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OPINION/SUMMARY

Freshwater science for the benefit of society: a perspective from early career researchers

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ABSTRACT
This research brief summarises the views of a group of early career freshwater researchers on 3 questions: What are the greatest threats to freshwater resources and how will they change over the next century? Is freshwater science effectively utilised to help society adapt to these threats? How will we ensure the benefits of freshwater science are reaped by society into the future? To address these questions we reviewed the current literature and discussed our findings in a series of group meetings. We concluded that freshwater resources will be most threatened by population growth, climate change, and eutrophication in the future. We provide examples of how the utilisation of freshwater science by society is reliant on effective monitoring systems, data sharing, and effective communication of topical scientific evidence to both the public and policy makers. Developments in these fields increase the likelihood of society benefitting from past and future research in freshwater science.

KEYWORDS
Climate change; cross-disciplinary; eutrophication; freshwater resources; knowledge exchange; population growth; scientific communication; societal behaviours

Introduction

Effective management of freshwater resources is a critical global challenge in the 21st century (Jury and Vaux 2005). Freshwater science is a vital tool that can produce evidence to support the effective management of freshwater resources. As a consequence, the Editor in Chief of *Inland Waters* (the journal of the International Society of Limnology) invited this group of early career researchers to consider their views in the context of the following 3 questions:

- What are the greatest threats to freshwater resources and how will they change over the next century?
- Is freshwater science effectively utilised to help society adapt to these threats?
- How will we ensure the benefits of freshwater science are reaped by society into the future?

To address these questions we reviewed the current literature and discussed our findings in a series of group meetings over the course of 1 year. This research brief summarises these discussions and offers our perceptions on the opportunities available to ensure more effective use of freshwater research to benefit society.

What are the greatest threats to freshwater resources and how will they change over the next century?

Population growth and economic development are the main drivers of deterioration in water quality. Together they increase rates of industrialisation, urbanisation, land use change, and food production, which intensifies demand for clean water while decreasing availability because of pollution (Jury and Vaux 2005). With the global population estimated to reach 9.2 billion by 2050 and per capita income expected to double between 2002 and 2030 (Selman and Greenhalgh 2009), the future will require a greater reliance on freshwater services at a time when the quality and security of freshwaters are decreasing (Vörösmarty et al. 2010). While birth rates in most developing countries continue to soar, it is the growing middle class in the developed world (with their resource intensive lifestyles) that place the greatest pressure on water resources globally (Bapna 2011). Meat consumption is a major factor in this regard; agriculture accounts for 85% of human water consumption (Selman and Greenhalgh 2009), with one-third of the global agricultural water footprint associated with meat production (Mekonnen

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and Hoekstra 2012). Furthermore, meat consumption is predicted to increase 54% between 2001 and 2030 (Selman and Greenhalgh 2009). Although agricultural intensification has improved economies and food security, it has also led to the unsustainable abstraction of surface and ground waters (Jury and Vaux 2005) and has caused widespread eutrophication.

Eutrophication is the greatest cause of water quality deterioration globally (Smith and Schindler 2009) and may also promote climate change through elevated methane emissions (Bastviken et al. 2011). Globally, 30–40% of lakes and reservoirs have been affected by eutrophication (UNEP 2005). In the UK, an assessment of the ecological status of lakes for the Water Framework Directive (WFD; European Commission 2000), found that, of the lakes with available data up to 2014, 74% in England, 50% in Wales, and 40% in Scotland failed to achieve a "good status" based on total phosphorus (TP) concentration (Jo-Anne Pitt, Project Manager, UK Environment Agency, pers. comm.). In the US, eutrophication is the cause of 50% of degraded lake surface area and 60% of degraded river stretches (USEPA 1996). The combined costs for the treatment and restoration of waterbodies and the losses to local economies due to eutrophication have been estimated to be £75–114.3 million per year for England and Wales (Pretty et al. 2003) and US$2.2 billion per year for the US (Dodds et al. 2009). While improvements to the quality of some freshwaters have been achieved through reduction of agricultural, wastewater, and industrial nutrient loading (i.e., nitrogen [N] and phosphorus [P]), legacy stores of P in lake sediments may continue to pose a threat to water quality for future generations (Spears et al. 2011, Sharpley et al. 2013).

Climate change is altering the spatial and seasonal distribution of fresh waters; generally, higher latitudes will experience more precipitation and increasing flood risk while lower latitudes will experience less precipitation and increasing water scarcity (IPCC 2014). Rising temperatures will increase snowmelt and change the timing of meltwater release, posing serious implications for ecosystems and freshwater provisioning and management (Jury and Vaux 2005). Climate change is also altering the phenology of biological events (e.g., reproduction; Thackeray et al. 2016) and can potentially de-synchronize species interactions (Ohlberger et al. 2014), which can significantly influence predator–prey relationships, alter trophic structure, and make freshwater ecosystems less resilient to other stressors (Thackeray et al. 2010). Interactions also exist between climate change and eutrophication (Moss et al. 2011). For example, under higher temperatures, P release from lake bed sediments may exacerbate algal blooms (Jensen and Andersen 1992) and increase the mineralization of catchment soils, leading to a heightened risk of elevated nutrient loadings to fresh waters (Rustad et al. 2001, Brookshire et al. 2011).

