring the area of influence of the tributary under both stratified and unstratified conditions, the model visually demonstrated (see Figure 5) the importance of Coriolis force in medium-size lakes where its relevance was often deemed questionable on the basis of the Rossby radius only. The model showed a systematic deflection of the inflowing waters towards the western shore of the lake, that triggers a clockwise gyre within the north-western bay. A few years later, this effect, reproduced in the model neglecting the wind field, was confirmed at a synoptic scale by the cross-analysis of images acquired during thermally unstratified periods by Landsat-8 and Sentinel-2 satellites, and of the 3D distribution of physical and chemical data[14].

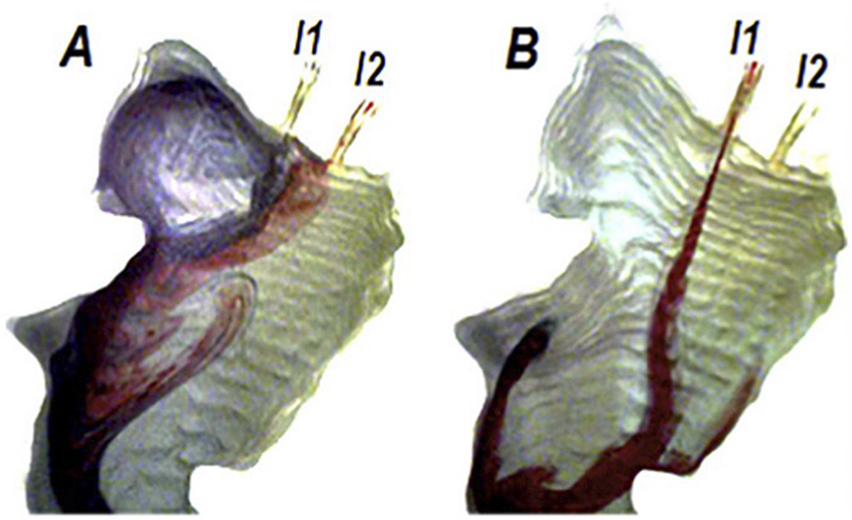

Figure 5 | Visualization of the results of two experiments with the rotating and non-rotating physical model. In case A the lake is thermally unstratified and the tributaries I1 (blue dye) and I2 (red dye) overflow the lake's water, each conveying the same discharge of 25 m³/s. In case B the lake is thermally stratified, with I1's temperature 4° C lower than the lake surface's temperature to simulate an interflow and discharge of 50 m³/s, but the rotating table is not in motion.

These studies showed that the coupling between the tributaries and Earth rotation contributes to explaining the reasons of horizontal anisotropy in water quality of the lake. Besides, the vertical distribution of the interflowing waters has strong implications on the lake water renewal time[15]. Using as a basis the idea of selective water withdrawal from the upper mixed layer, typical of a thermally stratified lake, and of horizontal homogenization, a mass balance that captures the relevant aspects of the thermal stratification was derived. The algorithm took into account the interflow or plunging flow of the tributary waters, whose role can be very important for the overall mixing, and it was proposed to estimate the water age probability distribution within stratified natural lakes where thermal stratification hinders complete mixing. The application of the model to Lake Iseo showed that the theoretical water renewal time T_{37}, when 37% of the original water should be still present within the lake, is at odds with the value of T_{37} computed from observed data, which suggested that this time in lake Iseo is actually 60% larger, due to the effect of thermal stratification. The obtained results emphasize the importance of interflow that significatively increases mixing, so decreasing the value of T_{37}. By evidencing the influence of interflow, the model sheds light on the increase in lake water age of this prealpine lake as a possible important consequence of climate change.

Actually, this increase could be triggered in the future by the expected modification in the regime of the lake tributaries, due to the progressive warming of the alpine area in the watershed of the lake, which includes a portion of the Adamello glacier. It also turns out that, in order to find out the response of a lake to climate change scenarios, a catchment-wise approach is required[4], calling for closer interaction between hydrologists and limnologists. Moreover, it shows that any modification of the hydrological regime of the drained watershed, although it does not affect the overall volume of water conveyed to a lake, can influence the age of water (and, therefore, eutrophication) by acting on the river temperature and on the discharge regime.

