

A climate change report card for water

Working Technical Paper

9. River and lake water quality – future trends

P. G Whitehead¹, R. W. Battarbee⁴, J. Crossman¹, J.A. Elliott², R.Wilby³, D.T. Monteith²

¹ School of Geography and the Environment, University of Oxford, South Parks Road, Oxford, OX1 3QY, UK

² Centre for Ecology and Hydrology- Lancaster, Library Avenue, Bailrigg, Lancashire, LA1 4AP, UK

³ Geography Department, Loughborough University, Loughborough, Leicestershire, LE11 3TU,

⁴ Environmental Change Research Centre, University College London, Gower Street, London, WC1E 6BT, UK

Executive Summary

It is now accepted that some human-induced climate change is unavoidable. Potential impacts on water supply have received much attention, but relatively little is known about the likely impacts on water quality. Projected changes in air temperature and rainfall will affect catchment water balance and hence river flows and the mobility and dilution of nutrients and contaminants. Increased water temperatures will affect chemical reaction kinetics, lake stratification, in stream process and freshwater ecological status. With increased flows there will be changes in stream power, water depths, water velocity and sediment loads. These will alter the morphology of rivers and the transfer of sediments to lakes, thereby impacting water quality and freshwater habitats in both lake and stream systems. This paper reviews the potential impacts of climate change on rivers and lakes in the UK. Widely accepted climate change scenarios suggest more frequent droughts in summer, as well as flash-flooding, leading to uncontrolled discharges from urban areas to receiving water courses and lakes. Invasion by alien species is highly likely, as is migration of species within the UK adapting to changing temperatures and flow regimes. Lower flows and reduced velocities result in higher river and lake water residence times, which will enhance the potential for algal and cyanobacterial blooms and reduce dissolved oxygen levels. Upland streams and lakes could experience altered acidification status, as well as increased dissolved organic carbon and turbidity, requiring action at water treatment plants to prevent toxic by-products entering public water supplies. Storms that terminate drought periods will flush nutrients from urban and rural areas and may cause acid pulses in acidified upland catchments. Tables 1 and 2 provide concise summaries of the expected impacts of climate change on future river and lake water quality.

Table 1 A Summary of the Impacts of Climate Change on Rivers (adapted from Hering et al, 2010)

Category		Response
Hydrology	Decrease in ice cover duration	Higher temperatures will reduce frozen soils coverage and stream ice duration in high altitude mountain areas.

	Increase in drought frequency and duration	Decreased summer precipitation and increasing air temperature in some parts of Central, Eastern and Southern UK could extend the length of dry ephemeral upper reaches of rivers.
	Change of rainfall to a more intermittent regime	Due to less precipitation and increased demand for freshwater, higher temperatures, and higher evapotranspiration, many small rivers could become intermittent with long dry phases in summer.
Morphology	Increased fine sediment	Extreme precipitation events increase surface runoff and lead to large amounts of fine sediments entering the streams; sediments accumulate and clog the bottom interstitial layers.
Physicochemistry	Increased nutrient loading	Nitrogen flux in the runoff and decomposition of the soil organic matter increases with temperature, which increases nutrient concentrations. Similarly with Phosphorus, lower flows mean less dilution of effluents and hence increased P concentrations in rivers. Both N and P enhance eutrophication of rivers. Eutrophication is further promoted by high water retention time during low flows periods. However, denitrification is enhanced during low flows and warmer conditions.
	Reduced water quality	Increasing water temperatures enhance production and decomposition intensity, thus leading to oxygen depletion, particularly at night and during algal blooms.
	Effects on nutrients	Higher water temperatures lead to a more rapid mineralization of organic matter (leaves, wood) and thus to eutrophication effects.
	Acidification	Increased winter precipitation increases acid runoff in upland streams confounding chemical and biological recovery from acidification
Primary production	Increased macrophyte/algal growth	Higher water temperatures and lower discharge enhance macrophyte and algal growth.

Secondary production and food webs	Increase of respiration rate	The metabolic rates of bacteria and fungi will rise with increasing temperatures. The primary production to respiration ratio will decrease.
	Reduced availability of leaves	Processing rates of leaves and wood increase with temperature. Floods in winter cause more than 50% of leaf inputs to be exported, leaving little detrital material available for invertebrate consumption.
	Replacement of cold water species (fish, macroinvertebrates)	Many fish and invertebrate species in cold regions are highly adapted to cold water and could vanish with higher temperatures.
	Increase or decrease of species number	Low temperatures are a migration and physiological barrier for many aquatic species. With temperature increase, several species can invade rivers in cold ecoregions.
	Increase of invertebrates	Certain invertebrates benefit from unpredictable flood events, e.g. in summer, which remove most invertebrates and thus favour species rapidly colonizing the competition-free space.
	Potamalization' - effects on invertebrates	Higher water temperature leads to the disappearance of species adapted to cold water temperature and the associated high oxygen content, e.g. several stonefly (Plecoptera) species. They are replaced by species typical for warmer water previously colonizing more downstream reaches. Thus, invertebrate species typical for small streams ('rithral') will be replaced by species from larger rivers ('potamal').
	Replacement of salmonid by cyprinid fish species	Higher water temperatures will reduce reproductive success of salmonid species and increase parasitic and predator pressure on the egg and young larval stages. Warm water cyprinid species will invade in cold water regions.
	Standing stock of cold water fish	Brook trout populations could either benefit from increased growth rates in spring and autumn or suffer from shrinking habitat and reduced growth rates in summer, depending on the magnitude of temperature change and on food availability.

	Spread of alien species	Higher temperatures often favour alien species that increasingly colonize small streams. These could be alien fish, macrophyte or macroinvertebrate species.
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Table 2 Summary of Impacts of Climate Change on Lakes (adapted from Hering et al, 2010)

Category		Response
Hydrology	Ice cover	Higher air, and thus higher water temperature, leads to a shorter ice-cover period. The relationship between air temperature and timing of lake ice breakup shows an arc-cosine function.
	Stratification	Higher temperatures result in earlier onset and prolongation of summer stratification. As a result, changing mixing processes occur and systems may change from dimictic to warm monomictic. A lack of full turnover in winter might lead to a permanent thermocline in deeper lakes.
	Water level	Increased temperature and decreased precipitation in conjunction with intensive water use (e.g. abstraction for irrigation) will decrease water volumes. This will lead to water level imbalances and, in some cases, to the complete loss of water bodies in more arid regions.
PhysioChemical Effects	Oxygen depletion	High temperatures will stimulate phytoplankton growth, which will lead to oxygen depletion in lake hypolimnia.
	Sulphate concentration	With less precipitation in El Nino years and resulting droughts, stored reduced S in anoxic zones (wetlands) is oxidized during drought, with subsequently high sulphate export rates. This will result in elevated sulphate concentrations and levels

		of acidity in lakes.
	DOC	Rising temperatures could exacerbate further levels of DOC that are already increasing in response to declining acid deposition.
	Acidification effects	Depression of acid neutralising capacity caused by increased precipitation that will limit biological recovery from acidification
	Total Organic Carbon (TOC) runoff patterns	Warmer Summers followed by wetter winters could produce higher TOC concentrations, depending on the specific timing of hydrological events. The pattern will vary from catchment to catchment.
	Water temperature effects on phytoplankton	Increasing water temperatures lead to shifts from a dominance of diatoms and cryptophytes to cyanobacteria. This effect is especially pronounced at temperatures > 20 C, since cyanobacteria (especially large, filamentous types) and green algae are favoured at higher temperatures.
Primary production	Water temperature effects on macrophytes	macrophytes will be suppressed by increasing turbidity from algae and rising DOC. Also increasing temperature may lead to changes in species composition, especially spread of thermophilous taxa
	Water temperature effects on zooplankton	Higher water temperature leads to shifts in zooplankton community composition. Higher, earlier population growth rates of <i>Daphnia</i> and earlier summer decline occur due to higher spring temperatures. As a result, higher <i>Daphnia</i> biomass leads to earlier phytoplankton suppression and a shift from a dominance of large- bodied to smaller species.

