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Abstract

Climatic change may have very diverse impacts on lakes and their water quality. This paper groups them to hydrologic, thermal, hydraulic, chemical, biochemical, and ecological ones. Their interrelations and potential changes, and their contributions to lake water quality problems, are reviewed and discussed, and checklist tables for planning, management, and impact assessment purposes are provided. Water quality problems are clustered to eutrophication, oxygen depletion, hygienic problems, salinization, acidification, toxic and cumulative substances, turbidity and suspended matter, and thermal pollution. Many of these problems may worsen due to the climatic change, yet an extreme uncertainty exists at any case specific level. Therefore, the possibility of water quality and quantity shifts due to climatic change are suggested to be integrated into contemporary planning and management in an adaptive manner, and the research and development of the impact assessment methodology are suggested to be focused on approaches that can handle extreme uncertainties. The very high uncertainty level in water quality management has obtained an additional highly uncertain component.

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Potential Impacts of Climatic Change on Lake and Reservoir Water Quality

Olli Varis[1] *and László Somlyódy*[2]

1. Introduction

As far as water quality aspects of lakes and reservoirs are concerned, which we call here lakes to be short, the management implications of possible impacts of the climatic change appear exceedingly few at present. They are marginal in comparison to those of many other human activities that introduce changes into the nature and into our environment. The research, impact assessment, administration, remediation, and restoration efforts concerning lake water quality are chiefly directed to conventional changes due to land use, waste management practices in industry and in settlements, policies in agriculture and forestry, construction projects, water allocation, and water supply.

The climatic change, however, although being still a highly obscure and uncertain concept (Fiering and Matalas 1990), receives at present rapidly increasing attention in water resources research and management (cf. Kundzewicz and Somlyódy 1993). Accordingly, the number of published studies concerning lake water quality is expanding. Climatic changes can affect water quality through many mechanisms, and even the direction of change - not to talk about quantitative estimates - is often difficult to specify. Moreover, water quality includes several different, use specific criteria. Most evident from the management view is that climatic change introduces an additional source of uncertainty, the relative role of which increases rapidly with increasing planning horizon.

Climatic change research including diverse impact assessment tasks is a field where individuals from various disciplines must solve problems together. No education provides expertise in all

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fields of natural, engineering, social, and management sciences that are required in the assessment of climatic change impacts in scales encountered in management. Holistic reviews and analyses are needed from different components of the ecological and social systems to ease the communication between specialists on different but often related fields, and to assist in focusing on most essential impacts and problems.

Our goals were (1) to offer a systematic view on changes that are potential to be expected in lakes and reservoirs, (2) to discuss how these changes affect water quality problems, water quality management, and water use, with special attention in the elucidation of the complex interrelationships yielding to lake water quality, and (3) to collect a checklist for researchers, planners and managers. First we list the most typical uses of lakes and most frequent water quality problems. Second, we discuss the possible impacts of climatic change on the natural phenomena and processes in lakes. Third, the impacts on water quality problems are discussed. Finally, conclusions are drawn.

2. Water Quality Problems and Lake Management

The term *water quality problem* does not refer to a problem that were similar in all lakes. Instead, water quality problems include several different issues owing to the following reasons: (1) high diversity of natural and man-made lakes, (2) high diversity of societal needs and preferences associated to the utilisation of surface waters, and (3) complexity of lake ecosystems. The most common water quality problems are:

- *Eutrophication* caused by the abundance of nutrients and other prerequisites of enhanced primary production.

- *Oxygen depletion* caused by degradation of organic matter in water.

- *Hygienic* problems due to pathogenic organisms such as viruses, bacteria (*Salmonella, Yersinia,* etc.), or protozoa (*Schizosomiasis, Plasmodium,* etc.).

- *Salinization* due to high concentrations of ions such as calcium, sodium, chloride, and sulphate. *Hardness* is caused by high concentrations of calcium, magnesium, and carbonates (HCO_3^- and $CO_3^=$).

- *Acidification* of lakes is caused globally mainly by atmospheric deposition of SO_2 and NO_x. Some industrial and mining activities also cause severe regional watershed acidification problems. The natural acidity and buffer capacity of waters differ greatly.

- *Toxic* or *cumulative* compounds such as heavy metals (Hg, Cr, Zn, Co, etc.), pesticides (DDT, Lindane, etc.), industrial wastes (PCB, organochlorides, etc.), or water ecosystem borne toxins (hepatotoxins and neurotoxins produced by blue-green algae, etc.).

- *Suspended* material and *turbidity* caused by inorganic or organic matter.

- Changed *thermal* conditions due to thermal pollution, flow control, or changed climate.

From the management perspective, the greatest motivation for water quality studies derives from the demands set by different uses, and conflicts between those uses. Water quality requirements are very case specific, and human activities affect them in many ways. Tables 1 and 2 summarise the most frequent uses of lake water, and their requirements and impacts on water quality. Many uses suffer from poor water quality but have no influence in it (Table 1), while many of them cause water quality problems but are not harmed by it (Table 2).

