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Review article

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ABSTRACT

Besides climate change impacts on water availability and hydrological risks, the consequences on water quality is just beginning to be studied. This review aims at proposing a synthesis of the most recent existing interdisciplinary literature on the topic. After a short presentation about the role of the main factors (warming and consequences of extreme events) explaining climate change effects on water quality, the focus will be on two main points. First, the impacts on water quality of resources (rivers and lakes) modifying parameters values (physico-chemical parameters, micropollutants and biological parameters) are considered. Then, the expected impacts on drinking water production and quality of supplied water are discussed. The main conclusion which can be drawn is that a degradation trend of drinking water quality in the context of climate change leads to an increase of at risk situations related to potential health impact.

Contents

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1. Introduction

Floods and droughts are the main impacts of climate change on water availability. Besides these quantitative impacts, surface water quality is also affected by climate change. For example, it seems obvious that a drought may imply at least a modification of surface or ground water quality (concentration) sometimes leading to water supply limitation. If surface water withdrawal can be directly affected by water quality degradation, wells pumping can be cut off for sanitary reasons (groundwater quality) as well as for security reasons (floods threats). However, even if these facts are well known, few scientific works have been published until recently on the impacts of climate change on water quality modification.

Actually, climate change is not the only factor affecting water quality. Integrated into the global change concept, land use evolution, deforestation, urban spreading and area waterproofing may also contribute to water quality degradation. But more often, water pollution is directly linked to human activities of urban, industrial or agricultural origin, and climate change could lead to degradation in surface water quality as an indirect consequence of these activities. When point source pollution is reduced in many countries (even if wastewater treatment plants begin to reach their capacity limits), climate (global) change impacts could tend to increase the diffuse pollution with for example urban or agricultural runoff. The climate change determinants affecting water quality are mainly the ambient (air) temperature and the increase of extreme hydrological events. Soil drying-rewetting cycles and solar radiation increase may also be considered.

First of all, temperature (in general) must be viewed as the main factor affecting almost all physico-chemical equilibriums and biological reactions. It is well known that all physico-chemical "constants" vary with temperature, and frequently increasing endothermic reactions. According to Arrhenius relation, kinetic of a given chemical reaction can be doubled for a temperature increase of 10 °C. Consequently, several transformations or effects related to water will be favoured by water temperature increase such as dissolution, solubilisation, complexation, degradation, evaporation, etc. This phenomenon globally leads to the concentration increase of dissolved substances in water but also to the concentration decrease of dissolved gazes. This last point is very important with respect to dissolved oxygen in water. In fact, its saturation concentration decreases of almost 10% with a 3 °C increase (10 mg/L at 15 °C). Remind that, whatever the IPCC scenario, the average global air temperature should increase between 1.8 and 4.0 °C (Bates et al., 2008) during the 21st century. Moreover, a drying tendency in summer is expected, particularly in subtropics, low and mid-latitudes, in addition with an extreme events increase in general (Bates et al., 2008).

Floods and droughts will also modify water quality by direct effects of dilution or concentration of dissolved substances. For low river flow rates, the main effect on water quality is as for a temperature increase, a concentration increase of dissolved substances in water but a concentration decrease of dissolved oxygen (Prathumratana et al., 2008; Van Vliet and Zwolsman, 2008). A correlative positive effect is the concentration decrease of some pollutants due to a low water velocity (aquatic plants assimilation of nutrients and adsorption/complexation of heavy metals on suspended matter and settling). These phenomenons will be detailed hereafter. For heavy rain falls and strong hydrologic conditions, runoff and solid material transportation are the main consequences. For countries in the temperate zone, climate change will decrease the number of rainy days but increase the average volume of each rainfall event (Brunetti et al., 2001; Bates et al., 2008)). As a consequence, drought–rewetting cycles may impact water quality as it enhances decomposition and flushing of organic matter into streams (Evans et al., 2005).