	Water temperature effects on cold water fish	Higher water temperatures (especially in the epilimnion) lead to the progressive reduction of thermal habitats for salmonids. As a result, cold-water species will disappear from littoral areas in spring and summer. Furthermore, higher water temperatures will reduce reproduction success of cold-water species and increase parasitic and predator pressure on the egg and young life stages.
Secondary production	Spread of alien species	Higher temperatures often favour alien fish, macrophyte or macroinvertebrate species.
Food webs	Water temperature effects on food webs	Increased water temperature generates principal shifts in food webs. As cyprinid planktivorous fish species are favoured supported, large zooplankton species are suppressed and grazing intensity is reduced.

1 INRODUCTION

The 2007 Conference of the Parties to the United Nations Framework Convention on Climate Change, in Bali, and the latest IPCC Report (2007) confirmed the consensus amongst scientists and policy makers that human-induced global climate change is now occurring. However, there is less certainty about the magnitude of future temperature changes and how these will drive precipitation, evaporation and hydrology at regional scales. Nonetheless, climate model scenarios provide the best available information for assessing future impacts of climate change on the water quality of rivers and lakes (Kundzewicz *et al.*, 2007, Bates *et al.*, 2008).

The *Freshwater* chapter in the IPCC Fourth Assessment Report (Kundzewicz *et al.*, 2007) was unable to consider the impacts of climate change on water quality in great detail, but this topic has attracted growing attention. For example, several European projects have focussed on this subject area. The EU Euro-limpacs Project was a multi-partner, €20-million research project which investigated climate change impacts on rivers, lakes and wetlands across Europe (Battarbee *et al.*, 2008, Kernan *et al.*, 2010). Further to this, a new project, REFRESH, (see <http://www.refresh.ucl.ac.uk/>) addresses the management of rivers and lakes to accommodate future climate change. Both projects used a wide range of integrated methods, including laboratory and field experiments, data analysis and process-based modelling. Such European projects have been complimented in the UK by a range of projects funded the Natural Environment Research

Council, UKWIR and the EA. These projects have highlighted water quality changes (Whitehead et al, 2009, Cox et al, 2012) and have collectively raised many questions about future climate change impacts such as:-

- How will climate change impact river flows and, hence, the flushing of diffuse pollutants or dilution of point effluents?
- In what ways might more intense rainfall events affect nutrients and sediments loads in urban drainage systems, rivers, lakes and estuaries?
- How might rising temperatures combined with water quality changes affect freshwater ecosystems?
- How might the carbon balance and recovery from acidification be affected in upland catchments?

A full set of questions that have been raised as part of Euro-limpacs are given in Appendix 1 and many of these have been answered by Kernan et al (2010).

This paper provides a review of river and lake water quality, in terms of their hydrological regimes, hydromorphology, nutrient status, mobilisation of toxic substances and acidification potential. Tables 1 and 2 summarise the potential impacts for rivers and lakes and their likelihood of occurrence. Assessing confidence or uncertainty is important for policy makers who have to judge how seriously to take potential threats. The significance of this is demonstrated in the “acid rain” projects in the 1980s, where information was supplied to planners and managers with uncertainty bounds (Cosby *et al.*, 1986). These data were then used in protocol negotiations in Geneva, and used to design management strategies. The projections for the recovery of rivers and lakes from acidification, under modelled management scenarios, have largely been proved correct (Wright *et al.*, 2005). This suggests that prediction using a good knowledge of experimental and field data, process based models and uncertainty analysis can be an extremely effective combined strategy to answer questions raised by policy makers, agencies and governments, and leads to evidence based decisions. The final section of this review considers the confidence in the science.

2 IMPACTS OF CLIMATE CHANGE ON RIVER WATER QUALITY

A summary of the potential impacts on river water quality is given in Table 1 above

Hydrology, Water Quality and Thermal Regimes

A review of surface water quality cannot be undertaken without considering changes in hydrological regimes. The UK Climate Projections 2009 (UKCP09) provide climate change projections with high spatial and temporal detail, and are the first dataset to give probabilistic assessments of future climate change (Murphy et al., 2009). The UKCP09 report summarized that under the medium emission scenario, by 2080s all areas of the UK will become warmer relative to the 1961-1990 baseline condition; more so in the summer than

in the winter. For example, summer mean temperature in parts of Southern England could increase by 4.2 °C (50% probability level). Precipitation patterns are projected to change significantly with more precipitation in winter (up to +33% change—50% probability level) and less in summer (down to -40% seen in the south of England—50% probability level). These probabilistic data are available for 23 river regions in the UK. Changes are projected for seven future 30-year time periods, with 10 years overlapping. It starts with the 2020s (2010-2039) and ends with the 2080s (2070-2099), each with low, medium and high emission level.

Marsh and Hannaford (2007) have shown that summer precipitation has already fallen to some extent (Figure. 1). Furthermore, the frequency of extreme events is also predicted to increase, with two-year (return period) winter precipitation event intensities estimated to increase by between 5% (low emissions) and 20% (high emissions) by the 2080s. These changes in precipitation have been used to simulate changes in flow across the UK (Cox et al 2012), Arnell, 2003; Limbrick *et al.*, 2000). More recently, Romanowicz *et al.* (2006) modelled changes in river flow for a range of catchments, under different climate model projections. They conclude that, by the 2020s, flows in winter could increase by between 4 and 9%, and that summer flows could decrease on average by 11%, but that this could range between 1 to 32% depending on catchment location, land use, soils, geology, and model uncertainty.

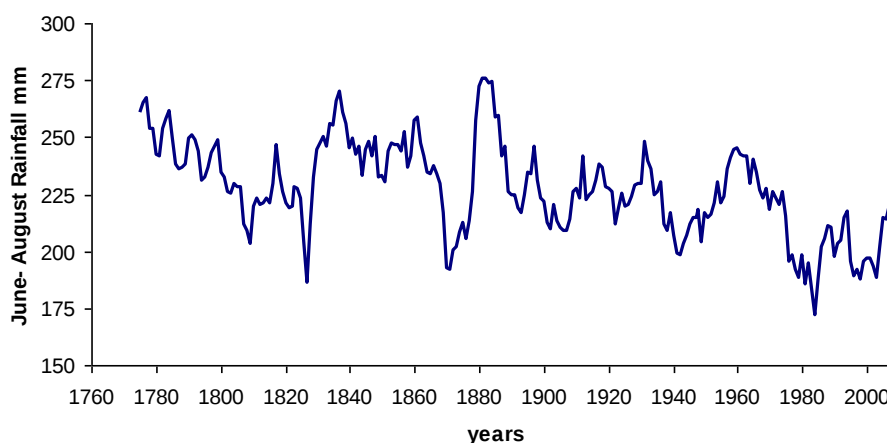


Figure. 1 Summer (June–August) rainfall totals (mm) showing long-term decline (Source: Marsh and Hannaford, 2007).

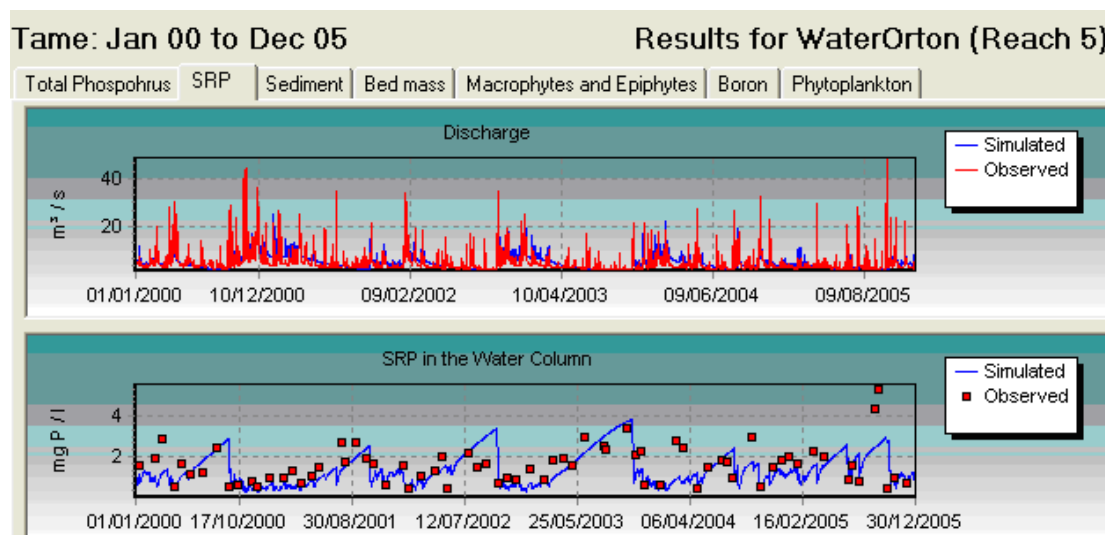


Figure. 2 Flow and phosphorus simulation and observed data for Water Orton on the River Tame in Birmingham, UK.