Regarding the climatic change and lake water quality management, we can raise the following questions. Will the potential impacts of climatic change affect decision making and water resources management. In which scale that would happen; in river basin scale or smaller? What technical means are available? The two first questions are rather case specific in character, and they should be raised at each case separately. The technical means can either be directed to the lake itself or to external factors driving the quality of the inflowing water. One can influence the hydrology, thermal balance, chemistry, biology, or ecology of the system. A variety of lake management alternatives for water bodies (Table 3) have been presented and most of them are in wide use globally (cf. Cooke et al. 1986, Moore and Thornton 1988, Gulati et al. 1990). Many of them, especially among the internal action alternatives, can best or solely be applied to small lakes or locally.

In the following, we will discuss the potential impacts of climatic change on (1) factors driving water quality such as water and nutrient inputs to the lake, and thermal distribution in the lake water body, and (2) internal factors such chemistry, biochemistry, and ecology of the lake. Also the water quality problems are discussed.

3. Impacts on Factors Driving Lake Water Quality

Climate

Information on climatic changes, with variables such as air temperature, precipitation, humidity, cloudiness, solar radiation, windiness and air pressure, and in their temporal and spatial variability, is taken here as given information, and the topic is thus not discussed in detail. However, some notes are made on their contribution to lake water quality.

Solar radiation penetrating the water body is among the major energy inputs to a lake. It warms up the water, and is the major contributor – together with *wind*, inflowing water, and *air temperature* – to the formation of thermal stratification. It is also the prerequisite to assimilation (primary production) by plants including phytoplankton. Therefore, it also controls many chemical cycles in a lake. Changes in the solar radiation caused by changes in *humidity, cloudiness*, and *air temperature* are thus prone to alter the thermal balance and primary production. Humidity also controls the thermal balance through evaporation process. Most of the climatic variables also have an impact on the hydrology of the watershed and the lake.

TABLE 1: Typical influences of lake water quality problems on most frequent lake water uses. E = eutrophication, O = oxygen depletion, H = hygienic problems, S = salinization, A = acidification, X = toxic and cumulative substances, M = turbidity and suspended matter, and T = thermal pollution. - stands for low or occasional influence, and – for high influence.

Use	E	O	H	S	A	X	M	T
Conservation	–	–	–	–	–	–	–	–
Recreation	–	–	–	-	-	–	–	-
Fisheries	-	–		-	-	–	-	-
Aquaculture	-	–		-	-	–	-	-
Water uses								
- Households	–	–	–	-	-	–	-	
- Municipalities	–	-	-	-	-	–	-	
- Irrigation, etc.	-	-	–	–	-	–	-	
- Industry	-	-	-	-	-	-	-	
Transport	-						-	
Flood control							-	
Hydropower							-	
Cooling basin								-
Waste transport and disposal	-							

TABLE 2: Typical impacts of most frequent lake water uses on water quality. E = eutrophication, O = oxygen depletion, H = hygienic problems, S = salinization, A = acidification, X = toxic and cumulative substances, M = turbidity and suspended matter, and T = thermal pollution. + stands for low or occasional impact, and **+** for high impact.

Use	E	O	H	S	A	X	M	T
Conservation								
Recreation			+					
Fisheries								
Aquaculture	**+**	+					+	
Water uses								
- Households								
- Municipalities								
- Irrigation, etc.	+			+				
- Industry								
Transport			+			+	+	
Flood control	+	+					+	+
Hydropower	+	+		+			**+**	+
Cooling basin	+	+				+		**+**
Waste transport and disposal	**+**	**+**	**+**		+	**+**	**+**	

TABLE 3: Lake water quality management alternatives. E = eutrophication, O = oxygen depletion, H = hygienic problems, S = salinization, A = acidification, X = toxic and cumulative substances, M = turbidity and suspended matter, and T = thermal pollution. · stands for low or occasional applicability, and • for typical applicability.

Option	E	O	H	S	A	X	M	T
External action								
Treatment of waste water & sewage	•	•	•			•	•	
Manipulation of inflowing water	·	·					•	
Land use in the catchment	·	·	·		·	·	·	·
Non-point source pollution control	•	·	·			•	·	
Liming of lakes & catchments					•			
Shifts in lake water volume or level	·	·		·			·	
Flow regulation	·	·					·	
Increased throughflow	·	·		·			·	
Internal action								
Ecotechnology, biomanipulation	•	·					·	
Chemical treatment of water (P inactivation, poisoning of algae etc.)	·	·					·	
Removal, treatment or covering of sediment	•	•				·	·	
Macroplant harvesting	·	·						
Aeration and mixing	•	•					·	
Outflow from hypolimnion	·	·		·			·	·

Hydrology and watershed

The hydrologic cycle is in close connection with the climate. The GCMs (Global General Circulation Models) provide climatic change scenario information on the most important components of the hydrologic cycle. However, information on the regional and local scale is usually a problem (cf. Smith 1990). According to Kundzewicz and Somlyódy (1993), hydrological models are needed to estimate components of the hydrological cycle on the basis of GCMs. Associated problems are scale and uncertainty. Mesoscale hydrological models – such as the rainfall pattern prediction model by Bárdossy and Plate (1992) which starts from the air pressure estimate of GCMs – are a promising way to derive mesoscale, climate change scenarios in water management. Improved integration of hydrological models and GCMs is obviously needed.