Invasive species further threaten ecosystem stability (Mota et al. 2014), and growth of transport networks and global trade increase the frequency of biological invasions (Hulme 2009) and transport of foreign pathogens (Havel et al. 2015). Improving biodiversity can enhance ecosystem productivity and its resilience to disruptions (Lapointe et al. 2014). Unfortunately, habitat loss, fragmentation, overexploitation, flow modification, and pollution are significantly reducing freshwater biodiversity in many regions, with extinction rates up to 5 times greater than in terrestrial ecosystems (Dudgeon et al. 2006).

These threats and others may interact in additive and synergistic ways to make management extremely difficult, particularly when tackling pressures in isolation (Piggott et al. 2015).

Is freshwater science effectively utilised to help society adapt to these threats?

The following actions may be surmised from observations where freshwater science is effectively utilised by society:

- use of "sensitive" monitoring systems, with detectable responses to pressures,
- data shared and/or freely accessible, and
- scientific evidence effectively communicated to stakeholders at the appropriate time.

Here we provide examples of successes and failures in the management of freshwaters.

Ineffective monitoring may restrict process-based understanding

Freshwater monitoring programmes are critical for underpinning effective management (Lovett et al. 2007); however, the success of these programmes has been mixed (Lindenmayer and Likens 2010). Key factors that undermine the reliability of monitoring programmes stem from design flaws, including a lack of clear central questions, failure to apply a rigorous statistical approach, insufficient frequency of sampling, and inappropriate selection of indicators (Lindenmayer and Likens 2009).

For example, analysis of the frequency of nutrient monitoring on the River Frome in southern England indicated that monthly water sampling could accurately support estimates of the annual loads for reactive silicon and total organic N, but weekly sampling was needed for P (Bowes et al. 2009). Furthermore, where sampling frequency was not adequate, significant nutrient loading from storm events could go undetected (Johnes 2007, Defew et al. 2013); this information becomes more important with the expected increase in occurrence of extreme weather events (IPCC 2014). Question-driven monitoring with clear aims designed around appropriate sampling scales is essential to detect changes and help us understand their effects on different aspects of the system (Dodds et al. 2012). A sampling regime appropriate to understand microbial dynamics within a season will be different than one needed to understand fluctuations in fish populations over decades. Designing monitoring programmes with clearly defined aims is critical to provide useful scientific information usable for research, management, and policy development.

In another example, nutrient loading to surface and groundwater from poorly managed septic tanks may be significantly underestimated throughout the UK and Ireland due to poor monitoring programmes (Withers et al. 2013). In response to this concern, a rural development policy was implemented in the Loch Leven catchment in Scotland, designed to ensure that septic tanks serving new developments do not increase net P loading within the lake catchment. This goal is achieved by calculating the P output of the proposed septic tank and mitigating 125% of its estimated P output through modification to an existing third party septic tank within the catchment (Loch Leven Special Protection Area and Ramsar Site 2011). Because available monitoring data are lacking, the policy was built on the precautionary principle but was later shown to be inaccurate, demonstrating the need for evidence-led policy development (Brownlie et al. 2014)

Where monitoring programmes are badly designed, resources can be wasted collecting data that do not produce useful information (Timmerman et al. 2010). This "data rich but information poor" syndrome is a well-documented problem in water quality monitoring programmes (Ward et al. 1986), and these datasets will have low statistical power and a reduced capacity to identify causal mechanisms. One additional significant risk to the implementation of effective monitoring programmes is the wide-reaching funding cuts that many freshwater scientists and environmental agencies are currently facing. In this respect, securing long-term funding from both private and public bodies to support monitoring of sentinel sites is a significant challenge that may be overcome by clearly presenting the benefits to society.

Ineffective sharing of data may slow development of new approaches

Freshwater systems are interconnected (e.g., by water continuum, landscape, and atmosphere) and impacted by multiple anthropogenic drivers (e.g., population growth, water demand, agriculture, and land use change). There is an increasing awareness that a cross-disciplinary approach, such as the integration of social sciences with natural sciences, is required to find solutions that tackle complex global threats (Holm et al. 2013). The understanding needed to develop effective solutions to these threats therefore relies on integrating multiple datasets (Pahl-Wostl et al. 2013). Many individuals within the environmental science community are shifting toward the opinion that sharing data is not only good, but an ethical obligation (Soranno et al. 2015). But while there may not be a reluctance to share data, low visibility of existing datasets, issues with differing/multiple terminology across disciplines (e.g., ecology, hydrology, and social science), and data consistency and comparability can make integrating datasets challenging, even within the field of freshwater science (Tress et al. 2007, Uiterkamp and Velk 2007). The recent use of "controlled vocabulary," where acronyms and jargon are defined in a table or appendix, could be useful to bridge language gaps among disciplines. Although progress has been made, methods and routes to allow effective collaboration among disciplines (e.g., social science, geosciences, and computer science) are still developing (Goring et al. 2014).

