1

The Looming Threat of Eutrophication

1.1 Introduction

The word ‘eutrophic’ originates from a word *eutrophy*, from Greek *eutrophia* meaning nutrition and *eutrophos* which means well-fed. Eutrophication has many different definitions depending on whether they describe solely the process of nutrient enrichment or whether they also include impacts and problems caused by such enrichment. In its simplest form eutrophication is defined as the over-enrichment of receiving waters with mineral nutrients, phosphorus, and nitrogen. It results in excessive production and growth of autotrophs, in particular algae, cyanobacteria (Box 1.1), and aquatic macrophytes (Correll 1998; Ansari et al. 2011; van Ginkel 2011). The increased bacterial populations and vegetation abundance result in high respiration rates leading to hypoxia (oxygen depletion). Hypoxia and algal blooms (Figure 1.1) are the two most acute symptoms of eutrophication (Ansari et al. 2011; UNEP 2017).

Hypoxia or oxygen depletion in a water body often leads to ‘dead zones’ – regions where levels of oxygen in the water are reduced to a point that can no longer support living aquatic organisms (Figure 1.1). Hypoxia in the northern Gulf of Mexico is defined as a concentration of dissolved oxygen less than 2 mg/l (2 ppm). In other oceans of the world, the upper limit for hypoxia may be as high as 3–5 mg/l. The new knowledge on oxygen depletion (hypoxia) and related phenomena in aquatic systems has been recently reviewed by Friedrich et al. (2014).

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Box 1.1 Cyanobacteria

Cyanobacteria, commonly referred to as 'blue-green algae' are microorganisms that structurally resemble bacteria. However, unlike other bacteria, they contain chlorophyll a and are the only photosynthetic prokaryotes able to produce oxygen. They are the oldest oxygenic phototrophs on Earth and include nearly 2000 species. Cyanobacterial blooms are highly visible, widespread indicators of eutrophication. Many of cyanobacteria species produce cyanotoxins that are toxic to humans and animals. The most common algae toxins found are microcystins associated with *Microcystis*, *Anabaena*, *Oscillatgoria*, *Nostoc*, *Hapalosiphon*, and *Anabaenopsis* species (Whitton and Potts 2000; National Toxicology Program 2017). Microcystis is one of the most common bloom formers in freshwater systems on every continent except Antarctica. This genus can produce a suite of potentially harmful compounds including toxins anatoxin-(a) and beta-methylamino-L-alanine (BMAA) (O'Neil et al. 2012).