In areas where the climate becomes more humid, the increased rainfall to evaporation ratio causes decrease in *retention time* of a lake. It is also prone to increase *erosion* and *nutrient leaching* from the catchment and thus contribute to the *non-point source pollution* entering a lake. The former typically counteracts and reduces many lake water quality problems such as eutrophication, oxygen depletion, and salinity. The latter enhances those problems, plus turbidity and hygiene. In areas that turn more dry, the impacts are inverse: the retention time increases, while erosion and nutrient leaching are likely to decrease if the vegetation is not destroyed. Increased retention and decreased throughflow concentrate pollutants and salts. A risk for salinization is noteworthy in areas where evaporation is expected to become greater than precipitation. Annual runoff has a nonlinear relationship with annual precipitation. Moreover, seasonal changes are often more important than annual ones (cf. Williams 1989).

In California's Central Valley, the $2xCO_2$ scenarios by Williams (1989) showed, that the frequency of wet years increased from 26 to 47%. This among other implications forms an increased incentive for protecting soils and vegetation. In Britain, where the climate is expected to get warmer and more humid, Whitehead and Jenkins (1989) prospected an increase in washoff of nutrients and herbicides from soil, and the consecutively increasing non-point source loading. They stress the roles of changing water pathways, increasing soil temperature, and increased use of agricultural chemicals due to warming climate as major reasons.

The climatic change may alter the *extension* and *water level* of a lake (cf. Hartmann 1990, Jacoby 1990), even by reducing it to a lake without outlet or drying it up. Such changes would have serious consequences on the whole ecosystem, and would affect water use drastically. The Laurentian Great Lakes, for instance, are under the risk of being lowered remarkably. Depending on the GCM used, $2xCO_2$ simulations have resulted in a drop of 0.5 to 2.5 m (Quinn and Croley 1983, Hartmann 1990, Smith 1991, see also critical comments by Balling 1991).

The expected changes in the hydrology of a certain river basin or a lake are today still very obscure. They are very case specific. It may even not be clear whether the attention should be paid on the mean behaviour of the system: changes in precipitation, humidity, snow cover, erosion, mass flows, water levels and lake volumes or in the extremes: frequency and intensity of *floods*, *storms* and *droughts*. Climatic change studies should perhaps respect more the water engineering tradition, in which extreme design conditions play a major role.

Changes in hydrology have direct effects on the thermal and hydraulic balances, in loads of nutrients and suspended matter to the lake. Variability and timing of quantity and quality of the incoming water must be considered. Even small changes in the hydrology and mass flows may influence lake water quality greatly, as was the case in the simulation study by Varis (1988, 1989) at Lake Kuortaneenjärvi, Finland, where the late summer blue-green algae blooms were found to be very sensitive to variations in quantity and quality of nutrient rich spring flood water.

Most of the case studies addressing hydrological changes due to climatic change present implications to water quantity management, and only marginally to water quality issues (e.g. Croley 1990, Lettenmaier and Gan 1990, Thomas 1990, Cohen 1991, Dooge 1992, Kaczmarek and Krasuski 1991, Lettenmaier and Rind 1992, Miller and Russel 1992). The major interest has been in the evaluation of the needs and possibilities to adapt water allocation policies to meet the problems raised by changing amount of water in the respective watersheds.

Thermal balance of a lake

The thermal balance and thermal stratification pattern, especially the depth and stability of the thermocline (the layer with a high temperature gradient), are the result of several hydrometeorological factors. The most important of them include thermal flux from the atmosphere, evaporation and precipitation, wind-induced turbulence, and energy input by solar radiation. Typically, they all are subjected to substantial natural variability.

Altered water *temperature* influences almost any hydraulic, chemical, and biological process in a lake. Considering *thermal stratification*, caused by density differences in water layers of different temperatures, the climatic change will have most notable impacts in cases where the stratification pattern is essentially altered. The characteristic thermal stratification patterns are:

- *Dimictic*: The lake stratifies two times annually. In summer, the upper water layers are warmer than the lower ones, and in winter during ice cover, the upper layers are cooler than the lower ones. Typical for deep lakes that freeze in winter.

- *Monomictic*: The lake stratifies only once a year, in winter or in summer. Typical for deep lakes that do not freeze in winter, and for shallow lakes that freeze.

- *Amictic* and *polymictic*: The lake develops no stable stratification, and the lake stratifies several times in a year, respectively. Typical for tropical lakes, and for shallow lakes that do not freeze.