This short and incomplete resume of the last 10 years of active research on lake Iseo shows how this lake has gradually become a multidisciplinary laboratory where many methods were synergistically applied and where the reasons for the interest in lakes by the community of hydraulic engineers were demonstrated. Similar problems affect most lakes in other parts of the world and everywhere our community has still a fundamental role to play in the fight against the consequences of eutrophication.

We believe that as a starting point the complexity of the challenge posed by the eutrophication of lakes must lead to a cultural change that recognizes the disruptive role of uncontrolled urbanization. Our community tends to see this problem mostly from the point of view of flood control, due to the increase of watershed imperviousness and interconnection.

However, reducing eutrophication in lake areas will go through the recognition and assessment of the role of polluted runoff and discharges by Combined Sewer Weirs (CSWs) which provide a too often overlooked but important nutrients contribution even in lakes where along the shore a sewer system has been in operation for many years[16, 17]. Finding solutions to this task is challenging, especially in strongly urbanized areas as the one around Lake Iseo.

Moreover, we have to realize that reasoning in terms of pollutant concentration is ineffective when dealing with lakes whose dominant functioning is an integrative one.

We also need a closer interaction with professionals and researchers from other areas, and to integrate biology and ecology within environmental hydraulics.

Finally, we have to revert to the fundamental tools of our professions and explore how they can be used also to contrast the increased water stability expected because of climate change. The use of downward-pointing impellers to remove polluted water from the photic zone[18], alternative hydropower exploitation schemes[19], hypolimnetic withdrawal or controlled mixing by proper inlet redirection should all be considered in an effort to do "whatever it takes" against this growing challenge.

Marco Pilotti is full professor of hydraulics at the Università degli Studi di Brescia, where he leads the group of environmental hydraulics. Over the last 30 years he has been researching in the field of sediment transport, of shallow water equations and of the physics of deep lakes, as typical problems of the mountain region where he lives. Communicating to his students the interest for hydraulics and for environmental modeling is the primary purpose of his teaching activity.

Giulia Valero is a researcher in hydraulics at Università degli Studi di Brescia, with physical limnology as leading area of her research. Her main research interest is the combination of field data and numerical modelling techniques to describe the physical processes occurring in lakes and studying their impacts on water quality.

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CHESAPEAKE BAY
A case study in resiliency and restoration

By Richard R. Arnold, William C. Dennison, Louis A. Etgen, Peter Goodwin, Michael J. Paolisso, Gary Shenk, Ann P. Swanson and Vanessa Vargas-Nguyen

Chesapeake Bay ("mother of waters" or the "great shellfish Bay" in Algonquin), is the largest estuary in the United States and arguably the best studied estuary in the world. Chesapeake Bay is immense, with the main stem stretching 200 nautical miles (315 km) from the mouth of the Susquehanna River to its terminus at the Atlantic Ocean and an overall watershed encompassing 64,000 mi^2 (165,000 km^2). The mainstem, tributaries, and Bay islands form thousands of miles of coastline (Figure 1). Because of its prominence in estuarine science and ecosystem restoration, developing a working knowledge of Chesapeake Bay science and restoration is important. Hopefully, this overview will whet the appetite to learn more from information available both in the scientific literature and on the Chesapeake Bay Program website www.chesapeakebay.net

Figure 1 | Chesapeake Bay as seen from the International Space Station (Photo courtesy of NASA).

Figure 2 | Chesapeake Bay Map. The Chesapeake Watershed includes New York, Pennsylvania, Delaware, Maryland, the District of Columbia, West Virginia, and Virginia.

The Bay is relatively shallow, average depth of 30 feet (8.5 m), with narrow deeper channels formed by drowned river valleys. The Bay was and is still incredibly productive with abundant fish and shellfish, waterfowl, marshes and aquatic grasses. The extensive Chesapeake watershed is connected to the Bay by a myriad of streams and rivers. The Chesapeake watershed extends into New York State, contains half of Pennsylvania, essentially all of Maryland, the majority of Virginia, all of the District of Columbia, and includes portions of Delaware and West Virginia (Figure 2). The rivers, creeks and streams that flow into the tributaries or directly into Chesapeake Bay dissect the watershed, and there's virtually nowhere in the watershed that is more than a few miles or kilometers from a stream that ultimately empties into Chesapeake Bay.