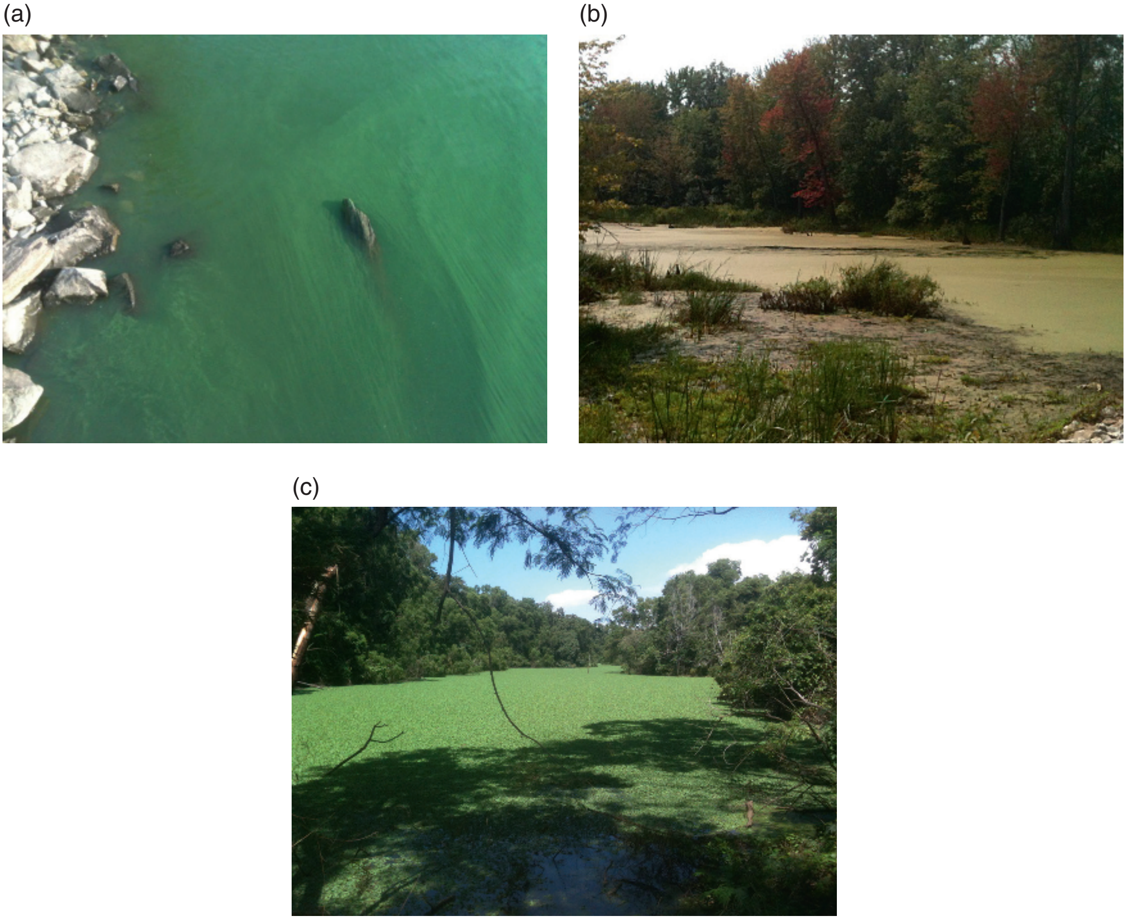

Figure 1.1 Examples of harmful algae blooms (HABs) in: (a) Lake Champlain in Philipsburg, Quebec, Canada–USA border; (b) Missisquoi River, a tributary of Lake Champlain, Vermont, USA; and (c) Tubarao Lagoon, Vitoria, Brazil. Source: A. Drizo.

1.1.1 Natural versus Cultural (Anthropogenic) Eutrophication

Eutrophication can be caused by both natural and anthropogenic processes and activities and it is very important to distinguish between the two. *Natural eutrophication* is a process caused by the incursion of nutrients from natural sources. It is a slow, inevitable, and irreversible process, where accumulation of nutrients in the water and the bottom sediments occurs gradually, over hundreds or thousands of years. Over time, it may result in an ultimate transformation of an aquatic ecosystem into a terrestrial biome (van Ginkel 2011; Ghosh and Mondal 2012). *Cultural eutrophication* (Box 1.2) is caused by anthropogenic activities – human, social, and economic, and their interactions.

Box 1.2 Cultural (Anthropogenic) Eutrophication

Cultural eutrophication is caused by human activities and their perpetual addition of nutrients to the environment. Unlike natural eutrophication, it is often a rapid process which can take place over several years or decades. Cultural eutrophication has been recognized as the single greatest cause of water quality deterioration in freshwater and coastal marine ecosystems worldwide (Smith and Schindler 2009; Schindler 2012). Although it has taken only 60 years for humans to create cultural eutrophication in many freshwater systems, some studies suggest their recovery may take 1000 years under the best of circumstances (Carpenter and Lathrop 2008).

The largest and well-established cause of cultural eutrophication is population growth and its incessant demand and pressure on land and water resources. Some of the examples include (i) changes in settlement patterns in urban and rural areas and subsequent land use; (ii) augmented food production and supplies, with the subsequent increase in fertilizer applications for crop growth and confined livestock and inland and marine aquatic farm production operations; (iii) increased wastewater volumes, which exceed existing wastewater treatment infrastructure capacities often resulting in illicit discharges; (iv) increased construction of infrastructure for water storage and transportation, including catchment and/or watershed alterations, such as building dams; (v) increased demand for leisure activities such are golf courses with high fertilizer demand; and (vi) increased use of fertilizer for home gardens and lawns.