Lower minimum flows imply less volume for dilution and higher concentrations downstream of point discharges such as wastewater treatment works (WTWs). This could counter efforts to improve water quality standards, and to meet Water Framework Directive (WFD) objectives to restore and protect freshwater ecosystems. For example, Figure 2 shows the inverse relationship between phosphorous levels and flow in the River Tame, downstream of Birmingham, during summer months. Phosphorus increases significantly in summer months as flows fall. This is a direct consequence of reduced dilution of WTW effluents. Under climate change, natural headwater flows in summer could be lower, thereby providing less dilution and higher concentrations.

Reduced dilution effects will also impact organic pollutant concentrations, with increased biochemical oxygen demand (BOD) and, hence, lower dissolved oxygen (DO) concentrations in rivers. Cox and Whitehead (2008) show that, under a range of UKCIP scenarios, DO in the rivers will be affected by enhanced BOD, and by the direct effects of temperature which reduces the saturation concentration for DO. In many rivers, algal blooms in summer are a feature of the river ecology and the frequency and intensity of these may increase. When an algal bloom occurs, there are large diurnal variations in DO and low oxygen levels can be exacerbated by pollution events during summer low-flow conditions. Williams *et al.* (2000) show that large diurnal variations in streams dominated by macrophytes occur and thus pollution events in such streams could also generate low DO levels.

The most immediate reaction to climate change is expected to be in river and water temperatures (Hassan *et al.*, 1998; Hammond and Pryce, 2007, Nickus *et al.*, 2010, Orr, 2012). River water temperatures show similar variability and longer term change to air temperatures when the latter are above freezing point, and, as air temperatures rise, river temperatures will increase. There has

already been a 1–3°C temperature rise over the past 100 years in large European rivers such as the River Rhine and the River Danube (EEA, 2007a). Small streams have shown an increase in winter temperature maxima in Scotland (Langan *et al.*, 2001), and there have been large increases in temperature reported for water courses in Switzerland at all altitudes (Hari *et al.*, 2006). There have been two sudden shifts in river temperatures, in 1988 and 2002, following changes in air temperature. Abrupt water temperature rises could have important implications for some aquatic organisms, if species are unable to adapt at the same pace. Furthermore, a recent study by Orr *et al* (2012) of long-term trends in UK surface waters revealed regional variations with generally rising temperatures and a mixture of flow changes across England and Wales, as shown in Figure 3. It should be noted, however, that river temperatures will also be affected by discharges of warm waters from power plants and sewage treatment works, and also by diffuse sources of warm groundwaters (Orr *et al*, 2012).

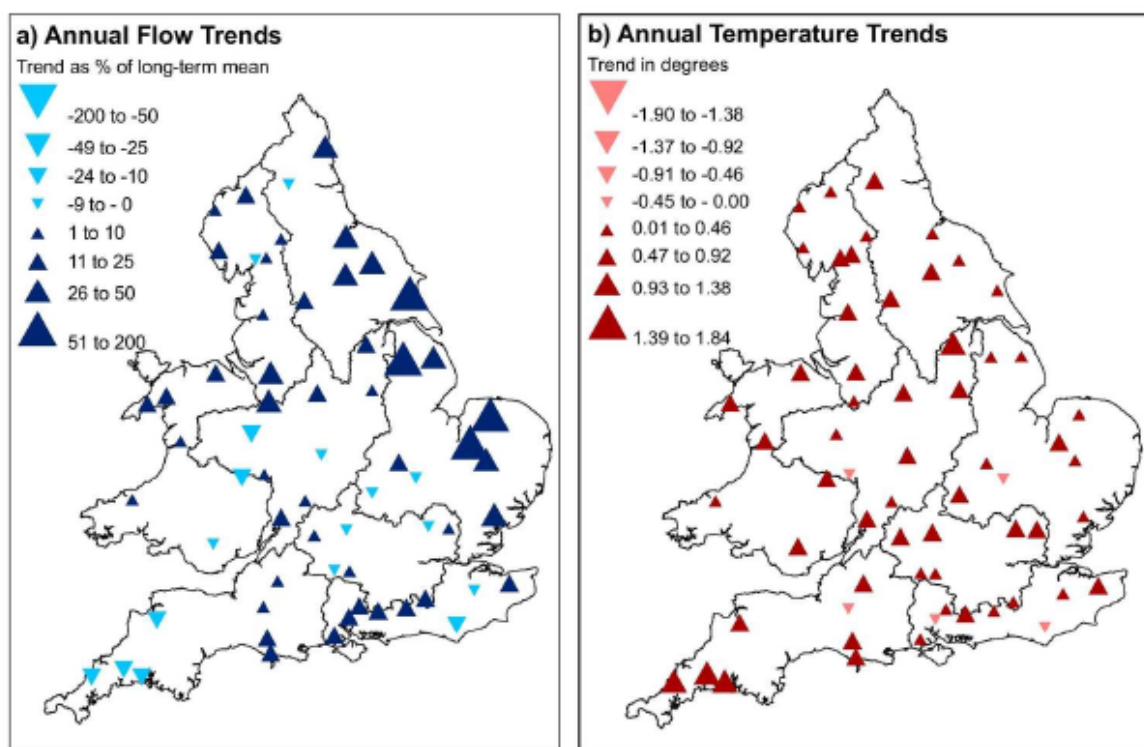


Figure 3 Annual flow and temperature variation in 63 benchmark catchments across the England and Wales (Flow trends are in blue b, temperature trends in red. Upward (downward) pointing triangles indicate increasing (decreasing) trends over the period 1990 to 2006. Flow trends are expressed as a percentage of the average for 1990 to 2006.

Most chemical reactions and bacteriological processes run faster at higher temperatures. In addition, temperature controls the growth rates of phytoplankton, macrophytes and epiphytes, making freshwater ecosystems sensitive to rising temperatures (Whitehead and Hornberger., 1984;

Wade *et al.*, 2002b). Water temperatures also regulate the behaviour of aquatic organisms, such as fish migration, and the timing of emergence and abundance of insect populations at different life-cycle stages (e.g. Davidson and Hazelwood, 2005; Durance and Ormerod, 2007). This has implications for meeting the WFD objectives, as reference conditions for the restoration and improvement of the ecology of streams could be more difficult under a future climate (Wilby *et al.*, 2006a).

Hydromorphology, Water Quality and Ecology

Climate change is expected to have far-reaching consequences for river regimes, flow velocity, hydraulic characteristics, water levels, inundation patterns, residence times, changes in wetted areas and habitat availability, and connectivity across habitats (Brown *et al.*, 2007, Hering *et al.*, 2010). More intense rainfall and flooding could result in increased loads of suspended solids (Lane *et al.*, 2007), sediment yields (Wilby *et al.*, 1997), *E. coli* and contaminant metal fluxes (Longfield and Macklin, 1999) associated with soil erosion and fine sediment transport from the land (Leemans and Kleidon, 2002).

In many parts of Europe, hydromorphology is a key factor controlling ecosystem behaviour. Alterations to river forms through channel straightening, loss of connectivity with flood plains, weir and dam construction, and loss of riparian vegetation also impact on river ecology. Under the WFD there is a requirement to reverse some of these changes and restore the ecology of rivers and lakes towards their natural states. However, climate change may act against restoration, making it difficult, if not impossible, to return to the previous ecosystem status (Battarbee *et al.*, 2005, Orr and Walsh, 2006), as illustrated in Figure 4 (from Battarbee *et al.*, 2005). Changes in climate could affect sediment transfer, channel morphology and inundation frequency, thereby altering ecosystems at both catchment and habitat scales (Verdonschot, 2000). The impact of low flows on biotic communities has been studied extensively in the River Lambourn, UK (Wright *et al.*, 1982). In this case, drought has a deleterious effect on aquatic ecology with *Ranunculus* being smothered by epiphytic algae (Wade *et al.*, 2002b). Drought also significantly damages macro-invertebrates, although recovery can be fast (Ladle and Bass, 1981).