The watershed is dominated by two major rivers, the Susquehanna to the north and the Potomac to the west. The region contains a diverse mix of major urban areas including Norfolk, Richmond, Washington, DC and Baltimore, as well as extensive agriculture on its Eastern Shore, within its Piedmont region, and nestled in the valleys of the Ridge and Valley.

Chesapeake Bay is naturally nutrient-retentive. This creates two important features: its productivity[11] and its vulnerability. Nutrients from predominantly human activities run off into the Bay both from the thousands of point sources and from diffuse non-point sources lying within its watershed. This causes excess algal growth which leads to low levels of oxygen in the water, creating 'dead zones' that negatively impact living resources[12]. Sediments transported from the watershed and from coastal erosion accumulate throughout the estuary, requiring dredging of the deeper regions to maintain shipping channels[7]. Toxins derived from industry, agriculture, neighborhoods, power plants, and automobiles enter local waterways and ultimately Chesapeake Bay. The long residence time within the Bay's waters and sediments diminishes the effect of regular flushing of nutrients, sediments and toxins into the ocean[4].

The Chesapeake region supports unique and diverse human cultures and livelihoods. Approximately 50,000 Native Americans had many villages along its shores and included the Algonquin peoples, the Sioux, and the Iroquois beginning about 10,000 years ago. Europeans first settled in the Chesapeake Bay region in 1607, in Jamestown, Virginia along the James River. Communities of watermen sprung up along its shores to take advantage of the rich harvest of oysters, blue crabs and fish. Many islands in the Bay were inhabited by Chesapeake Watermen, and the isolation of island communities created cultures that still retain traces of an Elizabethan English dialect. The abundant fish and shellfish harvests allowed these communities to be relatively self-sufficient. Farming was also prevalent both on islands and on the mainland. Due to declining fisheries resources and sea level rise, these island communities remain in only a few isolated locations.

Chesapeake Bay has been a strategic region throughout American history, serving as a highway for ships from Europe and other North American ports. Slavery played a prominent part in much of the watershed's economy. The Underground Railroad smuggled escaping slaves from plantations to the South, who took advantage of the myriad Chesapeake Bay waterways in their quest for freedom to the North.

Rigorous academic study of the Bay ecosystem began in earnest with the establishment of the University of Maryland Center for Environmental Science's Chesapeake Biological Laboratory (CBL) in 1925 in Solomons, Md. It was the first laboratory on the Bay and the first of its kind; a state-sponsored facility within the United States. Its founder, the pioneering scientist Reginald Truitt, established the laboratory in a small waterman's shack to better facilitate his work with Chesapeake Watermen on fisheries-related issues. Early research conducted at CBL, and other laboratories that sprang up, established the principle of two-layer water flow in estuaries, where fresher surface water flows seaward while salty and more dense water flows into the estuary from the Atlantic Ocean. Chesapeake scientists defined the biology, chemistry, physics and geology of the estuary, thus establishing the field of estuarine science and setting the standard for global estuarine research. For example, the local scientific organization, the Atlantic Estuarine Research Society, evolved into the international Coastal and Estuarine Research Federation and the local scientific journal *Chesapeake Science* evolved into the international *Estuaries and Coasts* journal.

In 1972, tropical storm Agnes dumped a historic amount of rain into the watershed. This led to flooding and the highest ever recorded runoff into Chesapeake Bay, exacerbating the challenges to an already stressed ecosystem. In response, local research institutions began documenting the declining health of the ecosystem; the U.S. Congress funded a five-year study of the Bay to better understand the loss of fisheries and wildlife; and in 1981, Maryland and Virginia formed the Chesapeake Commission (joined by Pennsylvania in 1985) to advise legislators on how to best manage the Bay's resources. The findings following this weather event highlighted some worrying signs of degradation, including low oxygen bottom waters and the widespread loss of aquatic grasses caused by excess nutrients, thus demonstrating the concept of coastal eutrophication.