A shift such as from dimictic pattern dominance to monomictic, or from monomictic to amictic or polymictic, or vice versa, are prone to change the lake ecosystem markedly. The balances of oxygen, nutrients, sulphur, iron, and many other substances may be remarkably altered. Substantial changes may also be induced by the shift in the depth of the thermocline. This alters the volumes and balances of different water layers. The issue grows in complexity if the lake is also chemically stratified, i.e., *meromictic*. This is often the case in deep, brackish water basins. Besides changes in air temperature, also altered radiation, quantity and temperature of inflow, and windiness are important factors contributing to stratification.

McCormick (1990) has studied the potential thermal and hydraulic impacts on Lake Michigan, Croley (1990) on Laurentian Great Lakes, and Orlob et al. (1990) on the Shasta-Trinity System, California. Hondzo and Stefan (1991) modelled and compared the heat balance and stratification of a particularly warm year to an average one in three lakes in north central US. Meyer et al. (1993) defined a number of hypothetical lakes, ranging from shallow to deep, around the globe in order to find the sensitive latitudes where the risk for the change in the stratification pattern is large. Then 8 real lakes were selected from the sensitive regions, and 2xCO_2 scenarios were performed to the heat balances and thermal stratification patterns of those lakes.

The length and other characteristics of the *ice cover* period have many physical, chemical, and biological influences. The most important among them are thermal balance, control of input solar radiation, and control of mass fluxes between the atmosphere and the water body. The most drastic impact would be the total lack of ice in lakes that used to freeze.

Several studies (Assel et al. 1985, Kuusisto 1987, Schindler et al. 1990, Assel 1991, Kauppi et al. 1992) have shown that the climatic change may yield in remarkable changes in ice cover of lakes. For instance, in Lake Superior and Lake Erie, the ice cover duration in 1951 to 1980 has been 13 to 16 weeks. The $2xCO_2$ scenarios by Smith (1991) and Assel (1991) have resulted in the reduction of the ice cover period ranging from 1 to 2 1/2 months, and winters without ice cover are to be expected. These results vary greatly depending on the GCM used. In six Finnish lakes that are presently frozen from 5 to 6 months, $2xCO_2$ results show a decrease of roughly 2 months in the ice-cover period (Kauppi et al. 1992).

Being sensitive to climatic changes, lake ice records have been used to detect changes in the climate, and to project future ice cover at the Red River, Manitoba (Rannie 1983) using records from the 19th Century, and at Lake Mendota, Wisconsin (Robertson et al. 1992) with data dating back to 1855 from present. The ice cover period of Lake Mendota will decrease by 11 days with a 1 ^{o}C warming. With a warming of 4 to 5 ^{o}C, ice free winters will occur approximately in 1 out of 15 to 30 years.

4. Impacts on Water Quality

Chemistry and biochemistry

The climatic, thermal, and hydrologic changes in a lake affect the chemical and biochemical cycles and balances in many ways. The most important elements among them regarding water quality studies include dissolved oxygen, inorganic carbon, phosphorus, nitrogen, sulphur, and iron. Additionally, ions responsible for the water salinity deserve attention.

Dissolved oxygen (DO) household, including processes influenced by oxygen, is in close relation with the climatic, thermal and hydraulic impacts: ice cover, water temperature, solar radiation, and stratification. It is also closely associated with nutrient cycles, biotic impacts, and the eutrophication problem. Primary production in illuminated water layer consumes CO_2 and produces oxygen. Degradation of organic material has an inverse impact: CO_2 is produced and oxygen is consumed. DO concentration influences many biochemical processes, e.g., in sulphur and iron dynamics. One of the major negative consequences of eutrophication is the depletion of DO from lower water layers. It is caused by degradation of organic material in layers not in contact with the atmosphere. Many fish species are very sensitive to low DO concentrations, both in maintenance and in reproduction. Often short extremes become critical.

The role of the *inorganic carbon* system has been emphasised in many textbooks (Ruttner 1940, Hutchinson 1957, Stumm and Morgan 1981). Increased partial pressure of CO_2 in the atmosphere causes increased concentration in water. Increased temperature yields in decreased solubility of gases. The CO_2–H_2CO_3 equilibrium is sensitive to pH, and it buffers it. Increasing CO_2 concentration in water also changes the equilibrium to acid direction. Additionally, the free inorganic carbon increases the *aggressivity* of water, and dilutes Ca and Mg from the rock and sediments. If they are available, the *hardness* of the water increases, if not, the acidification continues till other buffering cations are available. The expression hard water refers to large concentrations of alkaline earths, usually originated from calcareous deposits in the catchment. Soft water lakes are typically located in areas with igneous, acidic rock. They are especially prone to acidification.

For the calcium and magnesium buffered Lake Balaton, Hungary, Szilágyi and Somlyódy (1991) have calculated that the increased dissociation of inorganic carbon to water will probably be a more important contributor to *acidification* and to ionic composition than acid deposition. Doubling the atmospheric CO_2 concentration would yield in lowering of the pH value by 0.2 units, and to significant increase in the salt content and hardness of the lake water. Laboratory experiments and calculations for a set of other lakes are under way.

