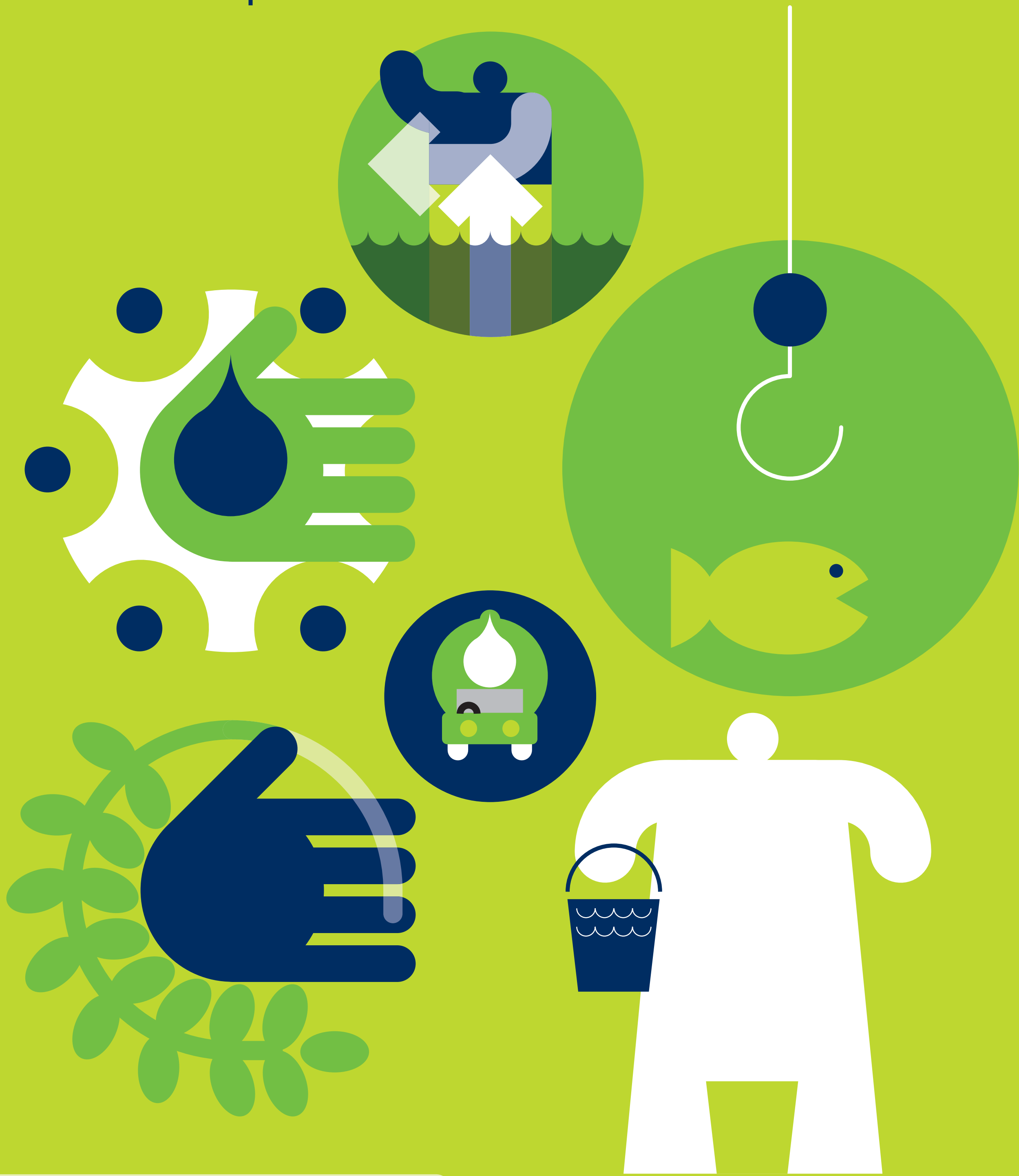
World Water Assessment Programme
Side publications series
SCIENTIFIC PAPER

The United Nations World Water Assessment Programme

Scientific Paper

Freshwater Biodiversity versus Anthropogenic Climate Change

Luc Vescovi, Dominique Berteaux, David Bird, Sylvie de Blois



United Nations Educational, Scientific and Cultural Organization
World Water Assessment Programme
UN WATER

The United Nations World Water Development Report 3

Water in a Changing World

Coordinated by the World Water Assessment Programme, the *United Nations World Water Development Report 3: Water in a Changing World* (WWDR3) is a joint effort of the 26 United Nations agencies and entities that make up UN-Water, working in partnership with governments, international organizations, non-governmental organizations and other stakeholders.

The United Nations' flagship report on water, the WWDR offers a comprehensive review of the state of the world's freshwater resources and provides decision-makers with the tools to implement sustainable use of our water. The WWDR3 represents a mechanism for monitoring changes in the resource and its management and tracking progress towards achieving international development targets. Published every three years since 2003, it offers best practices as well as in-depth theoretical analyses to help stimulate ideas and actions for better stewardship in the water sector.

Water in a Changing World has benefitted from the involvement of a Technical Advisory Committee composed of members from academia, research institutions, non-governmental organizations, and public and professional organizations. To strengthen the scientific basis and potential for implementation of its recommendations, interdisciplinary expert groups were also created for a number of topics, including 'Indicators, Monitoring and Databases', 'Business, Trade, Finance and Involvement of the Private Sector', 'Policy Relevance', 'Scenarios', 'Climate Change and Water', 'Legal Issues' and 'Storage'. An accompanying case studies volume, Facing the Challenges, examines the state of water resources and national mechanisms for coping with change in 23 countries and numerous small island developing states.

This series of side publications also accompanies the WWDR3, providing more focused, in-depth information and scientific background knowledge, and a closer look at some less conventional water sectors. These publications include:

Scientific Side Papers

This series provides scientific information on subjects covered in the WWDR and serves as bridge between the WWDR3's contents and scientific, peer-reviewed publications.

Sector and Topic-Specific 'Insight' Reports

The reports and documents in this series provide more in-depth information on water-related sectors, issues and topics in a stand-alone manner. The subjects of this series include Integrated Water Resources Management, transboundary issues and technology, among others.

Dialogue Series

Sectors and topics to which water is cross-cutting or important are covered in this series of side publications. Some examples of subjects discussed in this collection of reports include climate change, security, biodiversity, poverty alleviation and land use.

Published by the United Nations Educational, Scientific and Cultural Organization,
7 place de Fontenoy, 75352 Paris
07 SP, France

ISBN 978-92-3-104134-1

Design and typesetting by Pica Publishing
publish@picapublish.com

Cover graphics by Peter Grundy,
www.grundini.com

Table of Contents

Luc Vescovi
Conseil de la science et de la technologie, Quebec (formerly of Ouranos)

Dominique Berteaux
Université du Québec à Rimouski

David Bird
Université du Québec à Montréal

Sylvie de Blois
McGill University

Contributor
Yvon Maranda
Développement durable, Environnement et Parcs, Québec

Freshwater Biodiversity versus Anthropogenic Climate Change

Luc Vescovi, Dominique Berteaux, David Bird and Sylvie de Blois

Introduction

Based mainly on studies in Canada and Quebec and on literature reviews on the impacts of climate change (CC) on freshwater species, this paper presents (1) an exploration of the effects of climate change on freshwater biodiversity; and (2) a discussion of how this knowledge might be used to influence freshwater ecosystem management strategies. It is not a comprehensive review of the biodiversity-water-climate change issues but aims to discuss how, in a specific North American context, stakeholders are mainstreaming climate change and freshwater issues.

Biodiversity is an important component of freshwater systems and is controlled by temperature and hydrology. We review how climate change can affect habitats, leading to latitudinal and altitudinal shifts in river and stream biota, as well as to the increased prevalence of invasive species. Current approaches used to project the future effects of climate change, such as statistical niche and deterministic climate modelling, are presented and the need for monitoring tools to assess such changes is also considered. Finally, by discussing the management of invasive species and the management of watersheds, the paper aims to demonstrate that adaptation measures designed to cope with climate change need to be tailored holistically at the watershed level addressing different interacting stressors. A holistic approach in this context means that some types of ecosystem damage to lake systems that we can foresee occurring under a warmer, a wetter or a drier climate could be forestalled using measures that can be implemented immediately and over the coming decades – to repair damages to the surrounding watershed on which the lake depends and to increase the sustainability and resilience of these lands.

1. Context

The importance of biodiversity

Biodiversity (or biological diversity) is a broad concept. The United Nations Convention on Biological Diversity defines biodiversity as ‘the variability among living organisms from all sources including, *inter alia,* terrestrial, marine, and other aquatic ecosystems, and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems’ (UNEP, 1992, Article 2). Thus, biodiversity encompasses the complete range of genetic, species, and ecosystem diversity. Also, it underlies most biotic ecosystem processes, such as production and decomposition. Most estimates of the total number of species on Earth lie between five million and 30 million, of which only about two million species have been formally described (MEA, 2005).

Ecosystems provide services to humans, thereby bringing quantifiable economic benefits to society. The Millennium Ecosystem Assessment (MEA) has summarized the roles of biodiversity in the provision of ecosystem services as follows:

- Supporting role: includes the underpinning of ecosystems through structural, compositional, and functional diversity;
- Regulatory role: includes the influence of biodiversity on the production, stability, and resilience of ecosystems;
- Cultural role: includes the aesthetic, spiritual, and recreational benefits incurred by humans from biodiversity;
- Provisioning role: includes the direct and indirect supply of food, fresh water, fibre, etc.

Also, biodiversity has some intrinsic values that are independent of any human benefits and which cannot be readily quantified. For example, it has been argued that the health and wellbeing of other species should be valued in itself (MEA, 2005, pp. 140–3).