Extreme events could have significant impacts on upland rivers, releasing higher concentrations of sediments by erosion and re-suspension, thereby creating new or disturbed habitats downstream. However, this can be beneficial to upland stream ecology with natural formations of pool and riffle sequences and a wider range of habitats, such as meandering side channels, larger dead zone areas and deeper sediment zones to support aquatic life. An extensive study in German rivers shows that habitat restoration may be enhanced by the effects of a more variable flow regime (Hering *et al.*, 2008).

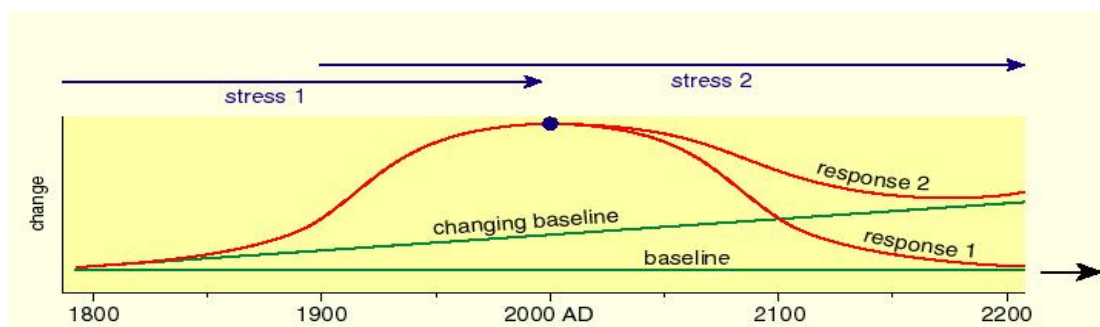


Figure. 4 Conceptual diagram illustrating ecosystem response to increasing and decreasing stresses (from Battarbee et al, 2005)

The PRINCE project (PRINCE-Preparing for climate change impacts on freshwater ecosystems) specifically addressed the potential impacts of climate change for selected UK freshwater ecosystems (Conlan *et al.*, 2007). It was shown that changes in climate could influence aquatic ecosystems through episodic pulsed effects (i.e. changes in the frequency, duration and magnitude of extreme events) and by progressive change in ambient conditions. Many cold-blooded freshwater species are sensitive to the water temperature regime, as they have a limited range of thermal tolerance. Thus, changes in the temperature regime could have significant effects on the life cycle of a wide variety of aquatic organisms. Temperature effects could combine with changes in water velocity and DO to affect the life cycles and inter-relationships of organisms such as invertebrates, amphibians, fishes and birds. In addition, there may be impacts on dispersal or migratory patterns across ecosystems, for example, between marine systems and freshwaters by long-distance migrants (Atlantic salmon, eel, shad), or across watersheds during inter-basin dispersal flights by invertebrates; and via the introduction, survival and population dynamics of exotic organisms.

In summary, climate change could affect: (a) the magnitude, frequency (return period), timing (seasonality), variability (averages and extremes) and direction of predicted changes of flow and water quality; and (b) the sensitivity and resilience of the ecosystem, habitat and/or species to those changes. Habitats that are already in vulnerable stream sections, such as headwaters, ditches and ephemeral ponds, could be the most sensitive to changing climatic conditions.

Nutrients and Eutrophication

There is a long history of increasing nutrient levels in UK Catchments. Figure 5 shows observed nitrate concentrations in the Thames since 1930 and these changes are largely related to changes in land use and fertiliser use (Whitehead, 1990). Thus climate induced change will be superimposed on these long term trends.

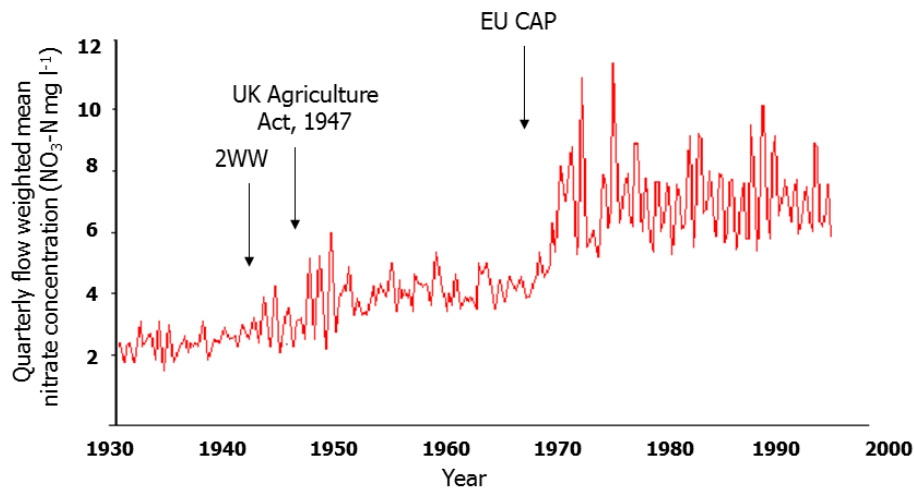


Figure 5 Nitrate Concentrations in the Lower Thames from 1930

Nutrient loads are expected to increase under climate change (Bouraoui *et al.*, 2002). However, assessing the impacts on eutrophication is not straightforward as it is a result of the complex interplay between nutrient availability, light conditions, temperature, residence time and flow conditions (Whitehead and Hornberger, 1984). However, using field or modelling experiments, it is possible to assess the impacts of climate change on individual components contributing to eutrophication. As has already been discussed, temperatures will rise, favouring increased growth rates of algae (Whitehead and Hornberger, 1984), especially cyanobacteria. Flow rates in summer could fall, thereby increasing the residence time of water in controlled reaches, as is typical for many lowland rivers. Increased residence times increase growth potential of algae, enhance the settling rate of sediments, and reduce water column sediment concentrations. This in turn reduces turbidity so that improved light penetration can enhance algae growth.

Meanwhile, nutrients released from agriculture would be less diluted, due to the reduced flows in summer. Whitehead *et al.* (2006b) simulated these combined effects on the River Kennet in terms of projected nitrate and ammonia concentrations. As shown in Figure. 6, nitrate concentration increases over time as higher temperatures increase soil mineralisation. This is particularly significant under high flow conditions following a drought. Whilst this was a theoretical modelling exercise, similar responses have been observed in the field. For example, Figure. 7 shows nitrate concentrations in the Thames at Days Weir at the termination of the 1976 drought (Whitehead and Williams, 1982). Nitrate-N concentrations rose from 4 mg/l to 18 mg/l as nitrates were flushed from the Thames catchment. Increased frequency of flushing events is expected under some climate change scenarios, and this extra nitrogen could enhance eutrophication in receiving water bodies. This may be more important for nutrient-poor upland rivers and lakes, and could be significant for estuary and coastal systems that ultimately receive the extra nutrients.

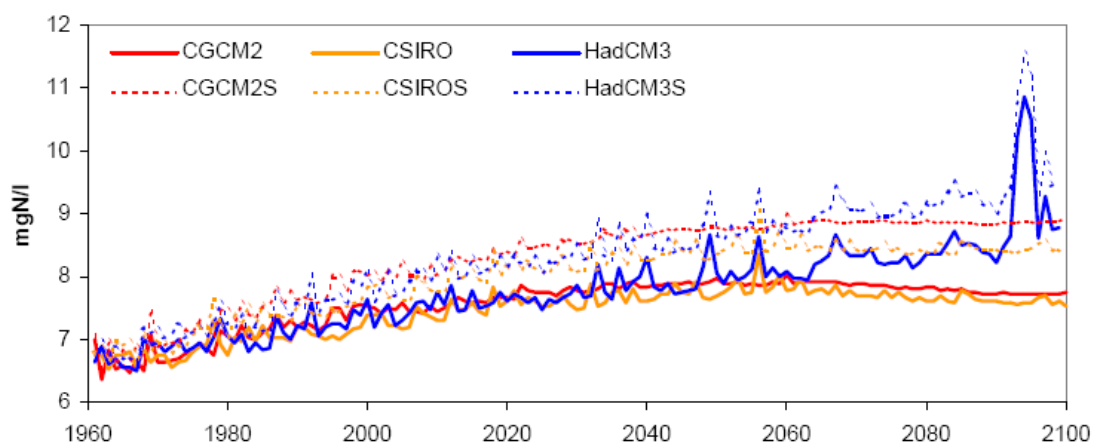


Figure. 6 Nitrate-N concentrations (fifth percentiles shown as dotted lines) over the 21st century under a range of GCMs (A2 emissions) for the upper Kennet River system.