Increased inorganic carbon adds to the *availability of carbon* to primary producers. The carbon availability has been suggested to be one of the major limiting factors in eutrophic lakes (King 1970, Shapiro 1973, 1990). During the hours with the most intensive primary production, the concentration of inorganic carbon in water declines locally, and biomass growth is limited accordingly. Therefore, increased availability of inorganic carbon may enhance primary production and contribute to eutrophication (Wetzel and Grace 1983, Byron and Goldman 1991). In the global carbon cycle, the fixation of carbon by phytoplankton is an important link and balancing feedback mechanism (Lashof 1989, Williamson and Gribbin 1991). Also the leaching of organic carbon such as humic compounds from the catchment may alter, and affect the carbon cycle and water quality in a lake (Arvola et al. 1992).

The dynamics of many other, important elements in lake ecosystems – above all *phosphorus, nitrogen, sulphur, silica*, and *iron* – are dominated by microbial activity, controlled primarily by DO concentration (redox potential), temperature, pH, and concentrations of various fractions and compounds of these elements. In general, increasing temperature accelerates reaction rates. Decreased redox potential caused by low DO availability affects many equilibrium reactions (Fig. 1). P cycle is sensitive to DO, particularly the near bottom concentration. Even a short – extreme – anoxic period near bottom can induce P mobilisation from sediment to water body, and change the lake permanently to eutrophic. It is very difficult and expensive to reverse this development. Typically, if surface erosion is increased from the catchment, P input is also increased. N cycle is in connection with the atmosphere, both through N fixation by blue-green algae and bacteria (source), and denitrification (sink). With increasing temperature, the solubility of gases decreases and processes such as denitrification and N fixation get accelerated.

Bicarbonates, carbonates, sulphates and chlorides of alkalis and alkaline earths dominate the ionic composition of fresh waters. The four major cations are Ca^{++}, Mg^{++}, Na^+ and K^+, and four major anions HCO_3^-, $CO_3^=$, $SO_4^=$, and Cl^-. Also silica is often a significant constituent of the total salinity in hardwater lakes, and iron in some conditions. The dominating processes controlling the salinity of lakes are weathering processes in the catchment, atmospheric precipitation, and accumulation of salts due to dominance of evaporation over outflow. *Salinization* problems are apparently notable in areas that are arid or are at risk of becoming arid.

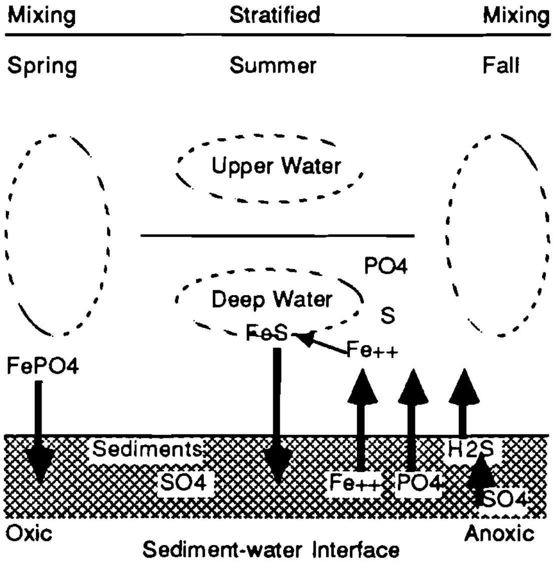

Fig. 1. Interactions of phosphorus, sulphur, and iron in oxic and anoxic conditions in sediment-water interface.

Ecology and biology

Whereas the potential changes in the physical and chemical domain of a lake are relatively easy to list, the changes in the flora and fauna, and on the whole ecosystem, are more difficult to foresee. Owing to the low level of understanding of these complex topics, the uncertainty associated is extensive. There are a number of – strongly interrelated – ecological issues to be considered (cf. Walker 1991), with complex feedback effects. They are driven by the hydrologic, hydraulic, chemical, and thermal environment.

Let us first discuss the *composition of flora and fauna*. Phytoplankton composition and dominant species are widely used as water quality indicators in limnology. Certain species are an important source of nutrition to zooplankton, and certain zooplankton species regulate the growth of many fish species. Additionally, some phytoplankton species are especially problematic to water supply and recreation. Those species are most often *blue-green algae* (cyanobacteria), many of which are able to form nuisance blooms, and are also able to form toxic strains. Blue-green algae are favoured by a number of factors (cf. Varis 1993), among which the following ones are relevant to climatic change studies: (1) elevated water temperature, (2) nutrient enrichment, (3) low N to P ratios, (4) low light energy availability, (5) high pH and/or low inorganic carbon concentration, (6) resistance to turbulence, and (7) ability to rest in anoxic sediments. When discussing the impact of climatic change to the competitive ability of blue-green algae in a lake, shifts in these issues should be considered.

A number of studies have issued the other *biotic communities*, and *food webs* in lakes. For instance, *zooplankton* by George et al. (1990) in Esthwaite Water, Cumbria, Britain and Arvola et al. (1992) in Pääjärvi, Finland; *bottom flora and fauna*, *macrovegetation*, and the *fish* by Hill and Magnuson (1990) and Magnuson et al. (1990) in the Laurentian Great Lakes, Trippel et al.