Climate change is one of multiple interacting stresses on ecosystems. Other stresses include habitat fragmentation through land-use change, overexploitation, invasive alien species, and pollution. Also, because of their role in the global carbon cycle, and because of the wide range of ecosystem services they provide that are essential for human well-being as noted above, it is now recognized at international level that the maintenance of natural ecosystems, including their genetic and species diversity, is essential to meet the ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC) (CBD, 2008; IUCN, 2008).

Biodiversity in fresh waters

About 29,000 species have been described in freshwater ecosystems, including about 12,000 species of fish and 17,000 other species from diverse groups such microbes, algae, nematodes, rotifers, insects, crustaceans, annelids, and molluscs (Abell et al., 2000, Moyle and Cech, 1996, Palmer et al., 2000). These figures are a gross underestimate because a large number of species are not described, particularly small species living in the sediments.

Freshwater ecosystems – rivers, lakes, aquifers, and wetlands – provide vital ecosystem services, including the support of important fisheries and the provision of drinking water, among others (see Table 1). The maintenance of biodiversity is one of the important keys to the retention of these ecosystem services (Palmer et al., 1997, 2000). Diverse assemblages of species may be able to use resources more efficiently and thus generate more productive ecosystems. They may also offer increased resistance against ecosystem collapse in the face of disturbance (Loreau et al., 2001, Cardinale et al., 2002).

Nutrient enrichment, hydrological modifications, habitat loss and degradation, pollution, and the spread of invasive species are currently acting in synergy to produce extremely high rates of extinction in freshwater biodiversity in all parts of the world. Extinction rates of 0.4% per decade for fish, 0.8% for gastropods and 0.1% for crayfish have been reported for North American freshwater fauna (Ricciardi and Rasmussen, 1999). If extinction rates continue to increase, they may reach 2.4%, 3.9%, and 2.6% for fish, gastropods, and crayfish, respectively (Ricciardi and Rasmussen, 1999). Also, Ricciardi and Rasmussen predict that many species considered at risk will disappear within the next century. At-risk species account for 49% of the 262 remaining mussel

Table 1 **Ecosystem services provided by freshwater ecosystems**

Supporting services	Bird and wildlife habitat Role in nutrient cycling and primary production Predator-prey relationships and ecosystem resilience
Regulatory services	Buffering of flood flows, erosion control through water/land interactions and flood control infrastructure Maintenance of water quality (natural filtration and water treatment) Soil fertilization
Cultural services	Recreation (river rafting, kayaking, hiking, and fishing as a sport) Tourism (e.g. river viewing) Existence values (personal satisfaction from free-flowing rivers)
Provisioning services	Water (quantity and quality) for consumptive use (for drinking, domestic use, and agricultural and industrial use) Water for non-consumptive use (for generating power and transport/navigation Aquatic organisms for food and medicines

Source: MEA, 2005

species, 33% of the 336 crayfish species, 26% of the 243 amphibian species, and 21% of the 1,021 fish species. Of course, causes of this high extinction rate are diverse. For example, non-native species pose a serious threat to indigenous freshwater fauna. European zebra mussels are out-competing native mussels in Canadian and North American lakes and rivers. Sea lampreys invade lakes and kill native fish by attaching themselves to them. Even sport fish transplanted from one lake to another can take over an ecosystem, driving less aggressive native fish toward extinction. Dams that obstruct river flow are also threats causing habitat deterioration. Unfortunately, climate change is now recognized as a dominant driver that may further exacerbate biodiversity losses currently observed in freshwater ecosystems (MEA, 2005).

The effects of climate change on freshwater biodiversity

The effects of climate change on biodiversity at large have already been observed and demonstrated in the past and are expected to increase in the future, according to predictive climate models and bioclimatic modelling (for example, Araújo and New, 2007; Thuiller, 2004). Very high extinction risks caused by global warming are predicted globally by Thomas et al. (2004). Species can respond to climate change in several ways. They can move to track climatic conditions, stay in place and evolve to the new climate, or they can become extinct. Although quick evolution is possible, movement that tracks climate is by far the most common response (Berteaux et al. 2004; Lovejoy and Hannah, 2004). Recent syntheses have shown that shifts in the phenology and distribution of plants and animals (for example, the advancement of biological events such as germination, hatching and emergence) have occurred in the last 30 to 40 years in the direction predicted by global warming scientists (Parmesan, 2006). Although not specific to freshwater systems, these overall trends also apply to freshwater biodiversity.

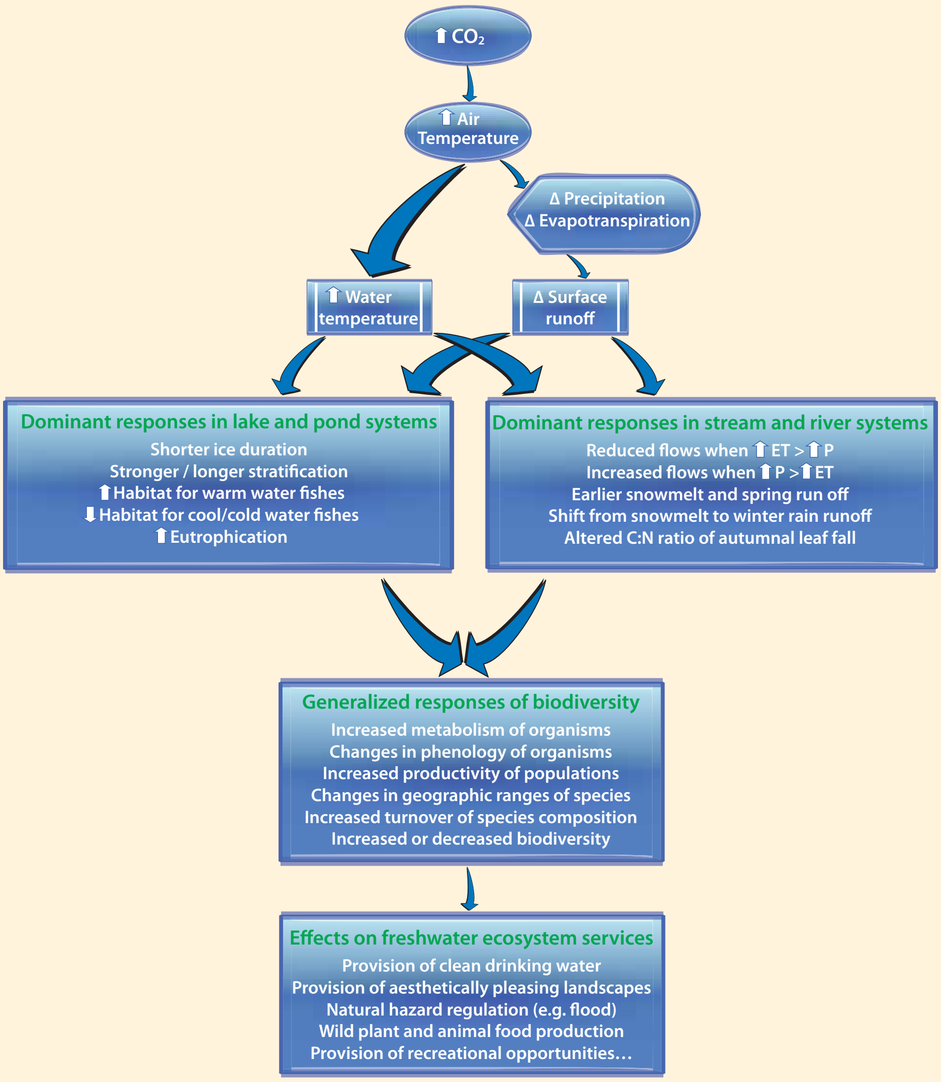
A changing climate will influence the seasonality of physical, chemical and biological phases in marine and freshwater ecosystems (for example, temperature and ice cover in rivers and lakes) impacting ultimately on ecosystem processes and biodiversity (International Baltex Secretariat, 2006). Analyses of the impacts of climate change on freshwater biodiversity have therefore emphasized responses to changing temperature in lakes and ponds, and responses to changing amounts and timing of water flow in rivers and streams (Allan et al., 2005; Figure 1). These two research directions are now progressively merged into a unified framework, as some of the impacts of climate change on metabolism, productivity, or range shifts seem ubiquitous. As presented in Figure 1, environmental changes are likely also to affect the services freshwater ecosystems provide to society.

Freshwater organisms are mostly ectotherms (i.e., they don't produce heat) and their metabolism increases with temperature within their range of tolerance. A first generalization about the effects of climate change on freshwater biodiversity is thus that climate warming will, overall, first increase the productivity of freshwater organisms (Benke, 1993, Allan et al., 2005). Warmer waters may for instance see increased growth rates of aquatic invertebrates and result in earlier maturation (Poff et al., 2002). Further changes in thermal regimes are expected to shift species ranges to the north (and/or to higher elevations), and greatly reshuffle communities. For example, paleolimnological records from lakes in the circumpolar Arctic revealed widespread species changes and ecological reorganizations in algae and invertebrate communities since approximately 1850 (Smol et al., 2005). The remoteness of the study sites coupled with the ecological characteristics of the involved taxa, indicate that changes are primarily driven by climate warming through lengthening of the summer growing season and related limnological changes (Smol et al., 2005).

Along with warmer water, projected changes in stream flow are expected to alter community structure. In the US, when considering climate change alone, the Sacramento River could lose 10%–18% (low and high climate change scenarios) of its fish species by 2080; the Colorado River 0–5% of fish species; the Rio Grande River 0–5%; and the Sabine River 11%–13% (Xenopoulos et al., 2005). Another example of drastic changes in aquatic ecosystems likely to be exacerbated by warmer climate is found in Australia, where there is much concern over acid sulphate soils that occur when wetlands, lakes and river beds are exposed to air as water levels fall. This triggers toxic chemical reactions harmful to biodiversity and to the services that water ecosystems provide. It is expected that these conditions will intensify with more severe droughts in catchments already stressed by water extraction for agriculture or other uses and anthropogenic modification of the water regime (Murray–Darling Basin Initiative, 2008). Thousands of wetlands, rivers and lakes (such as those in the Murray–Darling basin) are already affected or at high risk of acidification, which only compounds the problems of habitat loss due to drought. The speed at which these changes occur puts many species at risk of extirpation if they cannot escape, even temporarily, from the unfavorable conditions. Current and future research into the threatened aquatic ecosystems of Australia must focus on the impact of changed rainfall, evaporation and air temperatures on stream temperatures and flows and on spawning seasons for native fish species.