Solar irradiation increase could also alter water quality and especially characteristics of natural organic matter in freshwaters systems both by warming and UVB radiation (increasing photolysis) (Soh et al., 2008). Phototransformation should be seriously taken into account when evaluating the possibility of formation of UV transformation products from organic micropollutants such as pharmaceuticals (Canonica et al., 2008). Many papers consider pharmaceuticals to be photo reactive substances (Boreen et al., 2003; Buerge et al., 2006; Petrovic and Barceló, 2007).

This paper aims at reviewing the main impacts on water quality parameters, generally described for surface water (rivers and lakes), and the expected impacts on drinking water production.

2. Impacts on water quality parametes

Water quality parameters can be classified according to i) physico-chemical basic parameters (temperature, pH, dissolved oxygen, dissolved organic matter…) and nutrients, ii) micropollutants (inorganic and organic) including metals, pesticides and pharmaceuticals, and iii) biological parameters with pathogens microorganisms, cyanobacteria and water quality proxies (Table 1).

2.1. Basic parameters

A rise in surface water temperatures was observed since the 1960s in Europe, North America and Asia (0.2–2 °C), mainly due to atmospheric warming in relation to solar radiation increase (Bates et al., 2008). In European rivers, Zwolsman and van Bokhoven (2007), and Van Vliet and Zwolsman (2008) observed an average increase in water temperature of around 2 °C respectively in Rhine and Meuse rivers after the severe drought of 2003, with a pH increase (reflecting a decrease in CO_2 concentration), and a decrease in dissolved oxygen (DO) solubility reflecting a lower DO solubility under higher water temperatures. A DO decrease can also be associated to an increase in DO assimilation of biodegradable organic matter by microorganisms (linked to an increase in Dissolved Organic Carbon (DOC)) (Prathumratana et al., 2008). In the same study dealing with the surface water quality in the lower Mekong River, negative significant correlations were generally found between precipitation (or discharge flow) and DO, pH and conductivity (from 0.2 to 0.9). In several lakes in Europe and Northern America, the stratified period has lengthened by 2–3 weeks and water temperatures have risen of 0.2 to 1.5 °C, which have an influence on thermal stratification (Komatsu et al., 2007) and lakes hydrodynamics (Bates et al., 2008). Computer models predict an increase of around 2 °C by 2070 in European lakes, although this rise will also depend on lake characteristics and season (George et al., 2007; Malmaeus et al., 2006). It has been demonstrated that shallow lakes are likely to be the most vulnerable to climate change. Water temperatures have an impact on internal lake processes like diffusion, mineralization and vertical mixing (Malmaeus et al., 2006). Residence time of lakes would probably increase in summer by 92% in 2050 for lakes with short residence times George et al. (2007). Also, it is predicted that especially shallow lakes will experience an increase of temperature in epilimnion and hypolimnion during summer (Jöhnk et al., 2008), although man-made lakes (in The Netherlands) respond even more directly to weather variations (Mooij et al., 2005). Nevertheless, deepest lakes are most sensitive to climate warming on a long period of time due to their greater heat storage capacity and will consequently show the highest winter temperatures (George et al., 2007). An increase in water temperature has also an impact on lakes chemical processes with increases in pH and greater in-lake alkalinity generation (Psenner and Schmidt, 1992). Concerning the impacts of the predicted increase in winter precipitations on lake waters, it depends on the lake size. Small lakes with short residence times will be particularly sensitive to a change in rainfalls (George et al., 2007).

2.2. Dissolved Organic Matter

Dissolved Organic Matter (DOM) affects the functioning of aquatic ecosystems through its influence on acidity, trace metal transport,

Table 1
Impacts of climate change on water quality parameters.