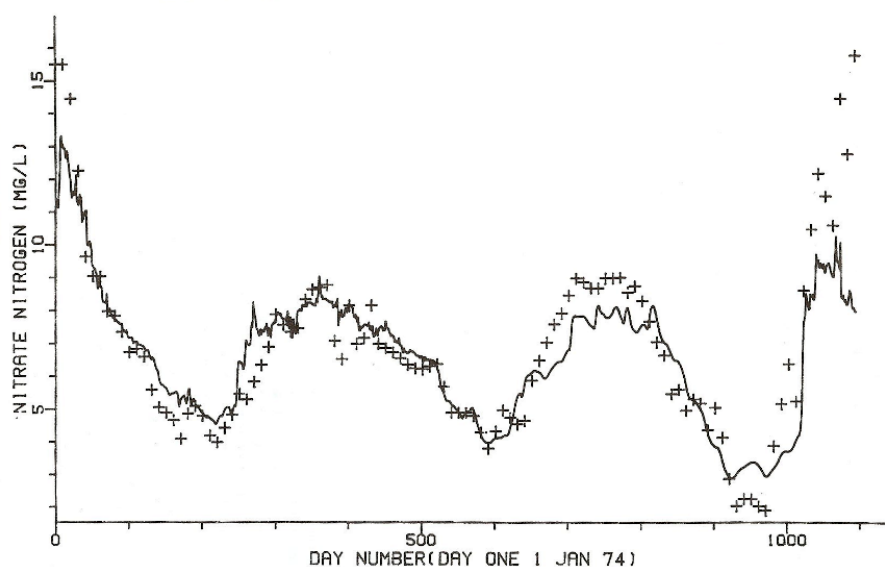


Figure. 7 Nitrate-N at Day's Weir on the River Thames during 1974, 1975 and 1976, showing increased concentrations when the drought ended (Whitehead and Williams, 1982).

Toxic Substances and Persistent Organic Pollutants (POPs)

Although many of the most toxic substances introduced into the environment by human activity have been banned or restricted in use, many persist, especially in soils and sediments, and either remain in contact with food chains or can be remobilised and taken up by aquatic biota (Catalan *et al.*, 2004; Vives *et al.*, 2005). High levels of metals (such as mercury, Hg, and lead, Pb) and persistent organic pollutants such as polychlorinated biphenyls (PCBs) are present in the tissues of freshwater fish in arctic and alpine lakes (Grimalt *et al.*, 2001, 2010; Vives *et al.*, 2004a). This attests to the mobility and transport of these substances in the atmosphere (Carrera *et al.*, 2002) and their

concentration in cold regions (Fernandez and Grimalt, 2003). Biomagnification within aquatic systems with long food chains can elevate concentrations in fish to levels lethal for human consumption. The major concern with respect to climate change is the extent to which toxic substances will be remobilised and cause additional contamination and biological uptake in arctic and alpine freshwater systems as water temperatures rise. Storm events and flooding might also increase soil and sediment erosion and lead to the re-mobilisation of metals and persistent organic compounds (Grimalt *et al.*, 2004a,b; Rose *et al.*, 2004). In the case of Hg, changing hydrology in Boreal forest soils may lead to the enhanced production of methyl mercury (Meili *et al.*, 2003; Munthe, 2008).

In Europe, mountains and remote ecosystems are directly influenced by temperature changes and are subject to the accumulation of persistent organic pollutants (POPs) (Grimalt *et al.*, 2001). Rivers and lakes in these environments provide information on the transfer mechanisms and impact of these compounds in headwater regions. Accumulation patterns depend on diverse aspects such as the time of their introduction into the environment (Gallego *et al.*, 2007). Polybromodiphenyl ethers (PBDEs) in fish from Pyrenean lakes showed higher concentrations at lower temperatures, as predicted in the global distillation model. Conversely, no temperature-dependent distribution of POPs has been observed in vertical lake transects, neither in the Tatra Mountains (Central Europe) nor in fish from high mountain lakes distributed throughout Europe (Vives *et al.*, 2004b). Concentrations of PCBs in fish show significant temperature correlations in all these studies.

In addition, leaching of heavy metals from old mining tailings, or in discharges from abandoned mines, can cause local breaches of quality standards. Simulations of the impact of climate changes in northern England show decreased surface contamination through dilution by cleaner sediment from hillslopes unaffected by mining activity (Coulthard and Macklin, 2003). Discharges of polluted water from mines depend on the extent of groundwater rebound (Adams and Younger, 2001).

Acidification and DOC in the Uplands

There has been a long history of acidification in base-poor catchments in the UK with pH levels falling, acidification rising, changes in base cations and damage to fisheries. However, reductions in sulphur emissions since the 1980s have initiated the recovery of many European streams and lakes that have been subject to acidification (Wright *et al.*, 2005). Models such as MAGIC (Model of Acidification In Groundwaters) successfully predicted this slow recovery (Cosby *et al.*, 1986, Whitehead *et al.*, 1997) and some studies warned of future problems associated with increased N deposition and climate change (Wilby, 1993; Wright *et al.*, 1995; Whitehead *et al.*, 1997; Monteith *et al.*, 2000). Effects of climate change could be significant, with higher temperatures affecting reaction kinetics, base cation dissolution rates and soil sulphate adsorption properties. Climate variables that could also affect acidification are increased summer drought, wetter winters, reduced snow pack, changes in hydrological pathways, and increased occurrence of sea-salt deposition events. Intense rainfall and wetter winter conditions favour acidic episodes (Wright, 2006, Evans *et al.*, 2008) as does rapid melt of snow packs (Laudon and Bishop, 2002). Acid pulses can, in turn, cause fish kills and loss of invertebrate species (Kowalik and Ormerod, 2006).

Droughts can further exacerbate acidification by creating lower water tables, aerobic conditions and enhancing the oxidation of sulphur to sulphate (Wilby, 1994; Dillon *et al.*, 1997). Acid anions are exported during subsequent storm events, along with heavy metals (Tipping *et al.*, 2003). Peat catchments in industrial regions are particularly vulnerable to climate change as they have significant stores of anthropogenically derived sulphur which could be released following summer droughts (Aherne *et al.*, 2006). Nitrogen is another source of acidification in upland catchments as nitric acid is a strong acid anion that can be flushed after droughts (Adamson *et al.*, 1998; Curtis *et al.*, 2005, Whitehead *et al.*, 1997; Wilby *et al.*, 2006b). The Norwegian CLIMEX study (Wright *et al.*, 1998; Wright and Jenkins, 2001) showed significant mineralization of nitrogen following increases in temperature and CO₂, and this converted a small catchment from acting as a nitrogen sink to a nitrogen source.

Dissolved organic carbon (DOC) concentrations have doubled across the UK since the 1980s (Monteith *et al.*, 2000; Freeman *et al.*, 2001; Evans *et al.*, 2001, 2005; Worrall *et al.*, 2003, 2004) (Figure. 8). In relatively undisturbed upland regions most DOC is thought to be derived predominantly from recently produced organic matter, although in severely degraded peatlands much older organic matter (i.e. peat) can make a significant contribution to overall fluxes. In upland waters water colour is often highly correlated with DOC, and as DOC increases water colour becomes increasingly brown. Whilst colour *per se* is not a public health issue, the chlorination processes at water treatment plants generate by-products, such as trihalomethanes, which are carcinogens (Chow *et al.*, 2003).

While the precise mechanisms responsible for rising DOC levels are not yet clear there is now strong evidence from local to international studies across northern Europe and North America that the large reduction in sulphur deposition has dominated these increases (e.g. Monteith *et al.*, 2007; De Wit *et al.*, 2007; Oulehle and Hruska, 2009; Haaland *et al.*, 2010; Ekström *et al.* 2011; Erlandsson *et al.*, 2008; Borken *et al.*, 2011; SanClements *et al.*, 2012). Recent experimental work supports the hypothesis that deposition-driven changes in soil acidity are responsible for increased organic matter solubility (Evans *et al.*, submitted) so that a larger proportion of net primary production is now being exported in dissolved fluvial form.