The accessibility of data was acknowledged in both the European Union (EU) Habitats Directive (European Commission 1992) and the WFD, with calls to improve the availability and suitability of data to assess diffuse pollution and the health of freshwater ecosystems. In the US, efforts to develop indicators to assess freshwater condition, in line with achieving the Millennium Development Goals, found that only 3 of 15 indicators could be fully assessed because access to suitable data is lacking (Revenga et al. 2005). A recent study on P flows within the EU found the lack of availability and accessibility of good quality data constrained the findings when quantifying societal P flows to waters (van Dijk et al. 2016). In some cases, data may exist but are not easily accessible, and/or data are privately held by the institute running the programme and available only at cost (Beniston et al. 2012), limiting the use of the data and the wider value gained from their collection. Data sensitivity may also be an issue; for example, commercially sensitive data collected by the water industry with a high research value may be protected (Swyngedouw 2005). Encouragingly, government environment agencies and institutions are increasingly sharing their data via online data portals, such as the US Environmental Protection Agency (USEPA) "data catalog" (http://catalog.data.gov/dataset) and the UK Environment Agency "geostore" (http://www.geostore.com/environment-agency/). Other global-scale data sharing initiatives such as the Global Lake Ecological Observatory Network (GLEON; www.gleon.org) are being developed to provide access to high spatial frequency monitoring data (i.e., Globolakes; www.globolakes.ac.uk), which will transform our ability to understand coherent and wide-scale changes in freshwater ecosystems.

Ineffective communication of scientific evidence may trigger ineffective policy responses

Effective communication of scientific evidence is largely reliant on the ability of freshwater scientists to communicate their findings clearly and succinctly. Failure in this regard may lead to a world challenged with the problems outlined earlier, even though the science needed to develop effective management strategies may already exist (Jury and Vaux 2005). We illustrate this point by contrasting the role of science communication in the management of flood events in the UK and the Netherlands.

Flood events are predicted to increase as a result of climate change (IPCC 2014). These events are the most common natural disaster in Europe (EEA 2004) and a major societal concern (Bradford et al. 2012). The hydrological mechanisms of flooding are well understood from the large and established knowledge base, but this knowledge is not always used effectively. Following the 2013–2014 winter floods in England, conflict between public opinion, scientific evidence, and political direction (Wintour 2014) resulted in public money being spent on dredging measures, the usefulness of which was contested by part of the scientific community (Emery and Hannah 2014). Arguably, if the accumulated scientific evidence base had been better communicated prior to these events, a better informed public could have helped drive a more effective and considered response from politicians (Thorne 2014). Instead, the policy response (i.e., increased funding for dredging and flood barriers) was contentious. In 2015, similar flooding events occurred again across the UK and caused major damage and several deaths (Gross 2016). By contrast, in the Netherlands the response from the government and the Ministry of Infrastructure and the Environment to the floods in 1993, 1995, and 1998 was generally well aligned, leading to effective management and acceptance by the public (Van Stokkom et al. 2005, Slomp 2012). Knowledge transfer to the public was instrumental in the success of these schemes. The Dutch government has undertaken responsibility to ensure flood education is taught in schools and universities, as well as to continually update education programmes to reflect the most current understanding of water management and ensure that this knowledge is communicated effectively to the public (Van Stokkom et al. 2005).

How can we ensure the benefits of freshwater science are reaped by society into the future?

From the previous section it is clear that, despite a number of successes, the potential benefits of freshwater science have yet to be fully realised. In this final section, we provide our opinions on how we, as early career scientists, can improve the utilisation of freshwater science by society into the future.

Improving monitoring

We believe one of the most critical aspects to improve monitoring programmes is to design them in collaboration with stakeholders. This measure would help balance societal needs with sound scientific design to provide the process understanding necessary for ecosystem management. Built into the design of these programmes should be an inherent ability to continually develop and improve them to take advantage of novel understanding and technologies.

Monitoring systems should be part of a greater system of understanding, including established and emerging predictive tools (e.g., process models and statistical early warning indicators). Many of these systems are complex and require specialist training to use and interpret the results, which can make delivery of recommendations to stakeholders slow and often ineffective. Artificial intelligence (AI) techniques such as neural networks, fuzzy inference systems, and genetic algorithms are being developed to make water quality models easier to use by non-specialists (e.g., user friendly interfaces and automated parameter selection (Chau 2006). The use of AI to simulate human expertise within problem solving software can simplify model usage and may be an effective way to apply freshwater science into user friendly applications for non-specialists (Chau, 2006, Vigerstol and Aukema 2011).