(1991) in Lake Constance, Germany, and Chang et al. (1992) in Douglas Reservoir, Tennessee. Minns and Moore (1992) have made a comprehensive study on fish yields of whitefish, northern pike, and walleye in 406 watersheds in eastern Canada. The results showed considerable redistribution of fishery capability; areas with high productivity will become marginal and areas presently marginal will have optimal conditions for the species considered. Large artificial efforts were suggested to redistribute preferred fish species.

Changes in growth season length, in retention time, and in other control factors may have impacts on the pattern of *ecological succession.* This is particularly noteworthy in areas with strong seasonality, where seasons are the major reason to succession patterns. Remarkable changes in the succession pattern between blue-green algae and other phytoplankton have been suggested to happen in the $2xCO_2$ simulation study by Varis and Taskinen (1993) at Lake Kuortaneenjärvi, Finland.

5. Impacts on Water Quality Problems

In the section 2 (cf. Tables 1 to 3) we clustered lake water quality problems in eight classes: *eutrophication, oxygen depletion, hygienic problems, salinization, acidification, toxic and cumulative substances, turbidity and suspended matter,* and *thermal pollution.* The potential impacts of climatic change on most important external and internal features concerning lake water quality, as described in Sections 3 and 4, are summarised in Table 4 (cf. Orlob et al. 1993). The Table includes the *directions* of interrelationships between those features, indicated as same, inverse, none, or non-universal. Many impacts are very case specific, they are a sum of several phenomena, or essential information is lacking, and direction of influence is not universally definable.

What are then the implications of the above described changes in the water quality problems in lakes? Table 5 contains the directions of these impacts, defined again as same, inverse, none, or non-universal. The following analysis concentrates on the *impacts with non-universally definable direction*, since the other cases are evident on the basis of Sections 3 and 4. Consecutively, many of those relations are due to several processes, and require lake specific consideration.

Eutrophication

There are several attributes potentially affected by climatic change that do not have a universally definable direction within the context of lake eutrophication (cf. Table 4 consecutively). The quantity of *solar radiation* penetrating to the lake influences the eutrophication development by changing the *thermal balance* and *stratification.* Such changes are likely be the greater the further the lake is located away from the equator (Meyer et al. 1993). Moreover, the light energy for primary production, and the competitive ability of nuisance algae are altered. These both have many indirect effects, and therefore the direction of change is lake specific.

Winds are also a major driving force in the formation of stratification. They mix the water body and increase the DO content of the water. Especially in shallow lakes, the amount of resuspension of sedimented material is controlled largely by wind. Increasing windiness enhances resus-

TABLE 4: Attributes potentially altered due to climatic change, and their typical influences on one another. + stands for effect in the same direction, and - for inverse direction. * indicates impact on indefinite, unknown, or case specific direction. Non-quantitative attributes are marked with † (cf. Table 5).

Influence from	To														
Climatic inputs	*St†*	*If*	*Fl*	*Dr*	*El*	*Rt*	*Wl*	*Ox*	*Ca*	*Nu*	*Sa*	*pH*	*Gs*	*Fs†*	*Bg*
Temperature	*	+	*	*		*	*	*	*		+		+	*	+
Humidity	*		+	-	*	-	+				*			*	
Solar radiation	*	+	*	*				*	*			*	+	*	*
Precipitation	*	*	+	-	+	-	+	*	*	*	-	*		*	
Winds	*	+	*	*	+			*	*	*	*	*		*	*
Thermal & hydraulic	*St†*	*If*	*Fl*	*Dr*	*El*	*Rt*	*Wl*	*Ox*	*Ca*	*Nu*	*Sa*	*pH*	*Gs*	*Fs†*	*Bg*
Stratification† (St)	▨	*				*	*	*	*	*		*	*	*	*
Ice free period (If)	*	▨	*		*			*	*	*		*	+	*	+
Hydrologic	*St†*	*If*	*Fl*	*Dr*	*El*	*Rt*	*Wl*	*Ox*	*Ca*	*Nu*	*Sa*	*pH*	*Gs*	*Fs†*	*Bg*
Floods (Fl)	*	+	▨	-	+	-	+	*	*	*	-	*	*	*	*
Droughts (Dr)	*	*	-	▨	*	+	-	*	*	*	+	*	*	*	*
Erosion, loading (El)			*	*	▨			*	*	+	+	*		*	*
Retention time (Rt)	*	*	-		*	▨	*	*	*	+	+		+	*	+
Water level (Wl)	*	*	*	-	*	*	▨	*	*	-	-			*	-
Chemical	*St†*	*If*	*Fl*	*Dr*	*El*	*Rt*	*Wl*	*Ox*	*Ca*	*Nu*	*Sa*	*pH*	*Gs*	*Fs†*	*Bg*
Oxygen (Ox)					*			▨	*	-		*		*	*
Carbon dioxide (Ca)					*			*	▨		+	-		*	*
Nutrient enrichment (Nu)								*	*	▨	+	*		*	+
Salinity (Sa)	*	+									▨			*	*
pH					*			*	*	*	*	▨		*	+
Ecological	*St†*	*If*	*Fl*	*Dr*	*El*	*Rt*	*Wl*	*Ox*	*Ca*	*Nu*	*Sa*	*pH*	*Gs*	*Fs†*	*Bg*
Growth season length (Gs)								*	*	*		*	▨	*	+
Foodchains, succession† (Fs)								*	*	*		*		▨	*
Blue-green algae (Bg)								*	*	+		+		*	▨