In Quebec, under climate change conditions, summer water flows are also expected to decrease (Fortin et al., 2007; Roy et al., 2008; Vescovi et al., 2009). Low flows can cause a reduction in habitat availability, food production and water quality (Bradford and Heinonen, 2008). Although many methods assessing the impact of low-flow conditions on aquatic ecosystems have been developed, substantial uncertainties in the prediction of the impacts of flow reduction remain (Bradford and Heinonen, 2008).

Figure 1 **Links between environmental drivers associated with climate change and the main responses of lentic systems (water not flowing), lotic systems (water flowing), and freshwater biodiversity and the potential effects on freshwater ecosystem services.**



Source: Luc Vescovi (based on Allan et al., 2005).

Allan et al. (2005) and the EPA (2009) have produced excellent syntheses of climate change on freshwater ecosystems and biodiversity. Many specific examples of the general trends described above can be found therein.

2. Assessing climate change effects on freshwater biodiversity

Approaches to project biodiversity responses to climate change

As stated above, there remain major uncertainties regarding the local and regional responses of the hydrologic cycle to climate change Intergovernmental Panel on Climate Change (IPCC, 2007). These uncertainties represent the greatest challenge in evaluating the future response of freshwater biodiversity to climate change (Allan et al., 2005). For example, declines in levels of one metre or more were projected for the Great Lakes of Canada and the USA in the mid-nineties (Mortsch and Quinn, 1996 and Mortsch et al., 2000). But subsequent models have predicted smaller decreases or even increases in water levels (Lofgren et al., 2002).

Impacts on biodiversity brought about by climate change are difficult to measure from climate data alone because change can result from the interaction of a number of pressures. Ecological relationships involving climate are typically scale-dependent, and experiments are thus notoriously difficult to implement (Krebs and Berteaux, 2006). Also, natural fluctuations of climate may take place over a longer period than the data collected. Therefore, there is no single method of measuring changes that can be directly attributed to climate change across all species and habitats. So detection of cause-effect relationships requires more extensive studies. However, analysing (past and future) climate variability via the development of simple indicators (climate and extreme events) is the first step to considering the pressure of climate change on biodiversity.

The strong association between climate and species distributions has led to the development of ecological niche (or climate envelope) models. These models develop correlative descriptions of current climate and distribution and then, given predicted future climate, project future species' ranges. Climate envelope models are a central tool for scientists wishing to explore the effects of climate change on living organisms (Araújo et al., 2005; Martínez-Meyer, 2005; Heikkinen et al., 2006). They have been criticized because they assume species distributions are at equilibrium with current climate, interpret species-climate correlations as causal, and ignore parameters such as dispersal and biotic interactions (Pearson and Dawson, 2003; Hampe, 2004). However climate envelope models can and will be improved and should be seen as powerful initial tools providing a first estimate as to the dramatic impact of climate change on biodiversity (Araújo and New, 2007; Guisan and Thuiller, 2005). They must be used as such rather than as providers of detailed (in time and space) definitive predictions. Imperfect predictions are exceedingly valuable when compared to no projection at all, as long as a measure of uncertainty can also be provided for (Berteaux et al., 2006), because they can offer a basis for planning and action, as has now been largely demonstrated by climate change scientists (IPCC, 2007).

Given a specific climate-change scenario, biologists have a number of tools to hand to project the effects of climate change on freshwater biodiversity. True prediction (which is based on causal relationships), is much more difficult to obtain than forecasting based on correlations. This is because of the complex, often indirect pathways relating a given biodiversity variable to its physical environment. (See Berteaux et al. 2006 for ecological definitions of the terms projection, prediction, and forecasting.)

In terms of scientific advancements, using a niche-based modelling approach (bioclimatic modelling) to understand the complex ecological links and limitations of the processes involved in terrestrial ecosystems, as well as recently in freshwater ecosystems, is an important field of investigation. (Araújo and Rahbek, 2006; Thuiller et al., 2006; Martinez-Meyer and Peterson, 2006; Dominguez-Dominguez et al.; 2006; Buisson et al., 2008).

The need for monitoring tools

One main challenge facing the climate change community is to adequately address the implications of long-term trends in climate change for short-term managerial commitments (Corfee-Morlot, 2003). For ecosystem managers, addressing the metrics (processes and indicators) of diagnostic value that attribute ecosystem changes to identifiable forcing factors (e.g. sea level rise, forest fire) is of great interest in providing an adapted response in terms of the conservation of ecosystems (OECD, 2006; Lavorel et al., 2007). Thus, some recent scientific studies in ecology and climate change are focusing on how external factors such as a changing climate and other direct or indirect anthropogenic actions are expected to affect the structure and functioning of ecosystems and how they will threaten the services they provide to society (Malcolm et al., 2006, Willis and Birks, 2006).

Bio-indicators

Living organisms respond to climatic variability and trends. Some of these responses may be useful as indicators of climate change. Based on an extensive review of the literature, the United States EPA (2009) examined these responses in freshwater ecosystems. Their main conclusions are the following:

- Since water level is often linked to important life-cycle stages in wetland organisms, and any changes in the timing and amount of water may influence these stages, wetland organisms (in particular wetland invertebrates) could be used as indicators of climate changes in hydrologic conditions over time. It is being suggested that this approach may be adaptable to river and stream systems. Various approaches to the use of invertebrate indicators have been suggested. Foremost among these is detection of loss of native taxa, but changes in density; range shifts; changes in timing of important life history stages and phenology; modification of morphology, physiology, and behaviour; and changes in gene frequencies can also provide valuable diagnostic information (EPA, 2009).
- Monitoring changes in community composition and any shifts from cold- and cool-water dominated systems to warm-water fish systems within an eco-region may be another good indicator. Assessments of impacts on ecological resources from projected climate changes have led to hypotheses about fish community composition; it is expected that cool-water and warm-water fish will be able to invade freshwater habitats at higher latitudes, while cold-water fish will disappear from low latitude limits of their distribution where summer temperatures already reach the maximum thermal tolerances of the fish. However, when they experience less winter stress, cold-water fish ranges at higher altitudes and latitudes may expand with increased duration of optimal temperatures.
- Coldwater fish species, and salmon species in particular, may be good indicators of climate change impacts in streams and rivers. Native brook trout populations may be a useful climate change indicator for streams and rivers for

certain regions since they often live at the edge of their thermal tolerance; therefore a decline in brook trout numbers in a certain area may be a sign of climate impacts. However, since a decline in this species could also be due to other stressors or even species competition, it would not always necessarily indicate climate impacts. The problem has to be studied carefully

- Species with widespread ranges and high thermal tolerance such as largemouth bass, carp, channel catfish, and bluegills, would not be good indicators of climate impacts since they are relatively insensitive and their ranges extend far south.

Ongoing studies should help scientists and stakeholders to better assess the situation and recommend adaptive measures.

Ecological integrity monitoring

Canada's natural and cultural heritage agency, Parks Canada, has developed an ecological integrity (EI) monitoring program to better assess changes that are being observed in managed park ecosystems (http://www.pc.gc.ca/progs/np-pn/ie-ei_e.asp). This program is based on conceptual models that provide a good example of the tools available to assess climate change effects on ecosystems. They succinctly represent the functioning of an ecosystem by using ecological indicators, and are used to clarify and structure ideas on the functioning and dynamics of ecosystems and to assist park ecologists in selecting appropriate EI measures. Four ecological indicators have been developed, corresponding to forest, wetland, Coastal and aquatic freshwater ecosystems. For each indicator, a suite of measures is being developed that incorporates all identified elements in the Ecological Integrity Framework, including biodiversity, process and functions, and stressors. These measures will allow Parks Canada's managers to determine the status of the indicators, and through long-term monitoring, determine trends in ecosystem health.

3. Maintaining ecosystem services: the case of toxic cyanobacterial blooms in lakes

The services provided by freshwater ecosystems depend on the maintenance of good water quality and healthy and diverse plankton communities. Climate change has modified the structure of biological communities in the lakes of several temperate countries, to the detriment of lake users (Mooij et al., 2005; Jöhnk et al., 2008; Figure 2). However, current information is not adequate to confidently assess the future impacts of climate change on water quality and aquatic ecosystems, including its socio-economic consequences (Bates et al., 2008). The likelihood of environmental change will require planning for prevention or mitigation of public health consequences. In the following discussion we emphasize the importance of treating the ecosystem holistically, especially when planning for adaptation to climate change, which will require modifications to be made to practices at the level of the entire watershed.

Changes in temperature, humidity and wind will modify the physical structure and properties of lakes. Lake water circulation, vertical exchanges and bottom water renewal are dependent on the physics of thermal stratification, which is in turn determined by lake size, lake depth, air temperature, the length of the ice-free season, the frequency and force of wind events, and the rate of water renewal by stream inputs. The latter four influences are meteorological, and are changing due to man-made atmospheric changes (Willett et al., 2007; Allan and Soden, 2008). These changes are modifying the physical structure of lakes, producing longer periods of stratification, increased stability during stratification, and increased surface temperatures (De Stasio et al., 1996). Cyanobacteria possess several unique adaptations to take advantage of these new conditions. Modification of lake thermal structure will therefore have repercussions on the dynamics of noxious cyanobacteria to the detriment of lake biodiversity and water quality.

Increasing temperature leads to noxious blooms

In parallel with the predicted changes in air temperature, lake and stream water temperature in North America should increase by between 1 °C and 7 °C at the surface, and by between 1 °C and 8 °C in bottom waters (Magnuson et al., 1997). Most chemical and biological processes are accelerated by increasing temperatures, in accordance with the Arrhenius equation that describes the thermodynamics of chemical reactions. As a result, large colonial cyanobacteria, which grow slowly in cold water, will grow more rapidly when conditions permit, so that blooms will occur earlier in the year, and with greater frequency.