Technological advances in data collection should also be embraced, such as high frequency, low resource monitoring of phytoplankton by flow cytometry (Read et al. 2014), especially where logistical and economic barriers can limit data collection via conventional methods. Furthermore, advances in satellite imagery, remote sensing, and computing hard/software have the potential to transform global water management, allowing large-scale monitoring and spatial characterisation of landscapes previously not possible (Andrew et al. 2014). The development and refinement of automated data analysis systems will allow faster responses to potential threats (e.g., flood risk). To support all of this work, data analysis and interpretation of monitoring systems may need to be categorised under "research" and "operation," with the research led by the scientific process. The operation of monitoring systems could be led by environmental agencies specialised in providing the high degree of confidence and accountability necessary to provide early warning of service provision losses and to trigger management interventions.

Improving data management

Technological advances in data acquisition enable the collection of much larger volumes of data, and increasing computing power is allowing us to process, analyse, and visualise increasingly large datasets. This technology provides significant opportunities to advance freshwater science (Szalay and Gray 2006). Training in "data mining" and "data screening" techniques may become increasingly important for freshwater scientists (Muggleton 2006) as manual exploration of "big-data" by individual researchers becomes more impractical, if not impossible.

Currently, a growing community of scientists use R (a programming language and software environment) to manage, statistically analyse, and visualise data. While the growing popularity of R may be in part because it is free, it is a powerful and flexible tool, well supported by an active online community. Freshwater scientists investing in R training are gaining access to an extensive array of novel statistical approaches, data visualisation tools, and data management techniques not available with simpler statistical programs, such as a range of generalized linear mixed models to analyse non-normal data (Bolker et al. 2009) and methods to visualise multi-way contingency tables (Friendly and Meyer 2016). This access may be particularly important when integrating multiple datasets and dealing with increasing volumes of data within the freshwater community.

Although data collection and analysis technology has advanced, the understanding of freshwater systems is still reliant on collaboration and data sharing between scientists and organisations (Hampton et al. 2013). A number of successful collaborations in large-scale multinational projects (e.g., GLEON) exist; however barriers such as terminology, non-comparable data formats, and difficulty publishing cross-disciplinary research may still hinder collaborations (Uiterkamp and Velk 2007). In light of these barriers, we recognise the need to publish not only scientific papers but also raw scientific data for others to use. Processes to "clean" big data are increasingly important, especially where data are collected using automated methods (Boyd and Crawford 2012); however, efforts required to clean raw data into formats easily used by others, with appropriate metadata, should not be underestimated. As individual datasets are published there will be a growing need to rationalise them, perhaps using data search engines not specific to a publisher but searchable on categories. An example is the mobile app Spatial Agent, released by the World Bank (http://apps.worldbank.org/), which allows the user to visualize multi-sectoral spatial and temporal data from a range of institutions (i.e., United Nations, NASA, and World Bank) by drawing upon their map and data services.

The use of citizen science to collect data and/or analyse large datasets using online tools and smart phone mobile apps (Kanhere 2011) has already been used successfully within numerous scientific disciplines (Heipke 2010, Muller et al. 2015). We felt that public participation in freshwater science may become an increasingly useful tool, one that carries co-benefits of communicating (freshwater) science to the public. Encouraging public involvement (Gao et al. 2015) and designing methods to harness the power of their participation (e.g., the use of apps) provides a new challenge that may require specialised training. Furthermore, quality control measures at all stages in the data collection process (from initial experimental design through to collection, reporting, and collation) must be implemented and monitored to ensure such methods provide reliable data (Pocock et al. 2014).

Improving science communication

Peer reviewed journal publications remain the primary communication pathway among academics, and in some instances "the work dies with the paper," potentially because scientific text is not always easily accessible to non-specialists (physically or intellectually). Individual researchers communicating their science to the public often have little knowledge or support on how to best engage with their audience (Fischhoff 2013). Furthermore, concerns that science outreach activities may result in research being misconstrued was reported in a recent survey of 3748 scientists (Pew Research Centre 2015). The survey found that while 87% of scientists believe they should take an active role in public policy debate, 79% were concerned by the lack of differentiation between well-founded and not well-founded scientific findings by the media, and 52% thought that simplification of scientific findings is a major problem for science in general. A possible solution would be to provide lay summaries to accompany scientific journal articles publicised through various forms of media (e.g., social media) and distilled to suit the interests of different audiences (Kuehne and Olden 2015). Twitter is increasingly being used by scientists to connect to a wider audience and to amplify the scientific and social impact of their publications (Darling et al. 2013, McHeyzer-Williams and McHeyzer-Williams 2016). While methods such as these can be used to distil scientific information into a story the media can "sell" (Sutton et al. 2013), we felt it was important to find a balance between simplifying the message to capture attention and ensuring sufficient depth of scientific detail to underpin, but not influence, public perception. We also felt it was important that the scientific message remains impartial in this respect.