A better understanding of the regional nature of these challenges prompted the formation of the Chesapeake Bay Program in 1983, a multi-state partnership with the Federal and local governments, the Administrator of the U.S. Environmental Protection Agency (EPA), and the Chair of the Chesapeake Bay Commission. This was marked by the signing of the first Chesapeake Bay Agreement. Over the past four decades, three additional agreements have been signed, each building on the commitments of the last, in 1987, 2000 and 2014. In the 1987 and 2000 agreements, largely voluntary nutrient reductions were called for by each jurisdiction. A major change was initiated when most of the Chesapeake waterways were declared impaired in the year 2000. During the following 10-year period when voluntary efforts did not achieve the nutrient reduction targets, a legislatively mandated nutrient diet known as the Total Maximum Daily Load or TMDL was initiated in the year 2010.

The current Chesapeake Bay Watershed Agreement, signed in 2014, addresses a diversity of issues including clean water, fisheries and their habitats, abundant conservation areas, rights to water access, a vibrant cultural heritage, and engaged citizens and stakeholders. The agreement has codified an adaptive management approach of setting goals, identifying the factors and gaps, developing a strategy to assess performance and actively managing the restoration. The management of the Bay now includes participatory modeling where stakeholders take part in building and parameterizing the management models. It was expected that this inclusive approach would increase stakeholder buy-in to the Bay models; surprisingly, it also resulted in greater accuracy in identifying where the nutrient loads are coming from. Broader sources of input into Bay models also allows for better accuracy of nutrient and sediment load predictions at a more localized scale[3].

Another advance has been a major effort to upgrade sewage treatment for the cities and towns within the watershed. The sewage treatment upgrades have led to rapid localized ecosystem responses including the resurgence of aquatic grasses known in the Chesapeake Bay as submerged aquatic vegetation or SAV[5]. The largest improvements in SAV health have been documented at the head of the Bay, leading to improvements in both water clarity and increased fish and shellfish production. SAV resurgence is also visible from a sequence of aerial photos adjacent to CBL. This is an indication that the nutrient reductions are beginning to make a difference.

In addition to sewage treatment upgrades, the Clean Air Act of 1972 mandated both catalytic converters for automobiles and smokestack scrubbers for power plants and factories, which have resulted in less nitrous oxide being discharged into the atmosphere. This has led to a reduction in atmospheric nitrogen deposition, which in turn has led to less nitrate in the streams and rivers entering the headwaters of Chesapeake watershed. Another positive sign for Chesapeake restoration is the recent return of bottlenose dolphins to their historic range within the Bay.

While wastewater and atmospheric source reductions have been strong and measurable, sediment runoff and nutrient loads from both urban areas and agricultural fields remain a challenge. Agriculture, which covers twenty-five percent of the watershed, generates runoff that is often high in nutrients from excess fertilizer and animal manure. The practice of planting winter cover crops over successive years has been shown to dramatically reduce ground-water nitrate levels. This has led to a concerted effort to incentivize farmers to use cover crops across the watershed and the state of Maryland has the highest percent adoption of cover crops in the US.

Urban stormwater runoff is exacerbated by the buried streams in towns and cities. Restoration efforts for urban runoff include implementing stormwater retention or treatment, detecting and repairing sewage overflows into the stormwater system, and replacing impervious surfaces with grassy fields and green roofs. In Washington, DC, large water-holding tunnels were constructed to capture stormwater that can be slowly fed into and treated by sewage treatment facilities.

Unfortunately, while there has been a high level of effort to make reductions from both urban and agricultural sources, clear results are generally not yet evident. Possible explanations may include unrealistic expectations, insufficient monitoring, lag times, and competing effects such as population growth and climate change[1].