One implication of this increased solubility is that DOC fluvial fluxes and concentrations may be becoming more sensitive to climatic effects. On shorter timescales there is no doubt that hydrological conditions affect DOC export, with lower DOC concentrations during drought and greater concentrations during high flows (Hughes *et al.*, 1997). Indeed, deposition variables alone are unable to account for some particularly high concentrations experienced at several sites during the autumn and winter of 2006 and 2007, and this could reflect the combination of a particularly warm dry summer in 2006 followed by lower than average autumnal rainfall (Monteith *et al.*, 2012,

in press). DOC modelling by Futter *et al.*, (2007) suggests that warmer, wetter climates could lead to higher levels of surface water DOC, but there remain large uncertainties due to the complex dynamics and biochemical processes controlling soil carbon flux.

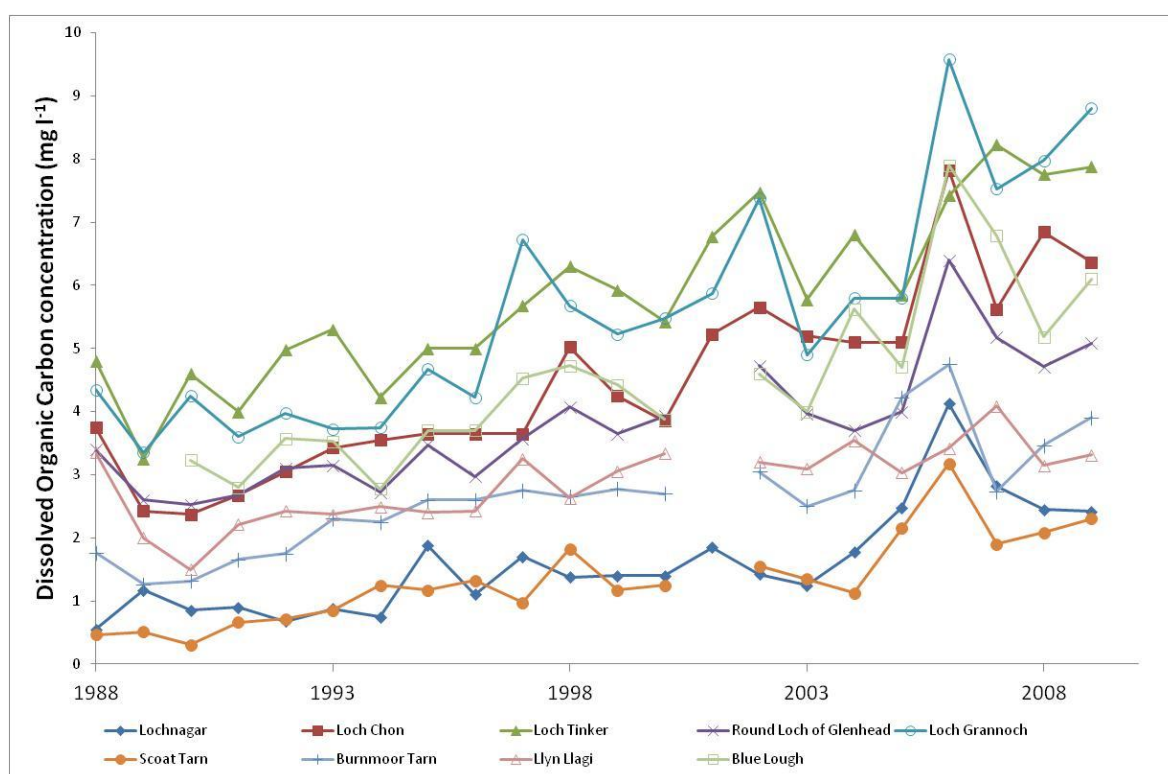


Figure. 8 Trends in DOC across the UK. Source: UK Upland Waters Monitoring Network.

Urban River Water Quality

Built environments are already “hot spots” of environmental change (Grimm *et al.*, 2008). Areas of impervious surface cover alter the hydrology and geomorphology of drainage systems, whereas municipal and industrial discharges increase loads of nutrients, heavy metals, pesticides and other contaminants in receiving surface water courses (Paul and Meyer, 2001; Clark *et al.*, 2007). In

addition, groundwater beneath industrial conurbations may be contaminated by microbiological agents, nitrogen, chlorinated and hydrocarbon compounds, and metals originating from the overlying land complexes or leakage from sewerage systems. Urban land uses also affect the patterns and rates of recharge to underlying aquifers as evidenced by detailed surveys for Birmingham (Ford and Tellam, 1994), Doncaster (Morris *et al.*, 2006) and Nottingham (Barrett *et al.*, 1999), in England, UK.

It is widely recognised that urban populations, infrastructure and institutions will come under increased pressure with climate change (Ruth and Coelho, 2007). Anticipated risks involve cooling of urban areas, urban drainage and flood risk, security of water resources supply, and outdoor spaces (including air quality and habitats) (Wilby, 2008). Potential impacts on urban water quality will be driven largely by changes in short-duration rainfall intensity overwhelming drainage systems, as well as rising sea levels affecting combined sewerage outfalls. The former could result in greater incidence of foul water flooding of domestic property, or uncontrolled discharges of untreated sewage with concomitant impacts on ecosystems. The summer 2007 flooding in England highlighted the extent to which water treatment works may, themselves, be vulnerable to flooding. Similarly, infrastructure located on low-lying coastal sites may be threatened by coastal erosion and/or inundation.

A summary of the potential impacts on river water quality is given in Table 1 above

3 IMPACTS ON LAKE WATER QUALITY

A summary of the potential impacts on lake water quality is given in Table 2 above

Hydrology, Water Quality and Thermal Regimes

Numerous studies have highlighted the links between the winter North Atlantic Oscillation (NAO) and coherent responses in lake water temperature, ice conditions, and spring plankton phenology across Europe (e.g. Blenckner *et al.*, 2007). Higher wind speeds could reduce lake stability, and enhance mixing of nutrients (George *et al.*, 2007). Conversely, higher temperatures lengthen the period of thermal stratification and deepen the thermocline (Hassan *et al.*, 1998). Shallow lakes may be particularly susceptible to climate-induced warming, changes in seasonal mean residence times (George *et al.*, 2007) and nutrient loads (Carvalho and Kirika, 2003). In upland lakes and streams in the UK the winter NAO has been shown to be negatively correlated with nitrate concentrations (through influencing terrestrial processing of N) (Monteith *et al.*, 2000) and positively with marine salt concentrations (do to enhanced levels of seasalt deposition in stormy winters (Evans *et al.*,

2001).

Climate impact assessments typically show associated changes in ecosystem functioning (Table 1), such as earlier blooms (Figure 9) or increased concentrations of planktonic algae (e.g. Arheimer *et al.*, 2005; Komatsu *et al.*, 2007). A sensitivity study of phytoplankton in Loch Leven, Scotland, showed larger responses to increases in phosphorus loads than water temperature (Elliott and May, 2008).

Changes in river flows into lakes will affect fluxes of nutrients and sediments entering lakes and these will affect water quality. Changes in hydrology will also affect stratification, thermocline behaviour and residence times (George *et al.*, 2007, Jeppesen *et al.*, 2010).

Nutrients and Oxygen balances

Nutrients in lakes and impacts of ecology have been studied in mesocosm (small artificial lake) experiments by Moss *et al.* (2003, 2004) and these have been extended to simulate climate change impacts, as part of Euro-limpac and REFRESH (Jeppesen *et al.*, 2010), a. These controlled environments show that growing seasons are extended by increased temperatures, as are growth rates of algae and zooplankton. Oxygen concentrations fall as temperature reduces saturation levels, and increased nutrient levels enhance respiration. This could, in turn, lead to increased risks of fish deaths even for tolerant species. The ecology of the mesocosms changed significantly with exotic species out-competing native species. Future projections suggest that oxygen levels may decline and cyanobacteria blooms may become more extensive. The findings from these mesocosm experiments could have implications for lowland rivers, as well as for shallow lakes, where water levels are controlled by weirs and where there can be long residence times in summer.