The internet, mobile technology, and social media are significantly changing how we communicate science, with the public shifting toward "online only" media as their primary source of information (Brossard and Scheufele 2013). This shift is a challenge, not only because online communication is continually and rapidly updated, but because the search engines and the presentation (or the reporters' "spin") of the key scientific results (e.g., using Twitter, Facebook, blogs, vlogs, and online articles) are often not controlled by the scientist. This omission can result in bias and/or misinformation, which when injected into open public discussions can shape public opinion as much as the evidence base itself (Brossard and Scheufele 2013). To resolve this challenge, the freshwater science community needs to engage with online communication, which may be best managed through journal offices and communications teams, as well as by research scientists. We consider that extra training should be provided to support better communication with the public through use of social media, data portals, and websites. Furthermore, scientists may find it increasingly useful to use visual and multi-media communication (i.e., video and infographics) to capture attention to their science (Rodriguez Estrada and Davis 2015). We can learn from past successes where media attention has been captured by translating complex scientific issues into media-friendly stories that can increase public awareness of the scientific evidence (Sutton et al. 2013).

Following the 2009 earthquake in the L'Aquila region in central Italy, 7 scientists and public officials, previously tasked with assessing the risk of earthquakes, were found guilty of manslaughter. In light of this, we feel that while the responsibility to communicate scientific findings should not be replaced by culpability, steps must be taken to demonstrate and communicate confidence and uncertainty in our predictions (Chong 2013). Stronger relationships between legal officers, communications experts, and scientists are needed to support this effort (Cash et al. 2003), especially for freshwater scientists responsible for generating the evidence for predicting major environmental events, such as floods. We also consider that stronger and direct linkages with scientists and policy makers will be needed if the best available science is to be incorporated into future management policies, especially if the Sustainable Development Goals are to be achieved (UNEP 2015).

Although online communication is creating a global community of freshwater scientists prepared to better manage our global resources, we believe that face-to-face networking is equally important, especially with stakeholders. For example, the seventh World Water Forum brought thousands of researchers, policy makers, and stakeholders together to address global water challenges (UNESCO 2015). A main conclusion from this event was, "…to ensure a water secure future for all into the next decade 'water' must be a top political priority." As freshwater scientists, it is important that we are aware of the global implications of our work and its role in policy development. We felt that while communication of evidence must be timely, to be truly effective it must not only increase knowledge but also trigger positive action. Using our scientific knowledge to generate action that can effect change will be a key challenge for current and future early career researchers in this century.

Disclosure statement

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References

Andrew ME, Wulder MA, Nelson TA. 2014. Potential contributions of remote sensing to ecosystem service assessments. Prog Phys Geogr. 38:328–353.

Bapna M. 2011. Seven billion: the real population scare is not what you think. World Resource Institute Insights.

Bastviken D, Tranvik LJ, Downing JA, Crill PM, Enrich-Prast A. 2011. Freshwater methane emissions offset the continental carbon sink. Science. 331:50.

Beniston M, Stoffel M, Harding R, Kernan M, Ludwig R, Moors E, Samuels P, Tockner K. 2012. Obstacles to data access for research related to climate and water: implications for science and EU policy-making. Environ Sci Policy. 17:41–48.

Bolker BM, Brooks ME, Clark CJ, Geange SW, Poulsen JR, Stevens MHH, White JSS. 2009. Generalized linear mixed models: a practical guide for ecology and evolution. Trends Ecol Evol. 24:127–135.

Bowes MJ, Smith JT, Neal C. 2009. The value of high-resolution nutrient monitoring: a case study of the River Frome, Dorset. UK. J Hydrol. 378:82–96.

Boyd DM, Crawford K. 2012. Critical questions for big data. Inform Commun Soc. 15:662–679.

Bradford RA, O'Sullivan JJ, Van Der Craats IM, Krywkow J, Rotko P, Aaltonen J, Bonaiuto M, De Dominicis S, Waylen K, Schelfaut K. 2012. Risk perception - issues for flood management in Europe. Nat Hazard Earth Syst Sci. 12:2299–2309.

Brookshire ENJ, Gerber S, Webster J, Vose JM, Swank WT. 2011. Direct effects of temperature on forest nitrogen cycling revealed through analysis of long-term watershed records. Glob Change Biol. 17:297–308.

Brossard D, Scheufele DA. 2013. Social science. Science, new media, and the public. Science. 339:40–41.