An important feature of the Chesapeake restoration effort is the plethora of non-governmental organizations (NGOs) that mobilize citizens, river keepers and waterkeepers. In addition, these NGOs coordinate citizen scientists and work with local communities to implement practices that serve to protect and restore

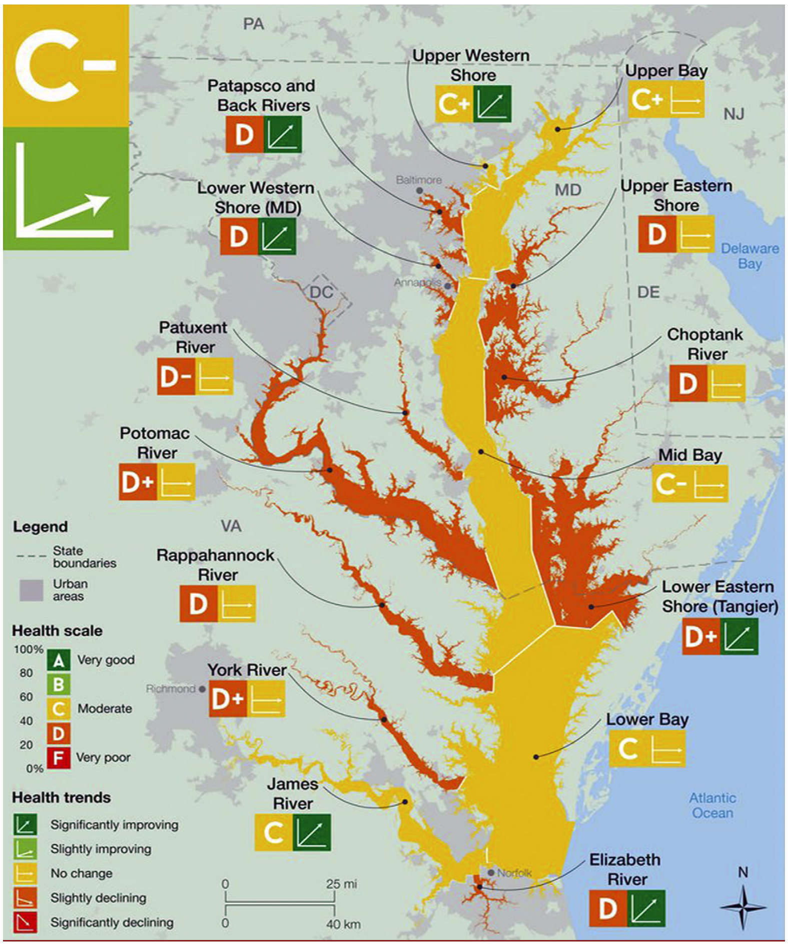


Figure 3 | 2019 Report Card for Chesapeake Bay[13]. Report card releases are high visibility events that effecti-ely shape public opinion and inform decision-makers (based on methods documented by Williams *et al.* 2009[13] photo credit: IAN Press 2020).

the Chesapeake watershed. With a growing population of over eighteen million people, engagement at the landowner level has proven absolutely critical. Further, with active engagement of citizens, it has become obvious that continued improvement in the ecosystem health of the watershed will only occur if it is balanced with the economic and social needs of its inhabitants.

A unique management tool developed by the University of Maryland Center for Environmental Science that has now been replicated on a global scale is the report card for the Chesapeake Bay (Figure 3). Started in 2007, it is the first scientifically rigorous assessment of the Bay using indicators of water quality and biodiversity collated from the Chesapeake Bay Program and its network data providers[14]. An ecosystem health "grade" accompanied by trend analysis is released annually with much fanfare in the media and among local leaders. The report card has proven to be a critical and highly effective tool to communicate the state of the ecosystem to all inhabitants of the region.

With a diversifying population in the watershed and changing needs of the watershed residents, the Chesapeake Bay Program recognizes that more social science research is needed. The Bay program identified these social science research needs to be the following: behavior change, economics, cultural landscape, communication barriers, and institutional change[9]. A coordinated and collaborative restoration effort for Chesapeake Bay is best articulated with a shared vision for what a restored Chesapeake Bay would look like. Recent interviews with Chesapeake Bay leaders resulted to a shared vision that reflect the increasing focus on the people and communities of the Bay and the holistic inclusion of cultural and social issues with the environmental issues providing Bay managers with a path forward[13].