Cultural eutrophication is considered controllable, because humans can take measures to reduce and/or minimize the negative impacts of their activities on the environment (van Ginkel 2011). Therefore, this type of eutrophication is the major topic of this book.

1.2 Trophic Classes of Water Bodies

Since the beginning of twentieth century, water bodies have been categorized according to their *trophic status*, based on concentration of chlorophyll, the transparency of water, and phosphorus mean concentration

Table 1.1 OECD criteria for trophic status of lakes.

	Total P (µg/l)	Chlorophyll a (µg/l)		Transparency (m)	
Trophic status	Mean	Mean	Max	Mean	Min
Ultra-oligotrophic	<4	<1.0	<2.5	>12	>6
Oligotrophic	<10	<2.5	<8	>6	>3
Mesotrophic	10–35	2.5–8	8–25	6–3	3–1.5
Eutrophic	35–100	8–25	25–75	3–1.5	1.5–0.7
Hypertrophic	>100	>25	>75	<1.5	<0.7

Source: OECD (1982). Reproduced with permission of OECD.

(Foundation for Water Research 2006). For standing waters, the Organisation for Economic Cooperation and Development (OECD), proposed a classification scheme consisting of three main trophic classes: oligotrophic for nutrient poor waters, mesotrophic for waters slightly to moderately enriched with nutrients, and eutrophic for waters excessively enriched with nutrients (OECD 1982). In addition they also proposed two boundary classes, ultra-oligotrophic class for the extreme nutrient deficiency and hypertrophic for extreme eutrophication (Table 1.1).

However, the classification for flowing waters according to their trophic status has been debated for the past few decades (Foundation for Water Research 2006). For example, Dodds et al. (1998) reviewed different classification systems for streams and proposed a simplified method based on frequency distribution of nutrients and chlorophyll to define three trophic categories.

The US EPA (2000a) proposed a two-phase approach where streams are initially classified according to their physical parameters associated with regional and site specific characteristics, including climate, geology, substrate features, slope, canopy cover, water retention time, discharge and flow continuity, channel morphology, and system size.

The following phase involves further classifying by nutrient gradient. However, their trophic state classification focuses primarily on chemical and biological parameters including concentrations of nutrients, algal biomass as chlorophyll a, and turbidity, and may also include land use and other human disturbance parameters (US EPA 2000a). More recently, the European Council Directive 91/271/EEC concerning urban waste-water treatment stated that if a river's soluble Phosphorus (P) concentrations exceed 100 µg/l it is excessively enriched with phosphorus (European Commission 2016c).

1.3 The Role of Phosphorus in Eutrophication

Phosphorus (P) is an essential component of nucleic acids and as such it has a central role in nearly all biochemical functions of every living organism (Correll 1998; Wyant et al. 2013). P is vital for plants for the synthesis of genetic material, phospholipid membranes, and metabolism (Plaxton and Lambers 2015). In contrast to carbon and nitrogen, P has no gaseous phase; it is found in the atmosphere only in small particles of dust. Phosphorus is present in the environment as a variety of organic and inorganic compounds. In the aquatic systems it can be found in three forms, as the free *ortho-phosphate* ion (HPO_4^{2-}), as a *polymer* of phosphate compounds ('*polyphosphates*') or as part of an *organic* phosphorus molecule such as DNA (nucleic acid). However, of the three forms only ortho-phosphate is bioavailable, e.g. it can cross the algal cell membranes and be assimilated by bacteria, algae, and plants (Correll 1998; Wyant et al. 2013).

In aquatic systems P is considered a 'growth-limiting' factor (Box 1.3) because it is usually present in very low concentrations (Schindler 1977). Typical soluble P concentrations in unspoiled rivers are often bellow 30 μg/l. Therefore, the additions of very small quantities of P (0.01 to 0.02 mg P/l) are sufficient to induce harmful algae blooms (HABs) in surface waters (Heathwaite and Dils 2000).

The role of phosphorus in causing eutrophication was first demonstrated by Schindler and his research team, over four decades ago (Schindler 1974). In order to elucidate the primary cause of eutrophication, they conducted a series of whole-lake experiments in the Experimental Lakes Area of north western Ontario, Canada. The lake was divided into two basins, of which one was fertilized with phosphorus, nitrogen, and carbon, and the other one only with nitrogen and carbon. Whilst the former one was covered by algal bloom within two months, in the later one there were no changes in species or algae quantity providing clear evidence that phosphorus has a vital role in eutrophication (Schindler 1974).