The effect of water heating on the growth of different sorts of organism in lakes is not solely positive. Different species have different temperature optima for growth, which influences the outcome of competition and its effect on dominance (Chu et al., 2007). In particular, warmer water favours cyanobacteria over other non-toxic forms (Coles and Jones 2000). Many species can adjust their metabolic rates to the ambient temperature, but the capacity to adjust varies among species and that capacity determines the seasonal and geographic limits of the different species (Abele et al., 2002). In general, an ecosystem pushed beyond its historical limits will lose thermosensitive species, which in the case of the plankton will encourage dinoflagellates and cyanobacteria. Tropical lakes can become heavily dominated by toxic cyanobacteria during the season of stable stratification (e.g. Vazquez et al., 2005).

Increased water temperature also interacts indirectly with other processes that favour noxious algal growth. For example, plankton biomass in many lakes depends on the internal regeneration of nutrients

Figure 2 **Accumulation of a cyanobacterial scum**

Lakeshore accumulation of a cyanobacterial scum in Missisquoi Bay, Lake Champlain, Quebec in mid-summer 2008. These noxious blooms are costly and dangerous to the health of those who depend on the lake for drinking water. Modelling of historical data has shown that three conditions must be met in order for a large bloom to occur: there must be an abundant supply of both nitrogen and phosphorus available to the plankton and the water temperature must be elevated. Increasing average water temperature over the past 15 years has been accompanied by increased bloom growth. © Isabelle Roy and David Bird.

throughout the summer, via decomposition processes in the sediments. These processes may be accelerated to an even greater extent by warmer water than is algal growth, which will increase the size of any bloom provoked by the heat. An additional contributing factor is that cyanobacterial nutrient requirements per cell are reduced in warmer water (Saunders and Kalff, 2001; Rhee and Gotham, 1981). The same nutrient load will therefore produce a heavier bloom in warmer water. In short, a series of independent factors is expected to favour an increase in the incidence and the importance of cyanobacterial blooms in a warmer, rainier and less windy climate.

Lengthening growing seasons favour blue-green algae

The period of inverse stratification of winter months, when light for photosynthesis is blocked by snow and ice, should decrease greatly, or disappear in certain lakes, and the summer stratification period should start earlier and last longer. The effects of earlier water heating, during the cold water period, can potentially have an impact as important as summer heat waves, by permitting the whole biological community to begin growing earlier. A rule of thumb is that each increase of one degree in annual mean temperature advances the date of stratification of a lake by about one week (Demers and Kalff, 1993).

Lake community components that will be favoured by an increased growing season include the submerged macrophytes and those species of cyanobacteria with a strategy of slow growth, large colony size and indigestibility. Rooney and Kalff (2000) showed that the structure and importance of the plant communities of five lakes in southern Quebec were strongly modified and amplified by an abnormally warm spring season in the year 1998, which reached a historically high temperature globally. Weyhenmeyer (2001) showed that the warming of Swedish lakes earlier in the year during the 1990s, favoured the growth of 'temperature-sensitive species', which included the cyanobacteria and the chlorophytes. The total biomass of phytoplankton was not changed; there was an evolution towards cyanobacterial blooms earlier in the year, which mirrors events in recent years in Quebec lakes and which led to a social crisis around the increased threat of toxic blooms.

Finally, Wiedner et al. (2007) suggested that the lengthening of the growing season that has already occurred in the temperate zone is responsible for the invasion of temperate lakes by the semitropical species *Cylindrospermopsis raciborskii*. Earlier spring water heating permits the germination of colonies of that toxic species, which dominates by allelopathy to prevent the growth of its competitors (Figueredo et al., 2007). *Cylindrospermopsis* has now been seen in the Great Lakes and has also been seen at bloom levels in a small lake on the Canadian side of the border (Conroy et al., 2007; Hamilton et al., 2005). The spread of toxic cyanobacteria in a 'greenhouse world' is a likely event that should be avoided if at all possible.

There is a direct connection between climate-associated blooms and the loss of biodiversity.

Species loss occurs due to loss of habitat (resulting from changes in water clarity, oxygen levels, temperature: see Crossetti et al., 2008); the development of trophic bottlenecks due to unsuitability of cyanobacteria as prey (Havens and East, 1997); direct toxicity to wildlife; and, finally, native species being replaced by invasive exotic species. It may be possible to forecast the spread of invasive species of cyanobacteria, and other noxious species, using analytical models (Crowl et al., 2008). First, transport models can be based on diffusion and network models, especially those mediated by human activities (Hastings et al., 2005; Bossenbroek et al., 2007). Second, vulnerable aquatic systems can be identified by climate-based and trophic-state-based niche models that predict the habitat characteristics and future geographic range of potential invasive species (Mellina and Rasmussen, 1994a and b; Morisette et al., 2006).

Preparation and mitigation for increasing cyanobacterial blooms

A rapid increase in the number of reported cases of cyanobacterial surface blooms in the lakes of Quebec, during the years 2004–2006, was characterized as a 'Cyanobacterial crisis' that made headlines throughout the summer of 2006. The crisis was partly due to the reaction of the public to new government regulations that resulted in closed lakes and no-use warnings sent out to cottage owners as soon as a new bloom appeared. A few well-publicized cases where the public was obliged to drink bottled water led to greater awareness of the risks of blue-green algal blooms. Then, increased vigilance on the part of recreational users led to an explosion of new reported cases.

But not all of the increase can be attributed to increased reporting. The weather in 2005 and 2006 gave a foretaste of the kinds of climate changes forecast for this century. Mean temperatures were up to two degrees warmer than historical averages, nighttime temperatures were especially higher, spring melt came a month earlier than normal, summer precipitation attained record low levels in several regions, and the rain that did fall occured in a series of extreme rain events associated with local flooding. The effect of intense surface runoff events in agricultural and developed watersheds led to the disruption of normal nutrient cycles and the fertilization of late-season phytoplankton communities. The result was the appearance of massive blooms in several lakes in which they had not previously been seen.

Quebec's cyanobacterial crisis led to increased recognition, by scientists and the public, of the importance of watershed protection for the maintenance of healthy, biodiverse plankton communities. The occurrence of heat waves, flooding and high winds changed water temperature and the water circulation regime within the lakes, but the impact of extreme weather effects in the drainage basins of the lakes was greater. Historically record precipitation levels falling on agriculturalized, denuded and impermeabilized drainage basins led to greatly accelerated nutrient flow into the lakes. The intense rain events, which previously would have been absorbed harmlessly by intact forested lands, fell on soils that were overfertilized by unsustainable agricultural practices. The normal water and nutrient flow pathways were accelerated by a combination of stream canalization, removal of streamside vegetation, and replacement of the original lakeshore forest with a ring of urban-style cottage developments with luxurious, heavily-fertilized lawns. The result was the development of massive cyanobacterial blooms, which were dominated by toxic species that reduced the diversity of the lake communities. The normal ecosystem services, particularly the provision of clean water, were impaired. This loss of clean drinking water was the most serious economic consequence, and most drinking water treatment stations were unprepared for the sudden assault of massive amounts of toxic biomass. The resale value of some of the large houses that had been built around the lakes fell. Another unfortunate result was the loss of recreational fishing due to the fear of toxin accumulation in the fish.

The cyanobacterial crisis of recent years, precipitated by several years of weather consistent with predicted greenhouse changes, provided a wake-up call for watershed-management groups throughout the priority watersheds shown in Figure 3. There has been a rapid recognition that current lakeshore development schemes are not sustainable. The government, in collaboration with lake associations, has developed a program to support the replanting of shorelines; local municipalities have enacted new tougher regulations on no-cut buffer strips ten metres wide around the lake; existing regulations are being more strictly enforced, and new inspectors are being hired to educate and enhance compliance. Reforming agricultural practices is a greater challenge that will require a greater investment of time, money and resources for research. The crisis has fostered investment in a diversity of community-based pilot programmes to seek solutions to the problem of agricultural nutrient losses and to develop drainage basin-level water- and nutrient-management plans.

It has required a crisis to rouse the public in Quebec, and its community-based watershed management groups, to take lake protection seriously. It is likely that new ways of farming will have to be developed and implemented. This necessary development can help in several related ways by reducing the effects of agriculture on the atmosphere and the hydrosphere and by providing greater structural diversity to the landscape, permitting it to sustain a diverse natural fauna. For example, agroforestry is a concept that can integrate agriculture, trees, watercourse protection and wildlife management while stimulating recreational and economic development. The appearance of important levels of cyanobacteria blooms in southern Quebec will have been a positive event if we can profit from the understanding it brings about the necessity of careful harmonization of all watershed activities with long-term sustainable practices in the face of future climate change.

4. Managing changes in freshwater biodiversity

Maintaining connectivity for migrating species

Migration or dispersal allows individuals to escape unfavourable conditions to take advantage of new suitable habitats made available by climate change. The speed at which climate change is occurring, though, puts many species at risk of extirpation if they cannot escape, even temporarily, from unfavorable conditions. Some examples of adaptation measures include fishways to help native fish swim the length of rivers, traps or the commercial harvesting of exotic fish species, re-snagging to provide fish habitats, and fostering local community involvement. It is not clear, however, whether such measures will remain effective with further warming.