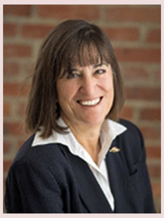
Dr Peter Goodwin is past-president of IAHR and is a professor and president of the University of Maryland Center for Environmental Science, a graduate university that provides independent scientific advice to help inform environmental policy and management state. Goodwin has worked on ecosystem restoration, ecohydraulics, and enhancement of river, wetland and estuarine systems throughout the world.

Dr William Dennison is UMCES' Vice President for Science Application, is a biologist with 40 years of experience in environmental research and science communication. In 2002, he founded the Integration and Application Network, a collection of Science Integrators and Science Communicators who partner with groups around the world to engage with diverse stakeholders to co-produce effective science communication products and environmental report cards.

Richard Arnold is UMCES' Director of STEM Engagement. He received his BS from Frostburg State University and MS from the University of Maryland in Marine and Estuarine Environmental Science. A global educator, he has taught Science and Mathematics in five countries. In 2004, he was selected as a NASA Astronaut in 2004 and has completed two missions to the International Space Station.

Dr Vanessa Vargas-Nguyen is a Science Integrator with UMCES' Integration and Application Network of the University of Maryland Center for Environmental Science. Originally a molecular microbiologist and marine scientist from the Philippines, she is an emerging transdisciplinary scientist and practitioner, specializing in science communication, socio-environmental assessments and synthesis, and stakeholder analysis and engagement through co-production.

Louis Etgen serves as the Executive Director of the Gunpowder Valley Conservancy. He has worked with several Chesapeake Bay environmental organizations including most recently as the Maryland State Director/Interim Executive Director for the Alliance for the Chesapeake Bay. During his career he has worked hard to bring people and organizations together to advance the collective goal of clean water throughout the Chesapeake Bay watershed.



Ann Swanson has served as a leader in the Bay restoration for nearly 35 years, the last 29 as the Executive Director of the Chesapeake Bay Commission, a tri-state legislative authority serving the states of Pennsylvania, Maryland and Virginia. She graduated with honors from the University of Vermont and Yale University; she served as a member of the University of Vermont's Rubenstein School of Environment and Natural Resources for 23 years, as Chairman for 11.

Dr Michael Paolisso is Professor of Anthropology at the University of Maryland, College Park, USA. Since 1997, Paolisso has been engaged in applied anthropology research on human and environmental issues confronting the Chesapeake Bay, including management of fisheries and agriculture, water pollution, restoration, social justice, socio-ecological adaptation and resilience, and climate change.

Gary Shenk is a USGS hydrologist at the EPA's Chesapeake Bay Program Office in Annapolis Maryland. He leads a multi-disciplinary team responsible for the development and operations for the CBP Partnership's watershed modeling effort. His work in Chesapeake modeling and monitoring informed the Chesapeake Bay Total Maximum Daily Load.

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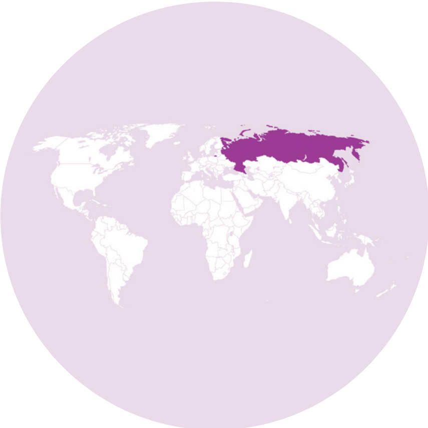
FAMOUS WOMEN IN HYDRAULICS

The IAHR task force on Strengthening Diversity Gender and Equity intends to raise the profile and visibility of women who are active within the organisation. IAHR wants to encourage women engineering engagement and a balanced membership is one of its strategic priorities. In this framework, Hydrolink will publish in every issue a short biography of a famous woman hydraulician. The next few bios will be drawn from Prof. Willi Hager's books 'Hydraulicians in Europe' (Volumes 1 and 2) and 'Hydraulicians in the USA'



Valentina Samsonovna Istomina
1899–1989, Moscow, Russia

In 1929, Valentina Samsonovna Istomina graduated from Bauman Moscow Technical University and continued working at the All-Union Research Institute for Water Supply, Sewer Systems and Hydraulic Structures (VNII VODGEO). In parallel, she taught at the Moscow Polytechnic School and was awarded the academic degree of candidate of technical sciences in 1937. In 1959, she submitted a PhD thesis. She was one of the first women in the Soviet Union to achieve such a high academic rank in hydraulics.