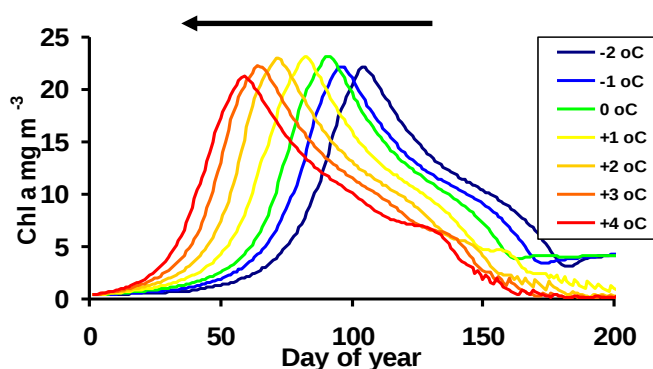


Figure 9 Effects of lake changing temperatures on algal blooms in Esthwaite Water, England (source: Elliott *et al.*, 2010).

Cyanobacteria

There is increasing evidence that recent changes in climate have had an effect on lake phytoplankton communities and it has been suggested that it is likely that Cyanobacteria will increase in relative abundance under the predicted future climate. A review by Elliot (2012) indicates that Cyanobacteria abundance increases with increasing water temperature, decreased flushing rate and increased nutrient loads. Also, warmer waters in the spring increased nutrient consumption by the phytoplankton community which in some lakes caused nitrogen limitation later in the year to the advantage of some nitrogen-fixing Cyanobacteria. Markensten et al. (2010) concluded that despite an increase in stratification duration, its impact on the Cyanobacteria was small compared to catchment influences (e.g. nutrient load). Therefore, the importance of nutrient availability also shows that it is possible to try and alleviate climate-driven effects through reducing the nutrient load to the lake.

Van Doorslaer *et al.* (2007) have also shown that zooplankton evolution can occur over relatively few generations, raising the possibility that ecosystems might maintain their current structure and functionality by adapting to temperature increases. However, whilst one or two species might achieve sufficient rates of change, it seems unlikely that whole ecosystems could evolve in parallel.

Toxics, DOC and Acidification

In the UK, research on toxics has focused both on upland lakes exposed to air pollutants from long-range transport, and on lowland systems exposed to pesticide use and transport. In particular, detailed studies at Lochnagar in Scotland have shown high concentrations of both trace metals and trace organic compounds in sediments (Rose *et al.*, 2001; Yang *et al.*, 2002,) and fish (Rosseland *et al.*, 2007), and Rose *et al.* (2012) have argued that increased storminess in future might cause the remobilisation of trace metals from catchment soils. Bloomfield *et al.* (2006) have undertaken a review of climate change impacts on pesticides in surface and groundwaters and conclude that changes in temperature, rainfall intensity and seasonality will affect pesticide release and transport. However, long-term land-use change driven by climate change may result in significant changes in pesticide use and release into rivers and lakes.

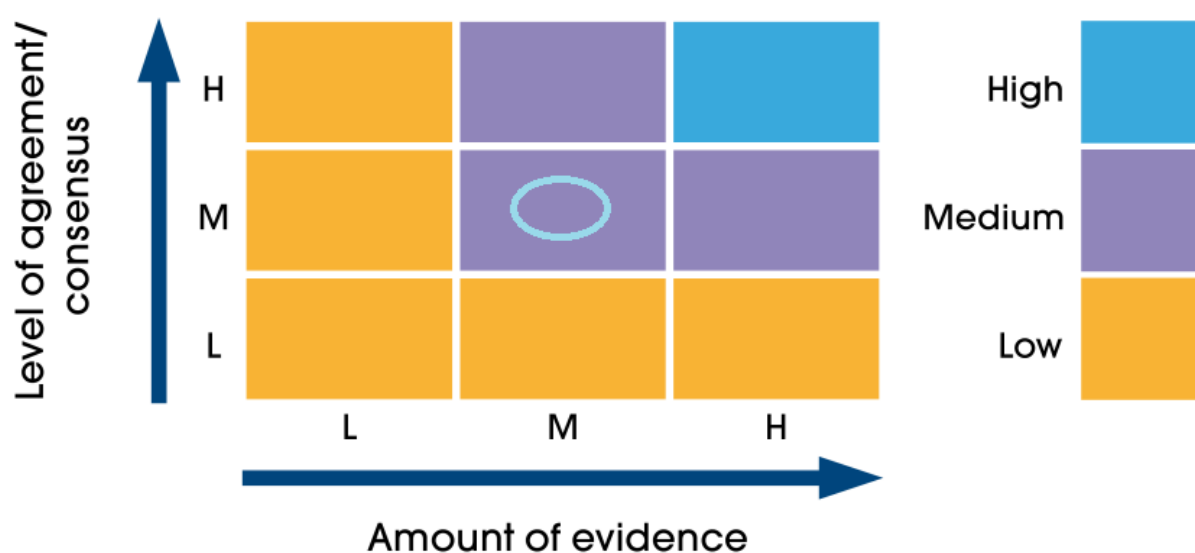
As in the case of the rivers, DOC trends have increased in Lakes primarily due to sulphate reductions, but again increasing solubility of organic matter in upland catchments may be making DOC levels more sensitive to temperature changes and changing hydrology.. Warmer and dryer summers would oxidize carbon sources and release increased concentrations of DOC and TOC once soils become wet and water is flushed from the catchments into rivers and lakes. In a similar manner, acidification could be exacerbated in upland lakes as changing hydrology? flushes pulses of acid water into lakes following drought periods (Wright et al, 2010)

A summary of the potential impacts on lake water quality is given in Table 2 above.

4 THE CONFIDENCE IN THE SCIENCE

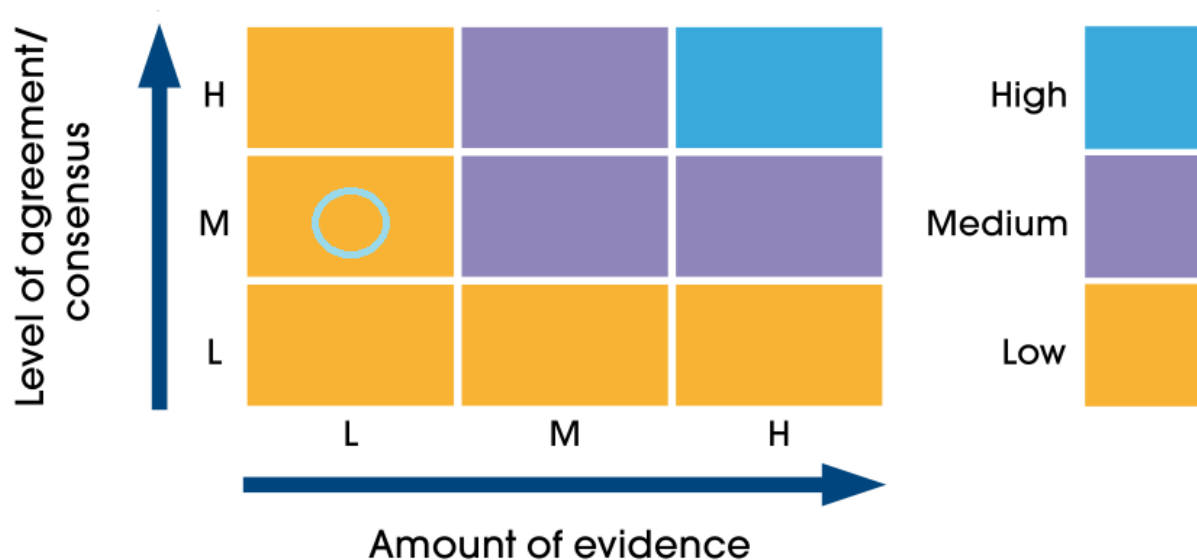
What is already happening: Medium

A medium confidence for the present state is based on the uncertainties that still exist in understanding the complex interactions between climate variables and water quality, including the linkages between physical, chemical and biological systems in rivers and lakes.



What could happen: Medium/Low

Medium/Low confidence for the future stems firstly from uncertainties about the effect of climate change on the physical, chemical and biological systems that determine water quality and also the uncertainty of the predictions that arise from the climate models on a catchment by catchment basis.