Brownlie W, May L, McDonald C, Roaf S, Spears BM. 2014. Assessment of a novel development policy for the control of phosphorus losses from private sewage systems to the Loch Leven catchment, Scotland. UK. Environ Sci Policy. 38:207–216.

Cash DW, Clark WC, Alcock F, Dickson NM, Eckley N, Guston DH, Jäger J, Mitchell RB. 2003. Knowledge systems for sustainable development. P Nat Acad Sci USA. 100:8086–8091.

Chau KW. 2006. A review on integration of artificial intelligence into water quality modelling. Mar Pollut Bull. 52:726–733.

Chong A. 2013. A risky business: professional and public scientific communication after the L'Aquila verdicts. In: Professional Communication Conference (IPCC), Vancouver, (BC): 2013 IEEE International; p. 1–5.

Darling ES, Shiffman D, Côté IM, Drew JA. 2013. The role of Twitter in the life cycle of a scientific publication. PeerJ PrePrints 1:e16v1.

Defew LH, May L, Heal KV. 2013. Uncertainties in estimated phosphorus loads as a function of different sampling frequencies and common calculation methods. Mar Freshwater Res. 64:373–386.

Dodds WK, Bouska WW, Eitzmann JL, Pilger TJ, Pitts KL, Riley AJ, Schloesser JT, Thornbrugh DJ. 2009. Policy analysis eutrophication of U.S. freshwaters: damages. Environ Sci Technol. 43:12–19.

Dodds WK, Robinson CT, Gaiser EE, Hansen GJA, Powell H, Smith JM, Morse NB, Johnson SL, Gregory SV, Bell T, et al. 2012. Surprises and insights from long-term aquatic data sets and experiments. BioScience. 62:709–721.

Dudgeon D, Arthington AH, Gessner MO, Kawabata ZI, Knowler DJ, Lévêque C, Naiman RJ, Prieur-Richard AH, Soto D, Stiassny MLJ, Sullivan CA. 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biol Rev Camb Philos. 81:163–182.

Emery SB, Hannah DM. 2014. Managing and researching floods: sustainability, policy responses and the place of rural communities. Hydrol Process. 28:4984–4988.

[EEA] European Economic Area. 2004. Impacts of Europe's changing climate: an indicator-based assessment. Copenhagen (Denmark).

European Commission. 2000. Council Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy Official Journal L327, 22/12/2000 0001 (The 'Water Framework Directive')

European Commission. 1992. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. Official Journal L206, 22/07/1992 0007-0050 (The 'Habitats Directive')

Fischhoff B. 2013. The sciences of science communication. P Nat Acad Sci USA. 110:14033–14039.

Friendly M, Meyer D. 2016. Discrete data analysis with R: visualization and modeling techniques for categorical and count data. Boca Raton (FL): Chapman & Hall/CRC. ISBN 978-1-4987-2583-5.

Gao H, Liu CH, Wang W, Zhao J, Song Z, Su X, Crowcroft J, Leung KK. 2015. A survey of incentive mechanisms for participatory sensing. EEE Communication Survey Tutorials 17.

Goring SJ, Weathers KC, Dodds WK, Soranno PA, Sweet LC, Cheruvelil KS, Kominoski JS, Rüegg J, Thorn AM, Utz RM. 2014. Improving the culture of interdisciplinary collaboration in ecology by expanding measures of success. Front Ecol Environ. 12:39–47.

Gross M. 2016. World under water. Curr Biol. 26:R47–R50.

Hampton SE, Strasser CA, Tewksbury JJ, Gram WK, Budden AE, Batcheller AL, Duke CS, Porter JH. 2013. Big data and the future of ecology. Front Ecol Environ. 11:156–162.

Havel JE, Kovalenko KE, Thomaz SM, Amalfitano S, Kats LB. 2015. Aquatic invasive species: challenges for the future. Hydrobiologia. 750:147–170.

Heipke C. 2010. Crowdsourcing geospatial data. ISPRS J Photogramm Remote Sens. 65:550–557.

Holm P, Goodsite ME, Cloetingh S, Agnoletti M, Moldan B, Lang DJ, Leemans R, Moeller JO, Buendía MP, Pohl W, et al. 2013. Collaboration between the natural, social and human sciences in global change research. Environ Sci Policy. 28:25–35.

Hulme PE. 2009. Trade, transport and trouble: managing invasive species pathways in an era of globalization. J Appl Ecol. 46:10–18.

[IPCC] Intergovernmental Panel on Climate Change. 2014. Climate change 2014: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the IPCC. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, et al., editors. Summary for policymakers. Cambridge (UK): Cambridge Univeristy Press; p. 1–32.

Jensen HS, Andersen FØ. 1992. Importance of temperature, nitrate, and pH for phosphate release from aerobic sediments of four shallow, eutrophic lakes. Limnol Oceanogr. 37:577–589.