One of the main issues raised by the need for species to migrate is the maintenance of landscape or habitat connectivity, defined broadly here as the spatial arrangement of aquatic habitats that allows physical or biological exchanges. It is imperative to preserve or restore networks of connected habitats and populations, to allow dispersing species to track the climate. For instance, the post-glacial dispersal of freshwater fish in Canada has been well documented (e.g. Bernatchez and Dodson, 1991; Mandrak and Crossman, 1992; Bernatchez and Wilson, 1998). Current patterns of genetic diversity of lake trout can be linked to past distribution patterns. Fish retreated to refugia when the glaciers covered the major part of the North American continent. Over time, isolated populations dispersed into the new suitable habitats created by the retreating glaciers. These changes occurred over geological time, however, and were facilitated by the numerous freshwater connections in the landscape. In the current landscape, the impacts of the predicted increase in global temperature for the next century will be exacerbated by the extensive changes in natural connectivity patterns caused by irrigation and drainage schemes, urbanization, agriculture, dams etc., and by changes in the physical properties and water quality of the remaining lakes, rivers and streams. Human-assisted migration (Marris, 2008) may not be a sustainable strategy for the majority of species.

Connecting aquatic habitats may play a crucial role in facilitating species dispersal, but the dispersing species will not always be native. In the lowlands of northeastern America, drainage of land for agriculture and highway construction has led to a proliferation of drainage ditches, which resulted in a massive network of anthropogenic linear wetlands connecting aquatic habitats and marshes. The invasive grass *Phragmites australis* (common reed) has taken advantage of these new corridors to rapidly disperse, threatening the biodiversity of adjacent native wetlands (Lelong et al., 2007; Maheu-Giroux and de Blois, 2007). It is believed that the recent warming trend has increased the potential for seed production in this species at higher latitudes (Brisson et al., 2008). The changes in landscape patterns combined with changes in reproductive strategies have led to a massive and rapid invasion of common reed in several regions.

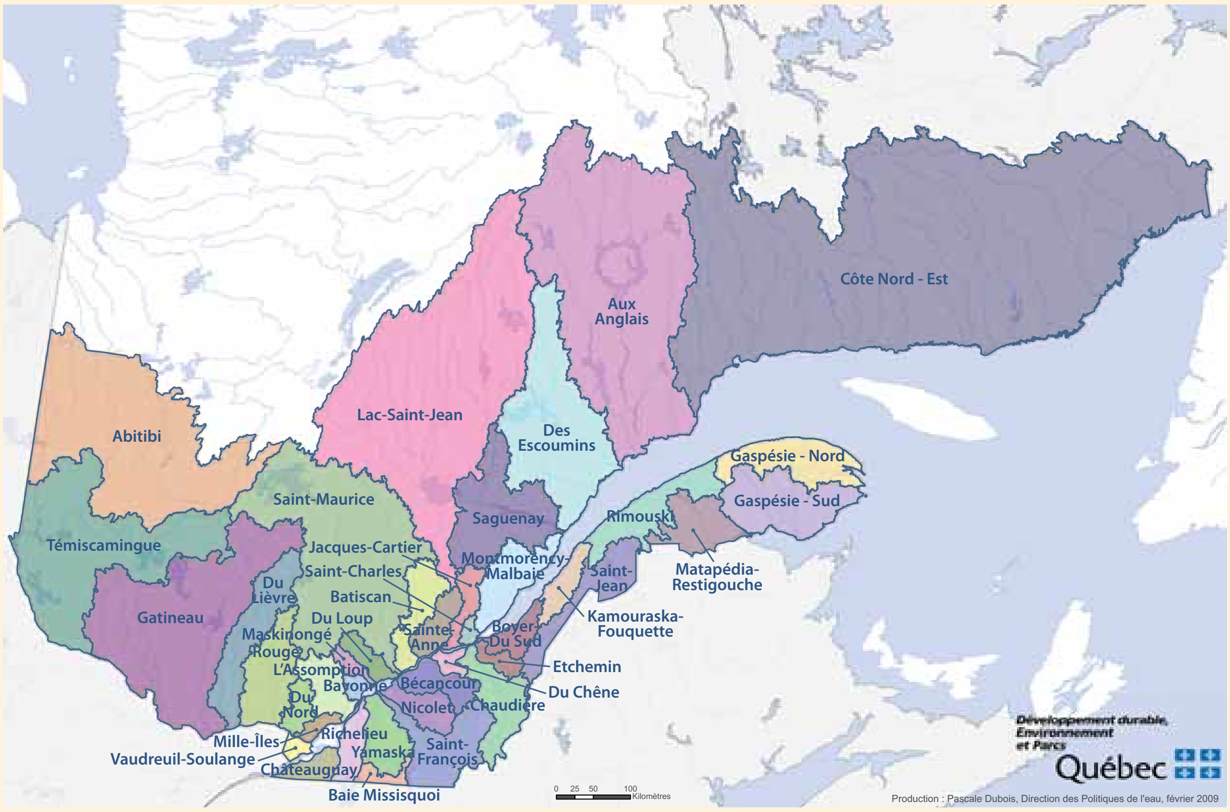
It is useful to think about connectivity patterns not only among similar habitats (e.g., river connected to lake) but also between land and water ecosystems. Freshwater ecosystems are greatly influenced by the spatial context in which they are found and the processes occurring in the surrounding land. The presence of riparian vegetation, for instance, can affect the overall temperature and water balance of a riverine system (Dahm et al., 2002). Measures to mitigate the effect of climate warming on the biota of rivers, lakes and streams must therefore take into consideration these boundary interactions not only from a sedimentation, nutrient or pollutant input perspective, but also from a thermal perspective.

Participatory watershed management as a response to climate change to preserve freshwater biodiversity

Over the last decade, holistic ecosystem watershed approaches to managing water resources have been implemented in many parts of the world, and particularly in North America – for example, via the US-watershed approach framework (EPA, 2002), the Quebec Water policy (ministère de l'Environnement, 2002) and the Canadian ecosystem initiatives (Environment Canada, 2002). A holistic ecosystem approach takes into account the inter-relationships between the air, water, land, fish, wildlife and people, and this ought to be stressed as the core of integrated water resources management (IWRM). In Canada, however, there is a real need to infuse socioeconomic, environmental and cultural factors as well as climate change into water management plans. Present practices have failed to respect natural hydrological characteristics and the flora and fauna of the surrounding areas, and the natural boundaries of hydrological units are sometimes incompatible with the administrative and jurisdictional boundaries. These shortcomings have impeded the development of long-term plans in the conservation and preservation of natural resources, in particular in highly populated areas (Vescovi, 2003).

The Quebec Water Policy, launched in November 2002, supports better water governance. The government is committed to gradually implementing watershed-based management for 33 major watercourses located primarily in the St. Lawrence plain. With the adoption in June 2009 of an Act to affirm the collective nature of water resources and provide for increased water resource protection, the entire Southern Quebec territory is now officially divided into 40 watershed-based management zones (Figure 3). Watershed-based management results in a better assessment of aquatic ecosystem problems and water quality and quantity, and makes it possible to identify sustainable solutions. If correctly applied, it helps define action priorities by considering the cumulative impacts on aquatic ecosystems. At the local and regional levels, watershed organizations are responsible for implementing integrated management by preparing a Master Plan for Water (MPW),

Figure 3: **Location of the 40 watershed management zones in southern Quebec.**



Source: Developpement durable, Environment et Parcs, Quebec

which includes watercourses, lakes, marshes and other wetlands, as well as any aquifers in the area. These organizations rely on public consultation and scientific expertise and interact with the governing bodies that have jurisdiction over water (county municipalities, ministries and other government agencies). They are also required to observe national priorities regarding the protection, restoration and development of water resources and to comply with relevant guidelines, regulations and legislation (Baril et al., 2006). There are currently 33 watershed organizations; new ones will be created to reach all 40 management zones.

Taking climate change into account within this watershed management framework is not easy. Some of the challenges include finding better ways of describing climate change effects on southern Quebec's watershed dynamics and transferring scientific knowledge to stakeholders. Indeed, climate change affects multiple sectors and, in a complex multi-usage watershed, adaptation strategies need to consider conflicting uses (for example, drinking water, irrigation, industrial uses, golf courses, etc.). A pilot project developed by Ouranos (the Quebec-based Consortium on Climate Change) and the Ludwig Maximilian University in Munich clearly shows that, before proposing any adaptive solution, there must be scientific (e.g., water budget) and socio-economic assessments, as well as close examination of specific case studies and uses at the watershed level (Vescovi et al., 2009). When conflicting uses occur, the concept of ecosystem integrity should be promoted to ensure that essential ecological services and biodiversity are maintained. Such a strategy may ensure that water ecosystems and society are better equipped to cope with climate change.

Conclusion

At the beginning of the third millennium, the world is facing an increasing demand for large quantities of quality fresh water, however multiple anthropogenic factors are already putting freshwater ecosystems under stress. In this context, climate change acts as an additional pressure compromising biodiversity and freshwater ecosystem function and potentially disturbing the ecological services they provide. Based on up-to-date literature reviews and experiences drawn from Quebec, Canada and elsewhere, propose that a watershed management approach, which provides spatial and temporal integration, is highly appropriate to cope with climate change. IWRM, if properly implemented, should incorporate these issues within its framework. However, far more research and integration is needed before adaptation measures can be implemented.

REFERENCES

Abele, D., Heise, K., Pörtner H. O., and Puntarulo, S. 2002. Temperature-dependence of mitochondrial function and production of reactive oxygen species in the intertidal mud clam Mya arenaria. *Journal of Eperimental Biology*,. Vol. 205. Cambridge, U.K., Company of Biologists, pp. 1831–41.

Abell, R. A., Olson, D. M., Dinerstein, E., Hurley, P. T., Diggs, J. T., Eichbaum, W., Walters, W., Wettengel, W., Allnutt, T., and Loucks, C. J. 2000. *Freshwater Ecoregions of North America: A Conservation Assessment*. Washington DC and Covelo, California, Island Press.

Allan, J. D., Palmer, M., and Poff, N. L. 2005. Climate change and freshwater ecosystems. *Climate Change and Biodiversity*. Lovejoy T. E. and Hannah L. (eds). New Haven Conneticut, Yale University. Press, pp. 272–90.

Allan, R. P. and Soden B. J. 2008 Atmospheric warming and the amplification of precipitation extremes. *Science*, Vol. 321. Stanford, California, HighWire Press (Stanford University Libraries), pp. 1481–4.