Schindler and co-researchers continued the whole ecosystem experiment in which they investigated roles of carbon, nitrogen, and phosphorus in controlling eutrophication for nearly four decades. The results from this long-term research corroborated their previous findings that the only way to reduce eutrophication is to decrease inputs of P (Schindler et al. 2008). However, despite evidence, scientists continued to debate the contribution of nitrogen and carbon to eutrophication, particularly in estuaries and coastal environments (e.g. Howarth and Marino 2006).

Box 1.3 The Law of the Minimum

The Law of the minimum concept was developed Carl Sprengel in early 1800s and later promoted by Justus von Liebig (van der Ploeg et al. 1999). *The law represents the origin of the theory of mineral nutrition of plants* and suggests that plant growth is controlled, not by the total amount of nutrients or resources available, but by the availability of the scarcest resource (limiting factor). Over the past century ecologists developed the concept for an aquatic system stating that plant and bacterial growth in an aquatic system would ultimately become limited by the availability of an essential element. This element would then constitute the limiting nutrient for that system at that time, and inputs of that nutrient could be managed to minimize and limit eutrophication (Correll 1998).

More recently, in the light of new European Union Water Framework legislation to control both nutrients (Chapter 3), Schindler (2012) revisited the controversy of which nutrient is the major cause of eutrophication. He discussed the common misconceptions and errors that affected scientific researchers' recommendations including (i) the assumptions that results from the short-term experiments where nutrients are added to small bottles or mesocosms can be extrapolated to whole ecosystems over long time periods; (ii) the investigations about strategies to reverse eutrophication are often made by adding instead of decreasing nutrients from water; and (iii) flawed logic and assumptions about ecosystem-scale nutrient cycling. Furthermore, he pointed out that despite claims that reducing nitrogen is essential to decreasing estuarine eutrophication, there is no documented case history of where this measure has been successful. Regarding criticisms on the lack of response to P control measures in some estuaries, he underlined the well-known fact that the largest human populations and the most intensive conversions of catchments have occurred in coastal areas. Therefore, in these catchments it may take decades to see the response to phosphorus reduction interventions and eutrified waters return to original, phosphorus-limited state (Schindler 2012).

A recent report by the Lake Winnipeg Basin Initiative and published by Environment and Climate Change Canada (ECCC 2017) provided further evidence that nitrogen reduction measures have no or minimal impact on reducing P levels in lakes. The report revealed that after spending $18 million on nitrogen reduction measures between 2012 and 2017, the amount of phosphorus entering the lake fell by less than 1% (ECCC 2017).

1.3.1 Phosphorus Pollution Sources

The annual discharge of P to the environment from human excreta (i.e. faeces and urine), greywater (bathroom and kitchen sinks, showers, baths, washing machines) and livestock animals globally is 44.8–45.1 million metric tons. In addition, pets (dogs and cats) contribute around 7–10 million metric tons annually, just in North America and EU countries, resulting in and annual discharge of 52–55 million metric tons of P (Box 1.4).

This discharge is dispersed via numerous sources which are broadly classified as:

- *Point* (end of a pipe) discharges and
- *Nonpoint* (*diffuse*) pollution sources

Both point and nonpoint discharges may originate from a variety of sources, including: municipal wastewater treatment facilities (largely sewage consisting of human wastes), agricultural (animal wastes, pesticides and fertilizers, agricultural surface and subsurface runoff from animal production areas such are farmyards, feedlots and composting piles, and crop fields), onsite residential septic systems (containing human wastes, detergents, other organic wastes from food; septic systems drainage [leachate]

