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Introduction

Nutrients and eutrophication: introduction

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Introduction

Cultural eutrophication stimulated by anthropogenic-derived nutrients represents one of the most common forms of compromised surface water quality in many developed and developing countries (Schindler 2012). In fresh water, both nitrogen (N) and phosphorus (P) can potentially contribute to eutrophication (Carpenter *et al.* 1998). In lakes it is more common that excessive P inputs are the primary cause of eutrophication (Schindler 1977) although both global (Elser *et al.* 2007) and national surveys (Abell *et al.* 2011*a*) have increasingly highlighted excessive N inputs as an equal or more important cause. Debate on the relative roles of N and P limitation of lake phytoplankton is highly contentious, with a P-limitation paradigm (Schindler *et al.* 2008) challenged by those who contend that both P and N control are key elements of eutrophication management in freshwater systems (e.g. Conley *et al.* 2009; Scott and McCarthy 2010). Eutrophication of temperate estuaries and coastal waters is also common, but in contrast to fresh water, N is more commonly the controlling nutrient (Carpenter *et al.* 1998).

Problems associated with eutrophication include a decrease in the ability of water to support aquatic life (including fish kills) due to oxygen shortages after the senescence and decomposition of aquatic plants, a loss of biodiversity, and the impairment of water use for recreation, industry (including agriculture) and drinking (Schindler and Vallentyne 2008). The proliferation of harmful algal blooms has increased in association with the prevalence of eutrophication (Hallegraeff 1993). Blooms of cyanobacteria (CyanoHABS) are a particular problem in fresh water associated with fish kills, taste and odour compounds, and the formation of carcinogens (e.g. trihalomethane) during chlorination of potable water (Codd *et al.* 2005). Water-soluble hepatic or neurotoxins arising from CyanoHABS can also kill livestock and harm humans (Dietrich *et al.* 2008).

While representing both a nuisance and a potential health concern, there is also a financial cost from eutrophication. Dodds *et al.* (2009) estimated that for fresh water in the US the economic cost in lost recreational water use, devaluation of waterfront real estate, protection of endangered or threatened species and treatment for drinking water was US$2.2 billion annually. Similar estimates in England and Wales put the figure at £75–114 million annually (Pretty *et al.* 2003). However, costs vary widely; Løvik (2009) estimated it took €110 million to decrease the discharge of P into one Norwegian lake (Mjøsa).

The sources of nutrients causing eutrophication are many and varied. While point sources (e.g. industrial effluent or wastewater discharges) still occur, even in agricultural catchments (Withers and Jarvie 2008), they tend to be more easily identified and managed or mitigated than diffuse sources. By their varied nature, mitigation of diffuse sources requires a deeper understanding of the sources and transmission pathways involved. Processing and transformations may also lead to lag times between the initiation of mitigation practices and a decrease in the nutrient concentration of fresh water is realised (Jarvie *et al.* 2013).

Most diffuse sources of N and P are agricultural in origin (McDowell *et al.* 2008). This means that the aforementioned sources and pathways will also be subject to decisions made on-farm, primarily around land use and profitability. Environmental considerations may be included in the decision-making mix, but tend to be acted upon only if there is a clear driver (Abell *et al.* 2011*b*). Legislation commonly forms the main driver, but voluntary actions can also be effective if the mitigation strategies are not onerous in terms of time and cost and they are used at 'leak points' (Bewsell and Drake 2008).

Tracing and accounting for actions close to the source of diffuse nutrient loss have become active areas of water-quality policy and advocacy. Linking action at 'the farm gate' to an effect in the receiving environment (e.g. in-stream or in a lake) via fundamental science, modelling and decision support tools enables land owners to make economic and environmentally sustainable decisions and plan for future expansion or, for example, land use change. However, surprisingly little research has successfully achieved this integration, largely as it requires mixing multiple disciplines and requires experiments that work across a range of temporal and spatial scales.

Recognising this gap in the literature, this special issue has brought together several papers whose collective aim is to demonstrate efforts in linking strategies to mitigate N and P losses from agricultural systems to effects or trends in receiving water bodies. The studies were carried out in a context of water-quality objectives and limits and their potential financial implications. Wider issues also address data quality and examine tools being used to collate and examine fate and transport pathways of nutrients and sediments, and their predicted effects.

It is hoped that these papers will provide exemplary methods of how to approach the measurement, monitoring and improvement of freshwater quality in agricultural catchments and thereby inform good management and policy.

Linking nutrient losses to effects and management across scales

The definition of water-quality reference conditions in streams and rivers enables determination of anthropogenic effects as the difference of present state from reference state. The concentrations or loads of water-quality indicators under reference conditions does not guarantee that a stream or river is therefore 'clean', however, as this is defined by an assessor's value set. However, it is important that reference conditions are estimated as accurately as possible. This avoids the setting of limits within a water-quality objective that is either not achievable because background levels are naturally high, or is insufficiently protective of the environment. By identifying the anthropogenic proportion we can also identify when management and mitigation strategies can have a large effect without excessive cost or be too restrictive as to result unnecessarily in land-use change. McDowell *et al.* (2013) compared two models to estimate median concentrations of water-quality indicators under reference conditions and anthropogenic inputs (by difference from current medians) for streams and rivers in New Zealand that were classified according to the River Environment Classification (REC) system. Use of the REC within the models enabled natural variation in climate, topography and geology to be taken into account to refine estimates of reference conditions across the country.

The setting of water-quality objectives and limits invariably includes some assessment of concentrations or loads. Accuracy is required in yield estimates not only spatially but also temporally so that sudden influxes of contaminants (e.g. storm flows) can be accounted for. Defew *et al.* (2013) examined the P load in a tributary of Loch Leven, Scotland, estimated from sampling intervals ranging from 2-hourly to weekly. The loads estimated via seven different methods were up to an order of magnitude different from the 'true' load estimated from sampling at high temporal resolution. A combination of finer temporal-resolution sampling and the selection of a suitable load estimation method is required if loads are to be determined accurately for use in nutrient management programmes and policy development.