Araújo, M. B and Rahbek, C. 2006. ECOLOGY: How does climate change affect biodiversity? *Science*, Vol. 313. Stanford, California, HighWire Press (Stanford University Libraries), pp. 1396–7.

Araújo, M. B. and New, M. 2007. Ensemble forecasting of species distributions. *Trends in Ecology and Evolution*, Vol. 22. Amsterdam, Elsevier, pp. 42–7.

Araújo, M. B., Pearson, R. G., Thuiller, W., and Erhard, M. 2005. Validation of species-climate impact models under climate change. *Global Change Biology*, Vol. 11. Oxford, UK, Blackwell Publishing, pp. 1504–13.

Baril, P., Maranda, Y., and Baudrand, J. 2006. Integrated watershed management in Quebec (Canada): a participatory approach centred on local solidarity, *Water Science and Technology*, Vol. 53, No. 10. London, IWA Publishing, pp. 301–7.

Benke, A.C. 1993. Concepts and patterns of invertebrate production in running waters. Edgardo Baldi Memorial Lecture. *Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie* Vol. 25. Stuttgart, Germany, E. Schweizerbart, Science Publishers, pp. 15–38.

Bernatchez, L. And Dodson, J. J. 1991. Phylogeographic Structure in Mitochondrial DNA of the Lake Whitefish (Coregonus-Clupeaformis) and Its Relation to Pleistocene Glaciations. *Evolution,* Vol 45. Malden, Massachusetts, Blackwell, pp. 1016–35.

Bernatchez, L. and Wilson, C. C. 1998. Comparative phylogeography of nearctic and palearctic fishes. *Molecular Ecology*, Vol. 7. Malden, Massachusetts, Blackwell, pp. 431–52.

Berteaux, D., Humphries, M. M., Krebs, C. J., Lima, M., McAdam, A. G., Pettorelli, N., Réale, D., Saitoh, T., Tkadlec, E., Weladji R. B., and Stenseth, N. C. 2006. Constraints to projecting the effects of climate change on mammals. *Climate Research*, Vol. 32, Oldendorf/Luhe, Germany, Inter-Research Science Center, pp. 151–8.

Berteaux, D., Réale, D., McAdam, A., and G Boutin, S. 2004. Keeping pace with fast climate change: can arctic life count on evolution? *Integrative and Comparative Biology*, Vol. 44. Oxford, UK, Oxford University Press, pp. 140–51.

Bossenbroek, J. M., Johnson, L. E., Peters, B., and Lodge D. M. 2007. Forecasting the expansion of zebra mussels in the United States. *Conservation Biology*, Vol. 21. Malden, Massachusetts, Blackwell, pp. 800–10.

Bradford, M.J., Heinonen, J.S. 2008. Low flows, instream flow needs and fish ecology in small streams. *Canadian Water Resources Journal.* 33 pp. 165–80.

Brisson, J., Paradis, E., and Bellavance, M. E. 2008. New evidence of common reed (*Phragmites australis*) sexual reproduction in Eastern Canada: a consequence of the recent global warming? *Rhodora*, Vol. 110. Cambridge, Massachusetts, New England Botanical Club, pp. 225–30.

Buisson, L., Thuiller, W., Lek, S., and Grenouillet, G. 2008. Climate change hastens the turnover of stream fish assemblages. *Global Change Biology*, Vol. 14. Oxford, UK, Wiley-Blackwell, pp. 2232–48.

Cardinale, B. J., Palmer, M. A., and Collins, S.L. 2002. Species diversity enhances ecosystem functioning through interspecific facilitation. *Nature*, Vol. 415. New York, Nature Publishing Group (Macmillan) pp. 426–9.

CBD (Convention on Biological Diversity). 2008. *Draft Findings of the Ad Hoc Technical Expert Group on Biodiversity and Climate Change.* Montreal, Canada, United Nations Environment Programme (UNEP). London. Available at www.cbd.int/doc/meetings/cc/ahteg-bdcc-01/other/ahteg-bdcc-01-findings-en.doc

Chu, Z., Jin, X., Iwami, N., and Inamori, Y. 2007. The effect of temperature on growth characteristics and competitions of *Microcystis aeruginosa* and *Oscillatoria mougeotii* in a shallow, eutrophic lake simulator system. *Hydrobiologia*, Vol. 581. Dordrecht, the Netherlands, Springer, pp. 217–23.

Coles, J. F. and Jones, R. C. 2000. Effect of temperature on photosynthesis-light response and growth of four phytoplankton species isolated from a tidal freshwater river. *Journal of Phycology*, Vol. 36. Oxford, UK, Blackwell Publishing, pp. 7–16.

Conroy, J. D., Quinlan, E. L., Kane, D. D., and Culver, D. A. 2007. *Cylindrospermopsis* in Lake Erie: testing its association with other cyanobacterial genera and major limnological parameters. *Journal of Great Lakes Research*, Vol. 33. Ann Arbor, Michigan, International Association of Great Lakes Research (IAGLR), pp. 519–35.

Corfee-Morlot, J. and Höhne, N. 2003. Climate change: long-term targets and short-term commitments. *Global Environmental Change*, Vol. 13. Amsterdam, Elsevier, pp. 277–293.

Crossetti L.O., Bicudo, D.C., Bicudo, C.E.M., and Bini, L.M. 2008. Phytoplankton biodiversity changes in a shallow tropical reservoir during the hypertrophication process. Braz. *J. Biol.* 68(4): 1061–7.

Crowl, T. A., Crist, T. O., Parmenter, R. R., Belovsky, G., and Lugo, A. E. 2008. The spread of invasive species and infectious disease as drivers of ecosystem change. *Frontiers in Ecology and the Environment* Vol. 6. Ithaca, New York, ESA Publications, pp. 238–246.

Dahm, C. N., Cleverly, J. R., Coonrod, J. A. A., Thibault, J. R., McDonnell, D. E., and Gilroy, D. J. 2002. Evapotranspiration at the land/water interface in a semi-arid drainage basin. Freshwater Biology, Vol 47. Oxford UK, Blackwell Science, pp. 831–43.

De Stasio, B. T.Jr., Hill, D. K., Kleinhans, J. M., Nibbelink, N. P., and Magnuson, J. J. 1996. Potential effects of global climate change on small north-temperate lakes: Physics, fish, and plankton. *Limnology and Oceanography*., Vol. 41. Waco, Texas, American Society of Limnology and Oceanography (ASLO), pp. 1136–49

Demers, E. and Kalff, J. 1993. A simple model for predicting the date of spring stratification in temperate and subtropical lakes. *Limnology and Oceanography*, Vol. 38. Waco, Texas, American Society of Limnology and Oceanography (ASLO), pp. 1077–81.

Dominguez-Dominguez, O., Martinez-Meyer, E., Zambrano, L., and De Leon, P. 2006. Using ecological-niche modeling as a conservation tool for freshwater species: live-bearing fishes in central mexico, *Consevation Biology.* Vol. 20, No. 6. Malden, Massachusetts, Blackwell, pp. 1730–39.

EPA. 2002. *A Review of Statewide Watershed Management Approaches*. Final report. April 2002. United States Environmmental Protecion Agency, Office of Water. Available at: http://www.epa.gov/owow/watershed/approaches_fr.pdf

——. 2009. Climate change effects on stream and river biological indicators: A preliminary analysis (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-07/085F.

Figueredo, C. C., Giani, A., and Bird, D. F. 2007. Does allelopathy contribute to *Cylindrospermopsis raciborskii* (Cyanobacteria) bloom occurrence and geographic expansion? *Journal of Phycology*, Vol. 43. Oxford, UK, Blackwell Publishing, pp. 256–65.

Fortin, L.G., Turcotte, R., Pugin, S., Cyr, J.F. and Picard, F. 2007. Impact des changements climatiques sur les plans de gestion des réservoirs Saint-François et Aylmer au sud du Québec. *Revue canadienne de génie civil*, Vol. 34, No. 8, pp. 934–45.

Guisan, A. and Thuiller, W. 2005. Predicting species distribution: offering more than simple habitat models. *Ecology Letters*, Vol. 8. Oxford, UK, Blackwell Publishing, pp. 993–1009.

Hamilton, P. B., Ley, L. M., Dean, S., and Pick, F. R. 2005. The occurrence of the cyanobacterium *Cylindrospermopsis raciborskii* in Constance Lake: an exotic cyanoprokaryote new to Canada. *Phycologia*, Vol. 44. Lawrence Kansas, International Phycological Society, pp. 17–25.

Hampe, A. 2004. Bioclimate envelope models: what they detect and what they hide. *Global Ecology and Biogeography*, Vol. 13. Oxford, UK, Blackwell Publishing, pp. 469–71.

Hastings, A., Cuddington, K., Davies, K. F., Dugaw, C.J., Elmendorf, S., Freestone, A., Harrison, S., Holland, M., Lambrinos, J., Malvadkar, U., Melbourne, B. A., Moore, K., Taylor, C., and Thomson, D. 2005. The spatial spread of invasions: new developments in theory and evidence. *Ecology Letters*, Vol. 8. Oxford, UK, Blackwell Publishing, pp. 91–101.

Havens KE, East, TL. 1997. Carbon dynamics in the grazing food chain of a subtropical lake. *Journal of Plankton Research* 19: 1687–11.

Heikkinen, R. K., Luoto, M., Araújo, M. B., Virkkala, R., Thuiller, W., and Sykes, M.T. 2006. Methods and uncertainties in bioclimatic envelope modeling under climate change. *Progress in Physical Geography*, Vol. 30. Thousand Oaks, California, Sage Publications, pp. 751–77.

International Baltex Secretariat. 2006. *Assessment of Climate Change for the Baltic Sea Basin –The BACC Project*. For the First International Conference on the Assessment of Climate Change for the Baltic Sea Basin, Göteborg, Sweden 22–23 May. http://www.baltex-research.eu/BACC/.