Box 1.4 Phosphorus Discharges into Environment

- A single adult in the industrialized world excretes 1–3 g P/day (as phosphate).
- About 3–3.3 million metric tons of P is generated annually in human excreta (i.e. faeces and urine) and greywater (bathroom and kitchen sinks, showers, baths, washing machines), globally (Mihelcic et al. 2011).
- Taking into account that a single cow excretes 35–50 g P/day and a pig 55 g P/day (Wyant et al. 2013), livestock animals generate an additional 41.8 million metric tons of P annually resulting in a total of 44.8–45.1 million metric tons of P.
- In North America and EU pets (dogs and cats) excrete additional 7–10 million metric tons of P annually, particularly in urban areas. An average dog produces about 340 g of waste per day containing 0.25% of P as P_2O_5. In 2017 about 182 million dogs and 207 million cats lived in homes as pets in North America and the EU (Statista 2018a).
- Phosphorus (P) concentrations measured in the wastewater streams and runoff (Figure 1.2) exceed quantities that induce HABs 100–60 000 fold, discharging vast quantities of P into the environment daily and further increasing eutrophication risks.

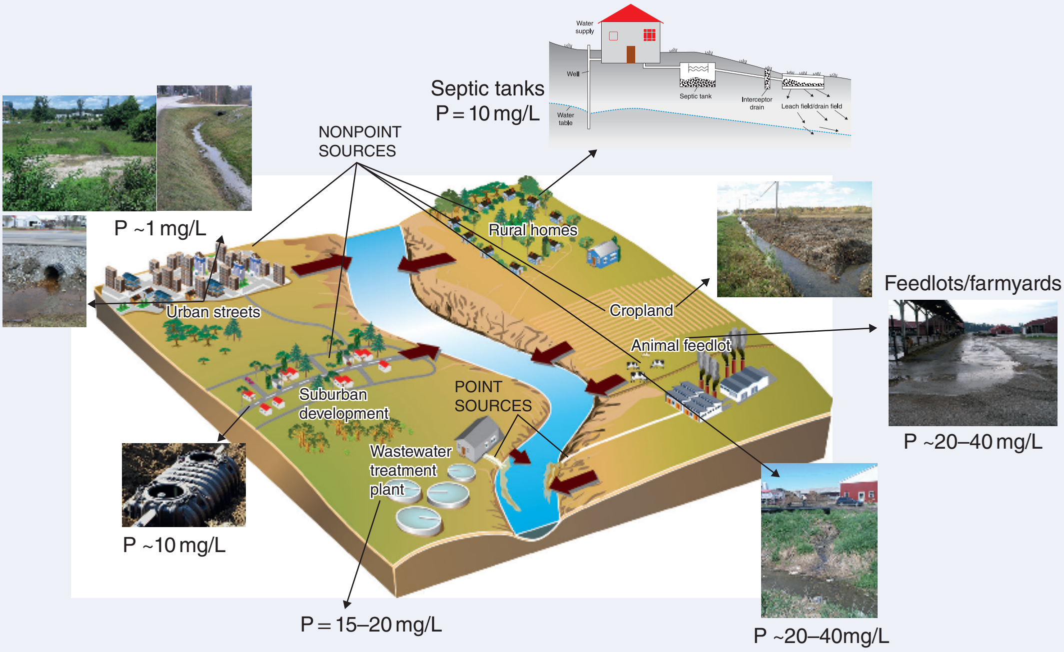

Figure 1.2 Typical P concentrations measured by the author and co-researchers in various point and nonpoint pollution streams across the USA. Source: A. Drizo. All photo images were taken by the author.

fields), industrial (chemical, organic, and thermal wastes), and urban and suburban runoff from car parks, commercial buildings, and houses (roofs and gardens), construction sites, golf-courses, and roads (Figure 1.2).

1.4 Impacts of Eutrophication

Eutrophication has many detrimental impacts on the environment, health (animal and human), and the economy (Table 1.2).

Table 1.2 Impacts of eutrophication.