**5 KNOWLEDGE GAPS**

There are substantial knowledge gaps and Appendix 1 lists a set of questions and gaps that emerged as part of the Euro-impacts project.. These gaps are being filled by a range of EU and NERC funded projects, although some basic science still needs support (Beniston et al., 2012), as does the task of predicting future climate, especially at the local scale. It is not too early to think about adaptation however, as climate change is almost inevitable now. As an example, Whitehead et al (2006) considered a set of mitigation/adaptation measures for the River Kennet. In a study of the likely future impacts of climate change on hydrology and water quality in the River Kennet, it was shown that a series of adaptation strategies could be used to mitigate the effects of climatic change. For example, reducing agricultural fertiliser use by 50% in the Kennet catchment has the biggest improvement (dotted line [Figure 11](#)), lowering nitrate concentrations to levels not seen since the 1950s. Reducing atmospheric sources of nitrate and ammonia by 50% does reduce the nitrate by about 1 mg/l compared with the climate effects (see grey line) but is a much smaller effect. Constructing water meadows along the river would be more beneficial, significantly slowing down the rising levels of nitrate (see dashed/dotted line). However, a practical proposition might be a combination of all three approaches to reduce fertiliser use by 25%, reduce deposition by 25% and to construct some wetland areas along the river system. This generates significant reductions in nitrate in the river (see black line). Thus adaptation strategies are possible using land use change. However, world wheat prices have been rising in recent years so one could expect more, rather than less, intensive agriculture in catchments, which may exacerbate the effects of climate change.

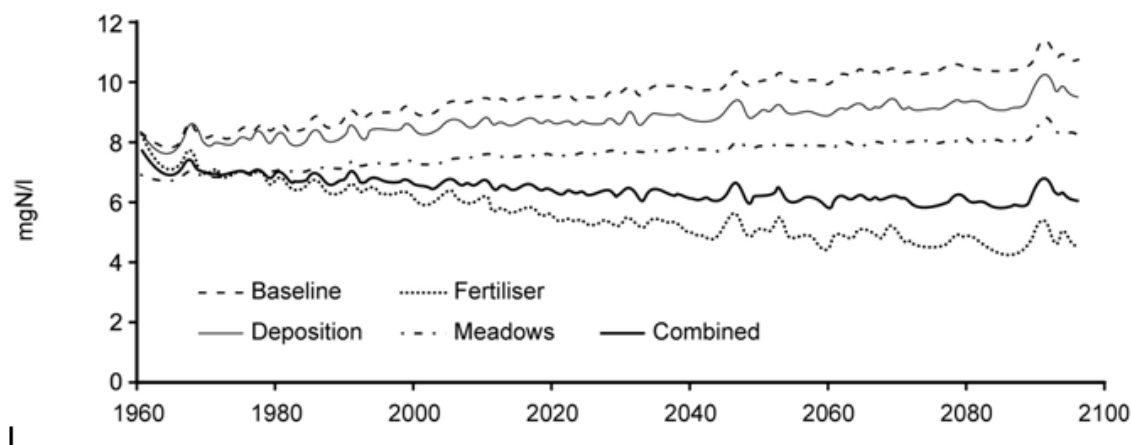


Figure 11 - Simulating the effects of climate change from 1960-2100 on Nitrate-N concentrations in the River Kennet together with a set of Adaptation Strategies

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APPENDIX 1 KNOWLEDGE AND INFORMATION GAPS

One of the outputs of the Euro-limpacs project was the identification of knowledge gaps. The following questions formed the basis of the Euro-limpacs science programme and are at the heart of the current international research agenda that aims to improve understanding of the potential effects of climate change on freshwater quality. Such an understanding is needed to identify the adaptive actions human society might need to take to avoid the unwanted consequences of climate change.

Direct effects of climate change on freshwaters

- What will the effects of lower flows be on pollutant concentrations in rivers?
- What are the potential impacts of changing climate on catchment chemical fluxes?
- How will a changing discharge regime affect stream ecology?
- How do changing air temperature and precipitation impact on discharge patterns in glacierised and non-glacierised upland river basins?

- How have freshwater biological communities responded to natural climate variability in the past?
- What effects will changing temperature and wind patterns have on the structure of lake water columns?
- How will changes in ice-cover duration, stratification and mixing regime affect lake biota?
- How will climate change affect the hydrology of marginal wetlands?
- What effects will changing hydrology and biogeochemical processes have on plant communities, nutrient dynamics and productivity in marginal wetlands?
- How will climate change affect the quality and quantity of dissolved organic carbon release from soils?
- What was the amplitude of natural variability of dissolved organic carbon concentrations in surface waters prior to any impacts from greenhouse gas-forced climate change?

Interactions between climate and hydromorphological/land-use change

- How do climate, hydrology, land use and morphology interact in space and time?
- How do these interactions affect aquatic ecosystems at the catchment scale?
- What effect will changing hydrological conditions (both directly and through morphological change) have on stream aquatic communities at the habitat scale?
- How will climate change affect mountain stream restoration?
- How will climate change affect channel morphology and stability in meandering lowland streams?

Climate change and eutrophication

- How will increasing temperatures and nutrient loading affect food-web relationships?
- How can climate and nutrient-induced changes in food-web structure be disentangled?
- How can food-web relationships be reconstructed using stable isotope techniques?
- Do nutrients structure ecosystems in different ways in different climates?
- How will climate change affect turbid phytoplankton-dominated lake ecosystems?
- What effects will increasing temperature have on the functioning of littoral wetlands?
- Are the predicted changes in temperature and nutrient dynamics comparable in amplitude with those currently recorded from the existing climate gradients?
- Can palaeolimnological techniques be applied to wetlands to examine past variations in hydrology and ecology?

Climate change and acidification

- Will changes in episodic and seasonal climatic events lead to increases in the magnitude and frequency of acid pulses in sensitive streams?
- What are the likely ecological effects of changes in the magnitude and frequency of extreme flows?
- How will climate change affect the setting of chemical and biological targets for surface waters recovering from acidification?
- How can dynamic models be used to simulate scenarios combining future climate change with future acid deposition?

Climate change and toxic substances

- How will climate change affect the loading of toxic substances to headwater systems?
- What effects will temperature change have on the redistribution and uptake of persistent

organic pollutants?

- Will increases in precipitation enhance mobilisation of mercury and methyl mercury in soils?
- Will climate change lead to a remobilisation of accumulated heavy metals and persistent organic pollutants from polluted soils, and their subsequent transportation into aquatic ecosystems?
- How will changes in river discharge affect trace metal remobilisation from flood-plain sediments?

Modelling climate change effects on surface water

- How can the impacts of climate change, land-use change and pollution be evaluated using a modelling approach?
- How can component models be used to assess the likely affects of climate change on freshwater systems?
- How can the uncertainty associated with component models be quantified?
- How can socio-economic scenarios be incorporated into modelling assessments of climate change effects?
- How can the spatial and temporal variation in the factors and processes controlling pollutant behaviour in coupled wetland–lake–river systems be simulated using models?
- How can models be best used to assist to manage the impacts of climate change on freshwaters?

Indicators of ecosystem health

- What chemical parameters are best suited as indicators of climate change?
- How can functional indicators be identified to address climate change impacts on wetlands, rivers and lakes?
- How can biological indicators of climate change be identified and can these be used to assess the response of communities to change?
- How can the different indicator types be linked to provide a common framework for rivers, lakes and wetlands?
- How can existing assessment and prediction methods for European freshwater systems be expanded and modified to address climate change?

Reference conditions and restoration strategies

- What reference conditions can be ascribed to different freshwater ecosystem types across Europe?
- How comparable are the different methods commonly used to establish reference conditions?
- What are the errors associated with methods used to establish reference conditions?
- How can reference conditions be used to establish restoration targets?
- To what extent is climate change already affecting restoration success?
- How might climate change affect both natural and human-induced ecosystem recovery?

Policy and management

- How do current policies, protocols and socio-economic pressures influence the drivers of change on freshwater ecosystems?
- What impact will future climate policies have on emissions and deposition of atmospheric pollutants?
- What tools are available for policy makers and managers for planning at the catchment scale?
- How best can stakeholders become involved in the development of tools for catchment management?

- What kinds of socio-economic tools are needed to aid decision making?