IPCC. 2007. Summary for Policymakers. *Climate Change. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B.,.Tignor, M., and Miller, H. L. (eds.). Cambridge, UK and New York, Cambridge University Press. http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf

——. 2008. *Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change.* Bates, B. C., Kundzewicz, Z. W., Wu, S., Palutikof, J. P. (eds). Geneva, Intergovernmental Panel on Climate Change (IPCC).

IUCN (International Union for the Conservation of Nature). 2008. Ecosystem-based adaptation: An approach for building resilience and reducing risk for local communities and ecosystems. A submission by the IUCN to the Chair of the UNFCCC's Ad Hoc Working Group on Long-term Cooperative Action under the Convention (AWG-LCA). Available at: http://cmsdata.iucn.org/downloads/iucn_submission_on_ecosystem_based_adaptation_final_6_dec_2008.pdf

Jöhnk, K. D., Huisman, J., Sharples, J., Sommeijerz, B., Visser, P. M., and Stroom, J. M. 2008. Summer heatwaves promote blooms of harmful cyanobacteria. *Global Change Biology*, Vol. 14. Oxford, UK, Wiley-Blackwell, pp. 495–512.

Krebs, C. J. and Berteaux, D. 2006. Problems and pitfalls in relating climate variability to population dynamics. *Climate Research*, Vol. 32. Oldendorf/Luhe, Germany, Inter-Research Science Center, pp. 143–9.

Lavorel, S. Flannigan, M.D. Lambin E.F. 2007. Vulnerability of land systems to fire: interactions among humans, climate, the atmosphere, and ecosystems. *Mitigation and Adaptation Strategies for Global Change*, Vol. 12, No. 1. Dordrecht, the Netherlands, Springer, pp. 33–53.

Lelong, B. Lavoie, C. Jodoin, Y. Belzile, F. 2007. Expansion pathways of the exotic common reed (*Phragmites australis*): A historical and genetic analysis. *Diversity and Distributions*. Vol. 13. Oxford, UK, Blackwell Publishing, pp. 430–37.

Lofgren, B. M., Quinn, F. H., Clites, A. H., Assel, R. A., Eberhardt, A. J., and Luukkonen, C. L. 2002. Evaluation of potential impacts on Great Lakes water resources based on climate scenarios of two GCMs. *Journal of Great Lakes Research*, Vol. 28. Ann Arbor, Michigan, International Association of Great Lakes Research (IAGLR), pp. 537–54.

Loreau, M., Naeem, S., Inchausti, P., Bengtsson, J., Grime, J. P., Hector, A., Hooper, D. U., Huston, M. A., Raffaelli, D., Schmid, B., Tilman, D., and Wardle, D. A. 2001. Biodiversity and ecosystem functioning: current knowledge and challenges. *Science*, Vol. 294. Stanford, California, HighWire Press (Stanford University Libraries), pp. 806–8.

Magnuson, J. J., Webster, K. E., Assel, R. A., Bowser, C. J., Dillon, P. J., Eaton, J. G., Evans, H. E., Fee, E. J., Hall, R. I., Mortsch, L. R., Schindler, D. W., and Quinn, A.F.H. 1997. Potential effects of climate changes on aquatic systems: Laurentian Great Lakes and Precambrian shield region. *Hydrological processes*, Vol. 11. Chichester, UK, Wiley Publishing, pp. 825–71.

Maheu-Giroux, M. and de Blois, S. 2007. Landscape ecology of *Phragmites australis* invasion in networks of linear wetlands. *Landscape Ecology* Vol. 22, No. 2. Dordrecht, the Netherlands, Springer, pp. 285–301.

Malcolm, J. R., Liu, C., Neilson, R. P., Hansen, L., and Hannah L. 2006. Global warming and extinctions of endemic species from biodiversity hotspots. *Conservation Biology*, Vol. 20, No. 2. Malden, Massachusetts, Blackwell, pp. 538–48.

Mandrak, N. E. and Crossman, E. J. 1992. *A checklist of Ontario Freshwater Fishes Annotated With Distribution Maps*. Ontario, Canada, Royal Ontario Museum Publications in Life Sciences.

Marris, E. 2008. Moving on assisted migration. Nature Reports Climate Change. New York, Nature Publishing Group (Macmillan). Available at www.nature.com/climate/2008/0809/full/climate.2008.86.html

Martinez-Meyer, E. 2005. Climate change and biodiversity: some considerations in forecasting shifts in species' potential distributions. *Biodiversity Informatics*, Vol. 2. Lawrence, Kansas, University of Kansas, pp. 42–55.

Martinez-Meyer, E. and Peterson, A. T. 2006. Conservatism of ecological niche characteristics in North American plant species over the Pleistocene-to-Recent transition. *Journal of Biogeography*, Vol. 33. Oxford UK, Blackwell Publishing, pp. 1779–89.

MEA (Millennium Ecosystem Assessment). 2005. *Ecosystems and Human Well-Being*: *Vol. 1: Current State and Trends*. Covelo, California, Island Press.

Mellina, E. and Rasmussen, J. B. 1994a. Patterns in the distribution and abundance of zebra mussel (*Dreissena polymorpha*) in rivers and lakes in relation to substrate and other physiochemical factors. *Canadian Journal of Fisheries and Aquatic Sciences*, Vol. 51. Ottawa, National Research Council of Canada, pp. 1024–36.

——. 1994b. Occurrence of zebra mussel (*Dreissena polymorpha*) in the intertidal region of the St Lawrence Estuary. *Journal of Freshwater Ecology*, Vol. 9. New York, Springer, New York, pp. 81–4.

Ministère de l'Environnement. 2002. The Québec Water Policy www.mddep.gouv.qc.ca/eau/inter_en.htm

Mooij, W. M., Janse, J. H., De Senerpont Domis, L. N, Hülsmann, S., and Ibelings, B. W. 2005. The impact of climate change on lakes in the Netherlands: a review. *Aquatic Ecology*, Vol. 39. Dordrecht, the Netherlands, Springer Netherlands, pp. 381–400.

Morisette, J. T., Jarnevich, C. S., Ullah, A., Cai, W., Pedelty, J. A., Gentle, J. E., Stohlgren, T. J., and Schnase, J. L. 2006. A tamarisk habitat suitability map for the continental United States. *Frontiers in Ecology and the Environment*, Vol. 4. Ithaca, New York, ESA Publications, pp. 11–7.

Mortsch, L. and Quinn F. 1996. Climate change scenarios for Great Lakes Basin ecosystem studies. *Limnology and Oceanography*, Vol. 41, No, 5. Waco, Texas, American Society of Limnology and Oceanography (ASLO), pp. 903–11.

Mortsch, L., Hengeveld, H., Lister, M., Lofgren, B., Quinn, F., Slivitzky, M., and Wenger, L. 2000. Climate change impacts on the hydrology of the Great Lakes-St. Lawrence System. *Canadian Water Resources Journal*, Vol. 25, No. 2. Ottawa, Canadian Water Resources Association, pp. 153–79.

Moyle, P. B., and Cech, J. J. Jr. 1996. *Fishes: An Introduction to Ichthyology*. New Jersey, U.S.A., Prentice-Hall.

Murray-Darling Basin Initiative. 2008. Available at: www.mdbc.gov.au

OECD (Organisation for Economic Co-operation and Development). 2006. *Metrics for Assessing the Economic Benefits of Climate Changes Policies: Sea Level Rise.* Paris, OECD.

Palmer, M. A., Covich, A. P., Finlay, B., Gilbert, J., Hyde, K. D., Thomson, R. K., Kairesalo, T., Lake, P. S., Lovell, C. R., Naiman, R. J., Ricci, C., Sabater, F. F., and Strayer, D. L. 1997. Biodiversity and ecosystem function in freshwater sediments. *Ambio*, Vol. 26. Lawrence, Kansas, Allen Press, pp. 571–7.

Palmer, M. A., Covich, A. P., Lake, S., Biro, P., Brooks, J. J., Cole, J., Dahm, C., Gilbert, J., Goedkoop, W., Martens, K., Verhoeven, J., and van de Bund, W. J. 2000. Linkages between aquatic sediment biota and life above sediments as potential drivers of biodiversity and ecological processes. *BioScience*, Vol. 50. Washington D. C., American Institute of Biological Sciences, pp1062–68.

Parmesan, C. 2006. Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics,* Vol. 37, Palo Alto, California, Annual Reviews, pp. 637–69.

Pearson, R. G. and Dawson, T. P. 2003. Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global Ecology and Biogeography*, Vol 12. Oxford, UK, Blackwell Publishing, pp. 361–71.

Peterson, A. T., Tian, H., Martinez-Meyer, E., Soberón, J., Sánchez-Cordero, V., and Huntley, B., 2004. Modeling distributional shifts of individual species and biomes. In Lovejoy T. E. and Hannah L. (eds), *Climate Change and Biodiversity*. New Haven, Conneticut, Yale University Press, pp. 211–28.

Poff, L. N., Brinson, M. M. and Day, J. W. Jr. 2002. *Aquatic Ecosystems and Global climate change: Potential Impacts on Inland Freshwater and Coastal Wetland Ecosystems in the United States*. Prepared for the Pew Center on Global Climate Change. Available at: http://www.pewtrusts.org/uploadedFiles/wwwpewtrustsorg/Reports/Protecting_ocean_life/env_climate_aquaticecosystems.pdf

Rhee, G-Y. and Gotham, I. J. 1981. The effect of environmental factors on phytoplankton growth: Temperature and the interactions of temperature with nutrient limitation. *Limnology and Oceanography*, Vol. 26. Waco, Texas, American Society of Limnology and Oceanography (ASLO), pp. 635–48.

Ricciardi, A. and Rasmussen, J. B. 1999. Extinction rates of North American freshwater fauna. *Conservation Biology*, Vol. 13. Malden, Massachusetts, Blackwell, pp. 1220–2.