Impact	References
Intensified growth and production of algae, cyanobacteria (blue-green algae) and aquatic plants typically appearing as algal scums or floating mats of plants and commonly referred to as 'algal blooms'. This excessive abundance in vegetation and bacteria increases respiration rates causing significant fluctuations in dissolved oxygen concentrations and water transparency, eventually leading to hypoxia	e.g. Correll (1998), Smith and Schindler (2009), Ansari et al. (2011), Ghosh and Mondal (2012)
Fish deaths and reduced biodiversity. Low dissolved oxygen causes loss of invertebrates and fish and through their decay, algae and bacteria proliferation, further reducing oxygen content of water and loss of biodiversity	Correll (1998), Ronka et al. (2005), Hautier et al. (2009), Ansari et al. (2011), Brownlie (2014)
Toxins excretion. Certain algal species in marine and freshwaters including cyanobacteria produce toxins that may seriously affect the health of fish, birds, and mammals. This can occur either through the food chain, or direct contact, or ingestion of the algae. Recent studies revealed that most cyanobacteria produce the neurotoxin beta-N-methylamino-L-alanine (BMAA) which had been linked with the development of neurodegenerative diseases (Alzheimer's and Parkinson's diseases, and Amyotrophic Lateral Sclerosis [ALS])	Briand et al. (2003), Foundation for Water Research (2006), Banack et al. (2010), Brand et al. (2010)
Aesthetics. Eutrophication causes increased turbidity, unpleasant odours, slimes and foam formation, diminishing the aesthetic value of waters	Ansari et al. (2011) and Ghosh and Mondal (2012)
Considerable economic losses. Algal blooms reduce potable water supplies, property values, tourism, and recreation. The losses of local economies due to eutrophication were estimated at $2.2 billion per year in the USA in 2009, and between £75 and £114.3 million per year for England and Wales in 2003	Dodds et al. (2009), Pretty et al. (2003), Brownlie (2014)
Global Climate Change will promote cyanobacterial growth and exacerbate algal blooms at much larger scales, further diminishing water availability and potable water supplies	Pearl and Huisman (2008), Moss et al. (2011), Paerl and Paul (2012), Jacobson et al. (2017)

1.5 The Extent of Eutrophication

The occurrence of cyanobacterial harmful algal blooms was first reported in an Australian lake 140 years ago (Francis 1878). During the past century and a half, the eutrophication of fresh and saline waters has been in continuous expansion across the globe (Vollenweider 1970; Schindler 1974; Selman et al. 2008; UNEP 2017; World Resources Institute 2018).

According to the World Resources Institute researchers the number of coastal areas worldwide experiencing symptoms of eutrophication and/or hypoxia increased 85% in just five years between 2008 and 2013 – from 415 to 762. Of the 762 sites, 479 were identified as experiencing hypoxia, whilst

228 sites showed other symptoms of eutrophication, including algal blooms, species loss, and negative impacts to coral reef congregations. The remaining 55 sites were systems in recovery from hypoxia (World Resources Institute 2018). It is estimated that as much as 78% of the assessed continental US coastal area and approximately 65% of Europe's Atlantic coast exhibit symptoms of eutrophication (Figure 1.3). The actual magnitude is most likely much greater given that in many regions of the world (e.g. Asia, Latin America, Africa) research and evidence collection on eutrophication is relatively recent (Le et al. 2010; Walton 2010; van Ginkel 2011; Kundu et al. 2015; World Resources Institute 2018).

In Europe, the European Environment Agency (EEA) declared eutrophication a pan-European problem of a major concern more than 20 years ago (EEA 1995). Despite all the efforts and vast investments, it remains a major threat to achieving the good status of waters required by the Water Framework Directive (European Commission 2015a). The bottom of the Baltic Sea represents the world's largest hypoxic 'dead zone'. Carstensten et al. (2014) recently reported a 10-fold increase of hypoxia in the Baltic Sea in the past 115 years, from 5000 to about 60 000 km^2 which they attributed mainly to increased inputs of nutrients from land.

The second largest zone is located in the USA, in the northern Gulf of Mexico, just under the Midwestern Corn Belt. Over the past 30 years (1985–2014) it had an average size of about 13 650 km^2 (or 5300 mile^2). However, in summer of 2017 the area of this dead zone increased 1.7 fold, to 22 730 km^2 or 8776 mile^2 (Charles 2017).