pension. Phytoplankton composition is also sensitive to windiness, owing to unequal buoyancy properties of different algae.

Depending on the quality of the *flood* water, and other inputs during a *drought*, eutrophication may be increased or decreased. The impact is also associated to stratification. Increased *inorganic carbon* input to water increases the availability of carbon to primary production. This enhances eutrophication. It also acidifies the water. Both the availability of carbon, and the acidification, are competitive drawbacks to the growth of blue-green algae. The phenomenon is complex, and more research is needed.

Increased *turbidity* and *suspended matter* act as catalysts in eutrophication, if nutrients including carbon are added in forms available to primary producers. Another mechanism enhancing eu-

TABLE 5: Attributes potentially altered due to climatic change, and their typical impacts on water quality problems. Note, that these directions, their impacts, and the priority of the problems are case-specific. E = eutrophication, O = oxygen depletion, H = hygienic problems, S = salinization, A = acidification, X = toxic and cumulative substances, M = turbidity and suspended matter, and T = thermal problems. + stands for effect in the same direction, and - for inverse direction. * indicates impact on indefinite, unknown, or case specific direction.

Cause	Problem impacted							
Specification								
Climatic inputs	E	O	H	S	A	X	M	T
Temperature	+	+	*	+				+
Humidity				-				+
Solar radiation	*	+		+			+	+
Precipitation				-	+	*		-
Winds	*	-		+	*	*	*	-
Thermal and hydraulic	E	O	H	S	A	X	M	T
Stratification	*	*	*			*	*	*
Ice free period	+	*	*				*	+
Hydrologic	E	O	H	S	A	X	M	T
Floods	*	*	+	-	*	*	*	-
Droughts	*	*		+	*		*	+
Erosion, loading	+	+	+	+	*	+	+	
Retention time	+	+	*	+	*	+	*	+
Water level	-	-	*	-	*	-	*	-
Chemical	E	O	H	S	A	X	M	T
Oxygen	-	-	-			-	-	
Carbon dioxide	*	*		+	+			
Nutrient enrichment	+	+	*				+	
Salinity				+	-	*		
pH	+	+	-		-	*	*	
Ecological	E	O	H	S	A	X	M	T
Growth season length	+	+	*				*	+
Foodchains, succession	*	*	*				*	
Blue-green algae	+	+	+			+	+	
Problems	E	O	H	S	A	X	M	T
Eutrophication (E)	▨	+			-	+	+	
Oxygen depletion (O)	+	▨				+	+	
Hygiene (H)			▨					
Salinization (S)				▨	-	*		
Acidification (A)	-				▨	+	-	
Toxicity (X)						▨		
Turbidity (M)	*	+	+			+	▨	
Thermal (T)	+	+	*	+				▨

trophication is the consumption of oxygen if turbidity is composed by biologically degradable constituents.

The changes in *ecological succession* and in *foodchains* can be so manifold that no universal patterns can be detected. The same applies to corresponding impacts due to all the other water quality problems as well.

Oxygen depletion

As a problem, oxygen depletion is very closely related to eutrophication, as can be seen from Tables 1 to 4. Regarding impacts with no universal direction, reference is given to eutrophication in the following attributes: *stratification*, *floods*, *droughts*, *ecological succession*, and *foodchains*.

The length of the *ice free period* defines the length of the growth season. It also greatly influences the stratification and thermocline depth in deep lakes. If the ice free period is extended, primary production is prone to increase causing more degradation and oxygen consumption in lower water layers. Concurrently, the volume of the lower water layers may go down. This enhances DO problems. Yet, correspondingly the DO problems under the ice cover may decrease.

Inorganic carbon dissociated in water and DO are closely linked through primary production and degradation of organic matter. Referring to impacts on eutrophication, no universal direction can be posed.

Hygiene

Increased water *temperature* and *nutrient enrichment* may contribute to the spreading of some water-borne diseases. Regarding the former, this is particularly the case if the lake does not *freeze* any more, and the *growth season* is not suspended by winter. Such conditions introduce the risk for spreading of diseases such as malaria and schizosomiasis. On the other hand, degradation of faecal pollution is accelerated in conditions with high biological activity, i.e., it degrades more rapidly in warm water than in cold water, and more rapidly in nutrient rich than in nutrient poor water, generally. The fate of hygienic pollution is influenced by *stratification*, *retention time*, and other corresponding conditions in the basin.