While it is important to consider nutrient loads within management plans whose objective is to decrease nutrient yields from agricultural land, it is also necessary to consider temporal changes and their likely effect. For instance, Jennings *et al.* (2013) showed that strategies to improve the management of P and decrease the load entering Lough Leane, south-west Ireland, were effective in decreasing the point source contribution from 41% in the mid-1980s to <10% at present. However, during summer, up to 60% of the P load to the lake was from a local wastewater treatment plant. Due to longer hydraulic residence times in the lake in summer compared with other times of year these inputs were likely to have a significant impact on lake productivity, highlighting the need to consider seasonal variation and not just annual loads in regulatory responses.

In an effort to detect the influence of best management practices over the long-term, Wilcock *et al.* (2013*a*) examined trends in water-quality indicators within streams of five dairy farm catchments across New Zealand. Although only inferences could be made (i.e. not direct cause and effect) mitigation efforts, including stream fencing and the greater use of land treatment for dairy shed effluent disposal, were highlighted as possible causes of improved stream clarity and decreased *E. coli* concentrations. Further examination of the potential sediment, nutrient and microbial sources and transport pathways within each catchment led to the development of both generic and catchment-specific mitigation strategies. Some strategies were heralded as being successful; however, the authors noted that a 3–7-year periodicity in climate cycles in addition to voluntary adoption and market forces, resulted in a slow rate of uptake. The inference is therefore that for many of these catchments a monitoring period of greater than 10 years may be required to see improvements in water quality associated with mitigation efforts.

Even if longer monitoring periods were to occur, there is no guarantee that the right indicators are being measured or that mitigation strategies will result in the required water-quality target. This can be due to an incomplete understanding of both the pathways and processes involved, their scales and how they interact with management actions. To encapsulate this complexity, Quinn *et al.* (2013) developed a catchment-specific Bayesian belief network to link different land management and mitigation scenarios to key socio-economic and aquatic values. The model predicted substantial increase in farm earnings and regional economic benefits but with a range of positive and negative water-quality impacts depending on the extent and location of mitigations in place. The results of this study highlighted the value in collating data and developing models of complex inter-disciplinary systems in order to focus on the water-quality objective and avoid unintended consequences (i.e. inefficient mitigation strategies).

The science of understanding the complexity of improving water quality was examined in two studies. The study by Wilcock *et al*. (2013*b*) examined catchment sources and pathways for water-quality contaminants. The study by Verburg *et al.* (2013) assessed the relative of these contaminants on an oligotrophic lake (Brunner). Wilcock *et al.* (2013*b*) found that while trends were decreasing (i.e. improving) for some water-quality contaminants, much of the load of suspended sediment, N and P came from storm flows or was from groundwater that was not encaptured in surface water inflows into the lake. Moreover, at the farm scale the measured loads closely matched modelled loads, indicating that attenuation in the stream network was limited and that mitigation should be directed mostly at the source. Verburg *et al.* (2013) then went onto assess the relative impact of the loads of N and P, finding that the Vollenweider model predicted a mean P concentration close to the observed concentration and that algal productivity was most strongly stimulated by additional inputs of P to the lake. They indicated using the Vollenweider model that at the present rate of increasing agricultural intensification and P loading from the catchment, Lake Brunner would likely change from oligotrophic to mesotrophic.

Lake management was also the subject of modelling work done to mitigate P loads and maintain drinking water quality in the subtropical Kaiping (*Dashahe*) reservoir in China (Nielsen *et al.* 2013). By adapting a surface water catchment model, a powerful scenario analysis was conducted of different mitigation technologies and practices. It was estimated that with the removal of sewage discharges and the installation of buffer zones along rivers, substantial gains could be made in reaching the targeted 13% load decrease. However, the authors noted that further research was required into the hydrological pathways involved in such a complex and artificially altered water infrastructure that included ditches, channels and ponds. In such a monsoon-influenced subtropical catchment the hydrological assessment would also certainly be affected by climate change, and hence knowledge about to how to adapt to changes in the frequency and intensity of rainfall was considered to be imperative.

Climate change was the subject of the final paper in this special issue (Hatfield *et al.* 2013). Using the Midwestern United States as an example, the authors highlighted the effects of climate change on food production, but also the delivery of nutrients to the Gulf of Mexico. They emphasised that under current trends, soil degradation is likely to impair future food production. Halting further soil degradation and minimising losses of nutrients into the region's waterways (and ultimately the Gulf) should be achieved by concentrating on the maintenance of soil hydrologic and plant-growth functions. Hatfield *et al.* (2013) considered that good soil management not only reduced losses of sediments and nutrients from agricultural land already under intensive production but that it could reduce pressure to expand into environmentally sensitive areas. As a whole, the papers in this special issue of *Marine and Freshwater Research* span many of the key scientific issues that were identified by participants of the 15th International Water Association Diffuse Pollution Conference in Rotorua, New Zealand, in 2011. A summary of those issues included that: (1) many ecological processes do not necessarily follow linear trajectories corresponding to changes in external forcings (e.g. catchment nutrient loads); (2) reductions in external nutrient loading are fundamental to effective control of eutrophication; (3) accurately quantifying storm loads of sediments and nutrients remains a major challenge; and (4) better interdisciplinary communication linkages are required to fully capitalise on technological advances that will enable improved management of diffuse nutrient sources. These themes are repeated throughout the special issue and demonstrate the global challenges of environmental services and change, human population growth, food supply and agricultural productivity in the 21st century.

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