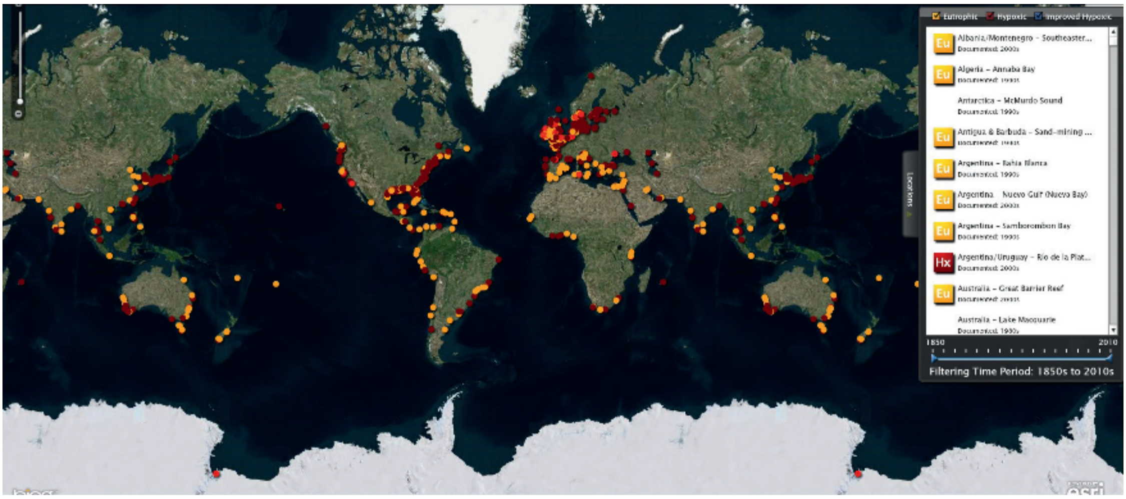

Figure 1.3 Interactive map of eutrophication and hypoxia. Source: WRI (2018).

1.6 Global Climate Change and Eutrophication

There has been increasing scientific evidence that rising nutrient inputs and global warming mutually intensify eutrophication symptoms (e.g. Pearl and Huisman 2008; Moss et al. 2011; O'Neil et al. 2012; Paerl and Paul 2012; Jacobson et al. 2017). This has been attributed to the fact that higher temperatures stimulate cyanobacteria growth and proliferation even at lower nutrient concentrations. For example, increase in surface water temperatures strengthens the vertical stratification of lakes, reducing vertical mixing and promoting accretion of dense surface cyanobacteria blooms. In turn, the blooms may intensify absorption of light, further increasing water temperatures (Pearl and Huisman 2008).

Global climate change also affects patterns of hydrological cycles, e.g. precipitation and drought. These changes could further enhance cyanobacterial proliferation and dominance. For example, more intense precipitation may increase surface and groundwater nutrient discharge into water bodies. Although the freshwater discharge may prevent blooms by flushing in a short term, they will intensify during periods of droughts (longer water residence times). In temperate climates and northern hemisphere this scenario typically occurs when elevated winter–spring rainfall and flushing events are followed by periods of summer droughts (Pearl and Huisman 2008). Recent scientific evidence has shown that eutrophication has also substantially altered fish assemblages and aquatic food webs around the world (Moss et al. 2011; Jacobson et al. 2017).

Despite extensive research during the past four to five decades, many key questions in eutrophication science remain unanswered. Much is yet to be understood concerning the interactions that can occur between nutrients and ecosystem stability. Recent research suggests that nutrients may strongly influence the fate and effects of other non-nutrient contaminants, including pathogens and emerging contaminants (Subirats et al. 2018). There is also limited evidence that eutrophication may promote climate change via greater release of methane from deoxygenated waters and sediments (e.g. Moss et al. 2011).

Further Reading/Resources

DUJS (2012). Eutrophication in the Gulf of Mexico: how Midwestern farming practices are creating a 'Dead Zone'. Posted 11 March 2012. https://sites.dartmouth.edu/dujs/2012/03/11/eutrophication-in-the-gulf-of-mexico-how-midwestern-farming-practices-are-creating-a-dead-zone/ (accessed 10 April 2019).

Fogg, G.E., Stewart, W.D.P., Fay, P. et al. (1973). *The Blue-Green Algae*. London: Academic Press.