Johnes PJ. 2007. Uncertainties in annual riverine phosphorus load estimation: impact of load estimation methodology, sampling frequency, baseflow index and catchment population density. J Hydrol. 332:241–258.

Jury WA, Vaux H. 2005. The role of science in solving the world's emerging water problems. P Nat Acad Sci USA. 102:15715–15720.

Kanhere SS. 2011. Participatory sensing: crowdsourcing data from mobile smartphones in urban spaces. Proceedings of the IEEE International Conference on Mobile Data Management; p. 3–6.

Kuehne LM, Olden JD. 2015. Opinion: lay summaries needed to enhance science communication: Fig. 1. P Nat Acad Sci USA. 112:3585–3586.

Lapointe NWR, Cooke SJ, Imhof JG, Boisclair D, Casselman JM, Curry RA, Langer OE, Mclaughlin RL, Minns CK, Post JR, et al. 2014. Principles for ensuring healthy and productive freshwater ecosystems that support sustainable fisheries. Environ Rev. 25:1–25.

Lindenmayer DB, Likens GE. 2009. Adaptive monitoring: a new paradigm for long-term research and monitoring. Trends Ecol Evol. 24:482–486.

Lindenmayer DB, Likens GE. 2010. Improving ecological monitoring. Trends Ecol Evol. 25:199–200.

Loch Leven Special Protection Area and Ramsar Site. 2011. Advice to planning applicants for phosphorus and foul drainage in the catchment. Scottish Environment Protection Agency and Perth and Kinross Council, Scottish Natural Heritage, Joint guidance report.

Lovett GM, Burns DA, Driscoll CT, Jenkins JC, Mitchell MJ, Rustad L, Shanely JB, Likens GE, Haueber R. 2007. Who needs environmental monitoring? Front Ecol Env. 5:253–260.

McHeyzer-Williams LJ, McHeyzer-Williams MG. 2016. Our year on Twitter: science in #SocialMedia. Trends Immunol. 37(Spec Issue 4):260–265.

Mekonnen MM, Hoekstra AY. 2012. A global assessment of the water footprint of farm animal products. Ecosystems. 15:401–415.

Moss B, Kosten S, Meerhoff M, Battarbee RW, Jeppesen E, Mazzeo N, Havens K, Lacerot G, Liu Z, Meester LD, et al. 2011. Allied attack: climate change and eutrophication. Inland Waters. 1:101–105.

Mota M, Sousa R, Araújo J, Braga C, Antunes C. 2014. Ecology and conservation of freshwater fish: time to act for a more effective management. Ecol Freshwater. Fish. 23:111–113.

Muggleton SH. 2006. 2020 Computing: exceeding human limits. Nature. 440:409–410.

Muller CL, Chapman L, Johnston S, Kidd C, Illingworth S, Foody G, Overeem A, Leigh RR. 2015. Crowdsourcing for climate and atmospheric sciences: current status and future potential. Int J Climatol. 35:3185–3203.

Ohlberger J, Thackeray SJ, Winfield IJ, Maberly SC, Vøllestad LA. 2014. When phenology matters: age-size truncation alters population response to trophic mismatch. P Roy Soc B. 281:20140938.

Pahl-Wostl C, Giupponi C, Richards K, Binder C, de Sherbinin A, Sprinz D, Toonen T, van Bers C. 2013. Transition towards a new global change science: requirements for methodologies, methods, data and knowledge. Environ Sci Policy. 28:36–47.

Pew Research Center. 2015. "How Scientists Engage the Public." Available from: http://www.pewinternet.org/2015/02/15/how-scientists-engage-public/

Piggott JJ, Townsend CR, Matthaei CD. 2015. Reconceptualizing synergism and antagonism among multiple stressors. Ecol Evol. 5:1538–1547.

Pocock MJO, Chapman DS, Sheppard LJ, Roy HE. 2014. Choosing and using citizen science: a guide to when and how to use citizen science to monitor biodiversity and the environment. Scottish Environment Protection Agency, Centre for Ecology & Hydrology.

Pretty J, Mason C, Nedwell DB, Hine RE, Leaf S, Dils R. 2003. Policy analysis environmental costs of freshwater eutrophication in England and Wales. Environ Sci Technol. 37:201–208.

Read DS, Bowes MJ, Newbold LK, Whiteley AS. 2014. Weekly flow cytometric analysis of riverine phytoplankton to determine seasonal bloom dynamics. Environ Sci: Process Impacts. 16:594–603.

Revenga C, Campbell I, Abell R, de Villiers P, Bryer M. 2005. Prospects for monitoring freshwater ecosystems towards the 2010 targets. Philos T Roy Soc Lond B. 360:397–413.

Rodriguez Estrad FC, Davis LS. 2015. Improving visual communication of science through the incorporation of graphic design theories and practices into science communication. Sci Comm. 37:140–148.