Together with Iosif Agroskin (1900-1968), Istomina founded seepage hydraulics in the Soviet Union. She did outstanding research work relating to the investigation of the physicomechanical properties of various soil types, their protection against seepage, the subsurface contour and applications to the stability of dams, and she investigated the action and proper selection of filters for drainage. The results of her research were successfully applied to hydraulic structures such as the Gizel'don, the Shatov, the Gorki and the Kuibyshev dams. In the early 1970s, Istomina was engaged in the design of large dams, including the Charvak, Nurek and Ragun projects. She was also associate editor of the main Russian hydraulics journal "Gidrotekhnicheskoe Stroitel'stvo". She was awarded the Order of the Red Banner of Labor, and the Medal for Labor Progress during World War II.

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IAHR'S FORTHCOMING SERIES OF MONOGRAPHS

By Damien Violeau

IAHR aims to provide researchers and practitioners with the best access to solid reference research works and state of the art knowledge by boosting its publication portfolio and introducing a new series of monographs, typically mid-sized publications (about 50 to 100 pages). This initiative is in accord with its new four-year strategic plan[1].

The new monograph series aims to bridge knowledge gaps, summarize existing knowledge, and disseminate recent advances in technologies and methods. Additionally, the monographs will succinctly present information on physical processes, measurement techniques, theoretical material, numerical modeling techniques, engineering applications, and historical and cultural matters in an appealing manner. IAHR intends that the monographs help people readily understand current and emerging concepts regarding focused topics.

The new series of monographs is now underway with seven selected promising editions:

- Artificial intelligence in hydroinformatics
- Bed shear stress in fluvial environments
- Ice issues at dams
- The lattice-Boltzmann method for hydraulic applications
- Hydraulic design guidance in a changing climate
- Measurement of gravel bedload in wadeable mountain streams
- Variational waves

Monograph publication will begin no later than 2022 and will start off with some more 'traditional' shaped text publications, but there is strong desire to explore if other forms of publication, such as a more web-based or interactive digital style are possible too to convene the knowledge transfer that is desired by IAHR's members and people beyond IAHR. Publications, therefore, will use a digital format rather than paper-print, in order for IAHR members to freely access these publications from IAHR's website. IAHR hopes this arrangement will significantly increase monograph accessibility and readership and substantially promote recognition of the monographs' authors. IAHR's many technical committees will be glad to consider additional topics for monographs. Proposed topics should be sent to IAHR via the email address mentioned below[2].

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1 | After the 2019 Panama City World Congress, IAHR established a new Committee on Publications, chaired by Prof. Robert Ettema (Colorado State University, USA). This Committee includes a task force (TF) to manage this new monograph series. The TF is chaired by Prof. Damien Violeau (EDF, France), with contributions from Prof. Vladimir Nikora (University of Aberdeen, UK), Prof. Claudia Adduce (University of Roma Tre, Italy), Dr Ellis Penning (Deltares, Netherlands), Prof. Ioan Nistor (University of Ottawa, Canada) and Estibaliz Serrano (Publication manager, IAHR secretariat).

2 | Prior IAHR monographs are listed at https://www.routledge.com/IAHR-Monographs/book-series/IAHRMON. Those monographs are books, longer and thus different from the new series of IAHR's incisive monographs.

IN-MEMORIAM

Prof. Ramón H. Fuentes Aguilar

1938–2021

Ramón Fuentes Aguilar, distinguished hydraulic engineer, professor and researcher, and Honorary Member of IAHR, passed away on January 27, at the age of 82, in Santiago de Chile.