Acidification

If directions and intensities of *winds* are changed, the sulphur and nitrogen concentrations of rain water may be altered. Also other undefined influence directions associated to acidification are dominated by *hydrology*. Depending on the rock and soil in the catchment, and the quality of flood water, they may contribute to acidification, in either direction. In areas with sulphur rich deposits, changes in ground water level may mobilise large amounts of acidifying sulphur to water.

Toxicity

This group of pollutants is highly diverse chemically, biologically, and ecologically. Therefore, a discussion of the undefined influence directions is more complicated than in previous cases. Important are the composition, distribution, and pathways (cf. Boyce et al. 1991) of these substances.

Turbidity

The composition of turbidity is also highly case specific. It may be composed of eroded, either inorganically dominated substances such as clay, or organic compounds such as humic acids. Also wind and ice erosion must be taken into consideration. Another type of substances causing turbidity is organic material produced in the water. In many areas, floods dominate the erosion loads to the water.

These substances behave very differently. Typically, however, adsorption-desorption reactions of P, for instance, are sensitive to water pH so that in decreasing pH, more P is dissolved. On the other hand, increasing pH may increase biological production.

Thermal problems

The prospected directions of influences due to thermal pollution are rather clear. Only stratification constitutes a non-universal component. Changes in stratification – induced by other factors described previously – may change the thermal transport and distribution in the water so that the fate and impact of thermal pollution are altered.

6. Conclusions

Lakes and reservoirs are complex systems. They can apparently be affected by climatic change in several ways. Many of the components and processes affected are interrelated and correlated. Impacts are largely but not totally lake specific.

Many water quality problems are at risk of becoming worsened by the climatic change; particularly eutrophication, oxygen depletion, salinization, acidification, and thermal problems. Perhaps most typically, the ageing processes – such as getting filled up, and increased production – are likely to be accelerated. In comparison to many other geological formations on the Earth's crust, lakes have a relatively short span of existence (cf. Hutchinson 1957). In this aspect, the origin and the history of the lake are crucial. Generalisations and classifications concerning lake type, climatic zone, and altitude, are needed, because different lake types will have different characteristic problems. Besides lake specific studies, more studies are needed in a regional and global basis to detect critical regions, critical lakes, or critical lake types concerning certain problematic change. Such studies have been conducted already, e.g., by Minns and Moore (1992) on the fish in eastern Canada, and by Meyer et al. (1993) on thermal balances including stratification and ice cover studies using hypothetical and real lakes located around the globe.

What changes in a lake will become most critical ones to water use, is not always self evident. There is a connection to the uses of the lake, and to the supply vs. demand conditions of water in the region. Identifying the most relevant problems to be targeted need thorough, holistic consideration. Tables 4 and 5 have been designed to assist in this procedure as checklists to start with. Both the means and the variability of climatic and lacustrine variables must be considered. Some impacts are due to shifts in the mean behaviour of the hydroclimatic system, but many impacts are introduced by extreme events, or by increased or decreased frequency of such events (cf. Katz & Brown 1992). Apparently, climatic change studies should be more in line with conventional approaches to water management where extreme design conditions are often the critical criteria. At the ecosystem level, the impacts will depend also on the rate of changes and on the capability of the ecosystems to adapt to the changes (cf. Walker 1991).

Climatic change impact assessment is a task with many aspects. Generally, it is not independent from other impact assessment needs, nor from development scenarios due to other factors such as pollution trends and land use changes. Impact assessment is subject to several methodological and philosophical problems (Laurmann 1991), and to extreme uncertainties, which have been discussed and emphasised almost invariably in the case studies reviewed. Even the direction of climatic changes, not to talk about quantitative estimates, is still often obscure at any case specific level. The spectrum of assessment methodology used should be wide, and the choice of the approach should be conscious. Relying upon simulations only, upon statistics only, upon risk analysis only, upon knowledge-based techniques only, or upon intuition only, is not the right way in our opinion. Clearly, computational techniques that are able to manage very high or extreme uncertainties deserve more attention than in present studies (cf. Kundzewicz and Somlyódy 1993). Methodological research and development should be focused into that direction.

Does the present knowledge and understanding of climatic change give reason to alter water management practices and policies? At least many of the hydrologically oriented references (cf. Section 3) present such suggestions for water quantity. In contrary, in the case studies reviewed in this paper, water quality management options (Table 3) have been far less discussed, especially as concrete recommendations for action. Whether climatic change scenarios have been taken into practice or will be taken in near future in defining rational waste water treatment level, land use, aeration, or any other water quality management option, is presently unclear to us, but we doubt that this will occur extensively. What is clear is that also contemporary, very high uncertainty level in water quality management has obtained an additional uncertainty component to be taken into account. There is evidently a need to integrate the chance of climatic change as one aspect to water quality management, and take this aspect into account in an adaptive manner. As devised by Fiering & Rogers (1989), conventional stationary-climate policy statements should be periodically checked and updated by responsible experts, concerning the rationality of the unchanging climate assumption.

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