Rustad LE, Campbell JL, Marion GM, Norby RJ, Mitchell MJ, Hartley AE, Cornelissen JHC, Gurevitch J, Alward R, Beier C, et al. 2001. A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. Oecologia. 126:543–562.

Selman M, Greenhalgh S. 2009. WRI policy note - eutrophication: sources and drivers of nutrient polluiton. World Resources Institute.

Sharpley A, Jarvie HP, Buda A, May L, Spears B, Kleinman P. 2013. Phosphorus legacy: overcoming the effects of past management practices to mitigate future water quality impairment. J Environ Qual. 42:1308–1326.

Slomp R. 2012. Flood risk and water management in the Netherlands. Rijkswaterstaat Ministry Infrastucture Environment.

Smith VH, Schindler DW. 2009. Eutrophication science: where do we go from here? Trends Ecol Evol. 24:201–207.

Soranno PA, Cheruvelil KS, Elliott KC, Montgomery GM. 2015. It's good to share: why environmental scientists' ethics are out of date. Bioscience. 65:69–73.

Spears BM, Carvalho L, Perkins R, Kirika A, Paterson DM. 2011. Long-term variation and regulation of internal phosphorus loading in Loch Leven. Hydrobiologia. 681:23–33.

Sutton MA, Howard CM, Bleeker A, Datta A. 2013. The global nutrient challenge: from science to public engagement. Environ Dev. 6:80–85.

Swyngedouw E. 2005. Dispossessing H_2O: the contested terrain of water privatization. Capital Nat Soc. 16:81–98.

Szalay A, Gray J. 2006. 2020 Computing: science in an exponential world. Nature. 440:413–414.

Thackeray SJ, Henrys PA, Hemming D, Bell JR, Botham MS, Burthe S, Helaouet P, Johns DG, Jones ID, Leech DI, et al. 2016. Phenological sensitivity to climate across taxa and trophic levels. Nature. 535:241–245.

Thackeray SJ, Sparks TH, Frederiksen M, Burthe S, Bacon PJ, Bell JR, Botham MS, Brereton TM, Bright PW, Carvalho L, et al. 2010. Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. Glob Change Biol. 16:3304–3313.

Thorne C. 2014. Geographies of UK flooding in 2013/4. Geogr J. 180:297–309.

Timmerman JG, Beinat E, Termeer K, Cofino W. 2010. Analyzing the data-rich-but-information-poor syndrome in Dutch water management in historical perspective. Environ Manage. 45:1231–1242.

Tress G, Tress B, Fry G. 2007. Analysis of the barriers to integration in landscape research projects. Land Use Policy. 24:374–385.

Uiterkamp AJM, Velk C. 2007. Practice and outcomes of multidisciplinary research for environmental sustainability. J Soc Issues. 63:175–197.

[UNESCO] United Nations Educational, Scientific and Cultural Organization. 2015. UNESCO-IHP at the 7th World Water Forum: strategies to strengthen water cooperation and diplomacy by reinforcing institutional and human capacity and promoting science based policy formulation in Member States. Daegu-Gyeongbuk, Republic of Korea; p. 12–17.

[UNEP] United Nations Environment Programme. 2005. Millennium ecosystem assessment synthesis report. pre-publication final draft, approved by MA Board on 23 March 2005.

[UNEP] United Nations Environment Programme. 2015. Policy coherence of the sustainable development goal. A natural resource perspective. Report compiled for UNEP by the International Resource Panel, developed with support from the International Institute for Applied Systems Analysis.

[USEPA] United States Environmental Protection Agency. 1996. Environmental indicators of water quality in the United States. Washington (DC).

van Dijk KC, Lesschen JP, Oenema O. 2016. Phosphorus flows and balances of the European Union Member States. Sci Total Environ. 542:1078–1093.

Van Stokkom HTC, Smits AJM, Leuven RSEW. 2005. Flood defense in the Netherlands: a new era, a new approach. Water Int. 30:76–87.

Vigerstol KL, Aukema JE. 2011. A comparison of tools for modeling freshwater ecosystem services. J Environ Manage. 92:2403–2409.

Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Glidden S, Bunn SE, Sullivan CA, Liermann CR, Davies PM. 2010. Global threats to human water security and river biodiversity. Nature. 467:555–561.

Ward RC, Loftis JC, McBride GB. 1986. The "data-rich but information-poor" syndrome in water quality monitoring. Environ Manage. 10:291–297.

Wintour P. 2014. Eric Pickles apologises over floods and blames Environment Agency advice. The Guardian. Published 9 Feb 2014.

Withers PJ, Jordan P, May L, Jarvie HP, Deal NE. 2013. Do septic tank systems pose a hidden threat to water quality? Front Ecol Environ. 12:123–130.