Ramón graduated as a civil engineer from the University of Chile in 1964. Then, in 1967, following the French standards, he graduated as a civil engineer from the University of Grenoble, France, where he went on to obtain his Ph.D. in 1969. From 1964 he worked as a researcher at the Hydraulic Laboratory of the University of Chile until 1975, when he was appointed Head of the Laboratory. In 1976 he travelled to Venezuela, where he stayed for 16 years working in theoretical and experimental research at the National Hydraulic Laboratory as the head of the Research Division. There he developed more than 40 studies on physical models of hydraulic works. During that period he participated as Professor in Postgraduate courses at the Central University of Venezuela, and at the University of Los Andes.

He returned to Chile in 1993 and became an industrial advisor and consultant in numerical and experimental applications in the metallurgical industry, and a professor in the Department of Mining Engineering at the University of Chile. He developed numerous collaborations as an advisor to public and private companies in various disciplines such as Mining, Transport Concentrate minerals, Dredging, Hydraulic Works, Transient Flows, among others, in Chile, Argentina, Venezuela, Zaire, Costa Rica, the Dominican Republic, Niger, and other countries.

Regarding Ramón's contributions to the scientific knowledge of multiple topics in fluid mechanics and hydraulics, we could write several volumes. I can only mention that, over five decades, his contributions have been invaluable on very varied topics, reflected in books, articles, presentations at congresses and meetings, conferences, lecture notes, etc. but we also know (those of us who worked close to him) that Ramón pioneered many ideas that later appeared in scientific journals many years later. For example I have recently read many articles on subjects such as particle settling velocity, Shields curve "rationalization", incipient movement of coarse sediments, velocity profiles in macro-rough flows, transition functions to represent multiple boundary layer problems, phases in the temporal evolution of the local scour process, and many more, and I know for a fact that Ramón had already developed those ideas decades ago, in several cases without actually publishing them. Perhaps few people also know that Ramón was also a pioneer in the use of computer resources as an aid for the processing of experimental data and for advanced calculations in hydraulic problems, for which he used an old computer with techno-logy prior to the emergence of the PC on a global scale. For this, his fluent handling of advanced mathematics and numerical analysis was very useful. In his years at the University of Los Andes, Ramón was dedicated to scientific production and his generation of innovative ideas was inexhaustible, having conducted dozens of theses and countless promotion work for professors at the ULA.

Regarding the particular traits of Ramón's personality, although in some areas the idea of a “difficult character” (perhaps “rough”) has spread, as a result of the image that was revealed by his “incisive” (but passionate) participations in the technical sessions of the congresses, once you got to know him, you learned that he was actually an extremely warm and gentle person, of great generosity, and with a particular sense of humour, not without irony and "acidity", but always with good intentions. The talks with Ramón were always nuanced (beyond the strict rigour of the information he provided) with very picturesque facts and anecdotes, usually seasoned with extremely attractive and colourful metaphors, which delighted his occasional interlocutors. In the "coffee-breaks" of the congresses it was common to see circles of numerous colleagues and friends celebrating some humorous or ironic comment... Almost certainly in the centre of that group was the figure of Ramón.

Ramón's contributions to the IAHR have been immeasurable, through five decades of active participation in all of the Association's activities, from the Latin American Division (LAD) to the highest leadership levels. It can be said that the almost guaranteed success (in terms of attendance and quality of contributions) of the Latin American Hydraulic Congresses is a kind of “registered trademark” and hallmark of the IAHR-LAD. In this sense, the actions of Ramón (as historical Permanent Secretary and later as Honorary Member) have played a preponderant role, through his particular imprint, leaving an indelible mark on those periodic meetings of colleagues and friends of the Water Sciences.

The figure and genius of the beloved Professor Ramón Fuentes will remain indelible in the memory of several generations of hydraulic engineers and researchers who had the opportunity to meet him and enjoy his unique talent and his particular warmth and generosity.

Héctor Daniel Farias | Professor and Researcher IRHi-FCEyT-UNSE, Argentina | Secretary IAHR-LAD

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