Rooney, N. and Kalff, J. 2000. Inter-annual variation in submerged macrophyte community biomass and distribution: the influence of temperature and lake morphometry. *Aquatic Botany*, Vol. 68. Amsterdam, Elsevier Science, pp. 321–35.

Roy, R. Pacher, G. Roy L. Silver. R. 2008. Adaptive *Management for Climate Change in Water Resources Planning and Operation.* Hydro Québec-IREQ, 75pp.

Saunders, D. L. and Kalff, J. 2001 Denitrification rates in the sediments of Lake Memphremagog, Canada-USA. *Water Research*, Vol. 35. London, International Water Association (IWA)Publishing, pp. 1897–1904.

Smol, J. P., Wolfe, A. P., Birks, H. J. B., Douglas, M. S. V., Jones, V. J., Korhola, A., Pienitz, R., Ruhland, K., Sorvari, S., Antoniades, D., Brooksk, S. J., Falluj, M. A., Hughes, M., Keatley, B. E., Laing, T. E., Michelutti, N., Nazarova, L., Nyman, M., Paterson, A. M., Perren, B.,Quinlan, B.,R. Rautio, M., Saulnier-Talbot, E., Siitonen, S., Solovieva, N., and Weckström, J., 2005. Climate-driven regime shifts in the biological communities of arctic lakes. *Water Research*, Vol. 102. Washington D. C., pp. 4397–402.

Thomas, C. D., Cameron, A., Green, R. E., Bakkenes, M., Beaumont, L. J., Collingham, Y. C., Erasmus, B. F. N., Ferreira de Siqueira, M., Grainger, A., Hannah, L., Hughes, L., Huntley, B., Van Jaarsveld, A. S., Midgely, G. E., Miles, L., Ortega-Huerta, M. A., Peterson, A. T., Phillips, O. L., and Williams, S. E. 2004. Extinction risk from climate change. *Nature*, Vol. 427. York, Nature Publishing Group (Macmillan), pp. 145–7.

Thuiller, W. 2004. Patterns and uncertainties of species' range shifts under climate change. *Global Change Biology*, Vol. 10. Oxford, UK, Blackwell Publishing, pp. 2020–7.

Thuiller, W., Savorel, S., Sykes, M., and Araujo, M. 2006. Using niche-based modelling to assess the impact of climate change on tree functional diversity in Europe. *Diversity and Distributions*, Vol. 12. Oxford, UK, Blackwell Publishing, pp. 49–60.

Turcotte, R., Fortin, L. G., Pugin, and S. Cyr, J. F. 2005. Impact des changements climatiques sur les plans de gestion des réservoirs Saint-François et Aylmer: résultats préliminaires. Calgary, paper presented at the Congrès annuel de l'Association canadienne des barrages.

UNEP. 1992. *Convention on Biological Diversity*. UNEP Nairobi.

Vázquez, G. Jiménez, S. Favila, M.E. Martínez, A. 2005. Seasonal dynamics of the phytoplankton community and cyanobacterial dominance in a eutrophic crater lake in Los Tuxtlas, Mexico. *Ecoscience*, Vol. 12 Quebec, Centre d'études nordique, Université Laval, pp. 485–93.

Vescovi L. 2003. The state of Canada's water. *Water Resources of North America*, A. K. Biswas (ed). Washington D. C. and Berlin, Springer.

Vescovi, L., Cyr, J.-F., Turcotte, R., Ludwig, R., Braun, M., Fortin, L.-G., Chaumont, D. and May, I. 2009. *A Multi Model Experiment to assess and cope with climate change impacts on the Châteauguay Watershed in Southern Quebec.* Paris, UNESCO-WWAP.

Weyhenmeyer, G. 2001. Warmer winters: are planktonic algal populations in Sweden's largest lakes affected? *Ambio*, Vol. 30. Lawrence, Kansas, Allen Press, pp. 565–71.

Wiedner, C., Rücker, J., Brüggemann, R., and Nixdorf, B. 2007. Climate change affects timing and size of populations of an invasive cyanobacterium in temperate regions. *Oecologia*, Vol. 152. Heidelberg and New York, Springer, pp. 473–84.

Willett, K.M., Nathan P., Gillett, N.P., Jones, P.D., Thorne, P.W. 2007. Attribution of observed surface humidity changes to human influence. Nature 449, 710–12.

Willis K. J., and Birks H. J. B. 2006. What id natural? The need for a long-term perspective in biodiversity conservation. *Science*, Vol. 314. Stanford, California, HighWire Press (Stanford University Libraries) pp. 1261–5.

Xenopoulos, M. A., Lodge, D. M., Alcamo, J., Marker, M., Schulze, K., and van Vuuren, D. 2005. Scenarios of freshwater fish extinctions from climate change and water withdrawal. *Global Change Biology*, Vol. 11. Oxford, UK, Blackwell Publishing, pp. 1557–64.

World Water Assessment Programme side publications, 2009

During the consultation process for the third edition of the World Water Development Report, a general consensus emerged as to the need to make the forthcoming report more concise, while highlighting major future challenges associated with water availability in terms of quantity and quality.

This series of side publications has been developed to ensure that all issues and debates that might not benefit from sufficient coverage within the report would find space for publication.

The 21 side publications released so far represent the first of what will become an ongoing series of scientific papers, insight reports and dialogue papers that will continue to provide more in-depth or focused information on water–related topics and issues.

Insights

Freshwater and International Law: The Interplay between Universal, Regional and Basin Perspectives — *by Laurence Boisson de Chazournes*

IWRM Implementation in Basins, Sub-Basins and Aquifers: State of the Art Review — *by Keith Kennedy, Slobodan Simonovic, Alberto Tejada-Guibert, Miguel de França Doria and José Luis Martin for UNESCO-IHP*

Institutional Capacity Development in Transboundary Water Management — *by Ruth Vollmer, Reza Ardakanian, Matt Hare, Jan Leentvaar, Charlotte van der Schaaf and Lars Wirkus for UNW-DPC*

Global Trends in Water-Related Disasters: An Insight for Policymakers — *by Yoganath Adikari and Junichi Yoshitani at the Public Works Research Institute, Tsukuba, Japan, for the International Center for Water Hazard and Risk Management (ICHARM), under the auspices of UNESCO.*

Inland Waterborne Transport: Connecting Countries — *by Sobhanlal Bonnerjee, Anne Cann,Harald Koethe, David Lammie, Geerinck Lieven, Jasna Muskatirovic, Benjamin Ndala, Gernot Pauli and Ian White for PIANC/ICIWaRM*

Building a 2nd Generation of New World Water Scenarios — *by Joseph Alcamo and Gilberto Gallopin*

Seeing Traditional Technologies in a New Light: Using Traditional Approaches for Water Management in Drylands — *by Harriet Bigas, Zafar Adeel and Brigitte Schuster (eds), for the United Nations University International Network on Water, Environment and Health (UNU-INWEH)*

Dialogue Series

Introduction to the IWRM Guidelines at River Basin Level — *by Toshihiro Sonoda for UNESCO-IHP, and the Network of Asian River Basin Organizations (NARBO)*

Water Adaptation in National Adaptation Programmes for Action: Freshwater in Climate Adaptation Planning & Climate Adaptation in Freshwater Planning — *by Gunilla Björklund, Håkan Tropp, Joakim Harlin, Alastair Morrison and Andrew Hudson for UNDP*

Integrated Water Resources Management in Action — *by Jan Hassing, Niels Ipsen, Torkil-Jønch Clausen, Henrik Larsen and Palle Lindgaard-Jørgensen for DHI Water Policy and the UNEP-DHI Centre for Water and Environment*

Confronting the Challenges of Climate Variability & Change through an Integrated Strategy for the Sustainable Management of the La Plata River Basin — *by Enrique Bello, Jorge Rucks and Cletus Springer for the Department of Sustainable Development, Organization of American States*

Water and Climate Change: Citizen Mobilization, a Source of Solutions — *by Marie-Joëlle Fluet, Luc Vescovi, and Amadou Idrissa Bokoye for the International Secretariat for Water and Ouranos*

Updating the International Water Events Database — *by Lucia De Stefano, Lynette de Silva, Paris Edwards and Aaron T. Wolf, Program for Water Conflict Management and Transformation, Oregon State University, for UNESCO PCCP*

Water Security and Ecosystems: The Critical Connection — *by Thomas Chiramba and Tim Kasten for UNEP*

Scientific Papers

Freshwater Biodiversity versus Anthropogenic Climate Change — *by Luc Vescovi, Dominique Berteaux, David Bird and Sylvie de Blois*

The Impact of Global Change on Erosion and Sediment Transport by Rivers: Current Progress and Future Challenges — *by Desmond E. Walling, Department of Geography, University of Exeter, for the International Sediment Initiative of IHP UNESCO*

Climate Changes, Water Security and Possible Remedies for the Middle East — *by Jon Martin Trondalen for UNESCO PCCP*

A Multi-Model Experiment to Assess and Cope with Climate Change Impacts on the Châteauguay Watershed in Southern Quebec — *by Luc Vescovi, Ouranos; Ralf Ludwig, Department of Geography, University of Munich; Jean-François Cyr, Richard Turcotte and Louis-Guillaume Fortin, Centre d'Expertise Hydrique du Québec; Diane Chaumont, Ouranos; Marco Braun and Wolfram Mauser, Department of Geography, University of Munich*

Water and Climate Change in Quebec — *by Luc Vescovi, Ouranos; Pierre Baril, Ministry of Transport, Québec; Claude Desjarlais; André Musy; and René Roy, Hydro-Québec. All authors are members of the Ouranos Consortium*

Investing in Information, Knowledge and Monitoring — *by Jim Winpenny for the WWAP Secretariat*

Water Footprint Analysis (Hydrologic and Economic) of the Guadania River Basin — *by Maite Martinez Aldaya, Twente Water Centre, University of Twente and Manuel Ramon Llamas, Department of Geodynamics, Complutense University of Madrid, Spain*

United Nations
Educational, Scientific and
Cultural Organization

World Water Assessment Programme

UN WATER