Water quality parameter			CC factors affecting WQ	Water body	Reference	Comments
Physico-chemicals	Basic parameters	pH	Droughts	River	Van Vliet and Zwolsman, 2008	Higher maximum values in Meuse river.
			Temperature increase	Lakes	Bates et al., 2008	Increase in pH.
			Rainfalls	River	Prathumratana et al., 2008	Negatively correlated (Mekong).
		DO	Droughts and temperature increase	Rivers and lakes	Zwolsman and van Bokhoven, 2007; Komatsu et al., 2007; Van Vliet and Zwolsman, 2008	Lower dissolved oxygen solubility and concentration.
			Rainfalls	River	Prathumratana et al., 2008	Negatively correlated (Mekong).
		Temperature	Droughts and temperature increase	Rivers	Zwolsman and van Bokhoven, 2007; Van Vliet and Zwolsman, 2008; Ducharne et al., 2007; Bates et al., 2008	Warming of the water column.
				Lakes	Jöhnk et al., 2008; Komatsu et al., 2007; Malmaeus et al., 2006; Mooij et al., 2005; George et al., 2007	Increase in the epilimnion and hypolimnion, especially in shallow lakes. Increase of temperature, stability of the water column and summer water residence times.
	DOC		Temperature and rainfalls increase	Streams and lakes (peatlands)	Monteith et al., 2007; Evans et al., 2005; Worral et al., 2004; Hejzlar et al., 2003	DOC increase (UK, Scandinavia, Czech Republic, Northeastern USA and Canada).
					Clark et al., 2008; Prathumratana et al., 2008	DOC flux increase during storm events (UK and Mekong basin).
	Nutrients		Droughts	River	Van Vliet and Zwolsman, 2008; Zwolsman and van Bokhoven 2007	Sediment release during droughts. Ammonium increase.
			Temperature increase	Surface and groundwater	Wilhelm and Adrian, 2008	Increase mineralization and release of N, C and P from soil OM.
				Lakes	Wilhelm and Adrian, 2008; Jackson et al., 2007; Malmaeus et al., 2006; Komatsu et al., 2007; Petterson et al., 2003	Sediment nutrients release and pulses into the euphotic zone. Strong changes in nutrient loading in shallow lakes. Elevated phosphate and ammonium concentrations in the hypolimnion during the warm period.
			Temperature and rainfalls increase	River basins, lake, fjord and groundwater	Kaste et al., 2006; Arheimer et al., 2005; Ducharne et al., 2007; Zhu et al., 2005; Wilby et al., 2006; Weyhenmeyer, 2008	Increase N river loading (Norway) and nitrate load (UK river and Seine groundwater). Increase N and P (Sweden) and nutrients (Canada) loading. Climate change effects could be comparable between small and large lakes.
			Heavy rainfalls	Stream and lakes	Drewry et al., 2009; Mooij et al., 2005; Prathumratana et al., 2008	Australia, Mekong basin. Increased P loading of Dutch lakes.
				Forested watershed	Bhat et al., 2007	Total Kjeldahl nitrogen (TKN) loading increase (USA).
Micropollutants	Inorganics	Metals	Droughts	River	Van Vliet and Zwolsman, 2008; Zwolsman and van Bokhoven, 2007	Selenium, Baryum, mercury, zinc, cadmium, lead and nickel increase.
			Temperature increase	High alpine lakes	Thies et al., 2007	Increasing amount of snowmelt lead to a micropollutants increase (European Alps).
			Heavy rainfalls	Streams	Rothwell et al., 2007	Correlations between DOC and metals mobilisation (UK).
			Temperature and rainfalls increase	Stream	Pédrot et al., 2008	Humic and fulvic acids mobilized various trace elements (Brittany).
					Olivie-Lauquet et al., 2001	Trace element release coincide with a decline in redox potential and increase of organic carbon content (Brittany)
	Organics	Pesticides	Temperature and rainfalls increase	Surface & groundwater	Bloomfield et al., 2006	Changes in rainfalls intensity and seasonality and increased temperatures are main climate drivers for changing pesticides fate and behaviour.
			Drying and rewetting cycles		Lennartz and Louchart, 2007	Soil drying increased the biding of herbicidal compounds.
			Rainfalls increase	Streams	Probst et al., 2005	Increased precipitations lead to an increase of pesticides flux.
		Pharmaceuticals	Temperature increase	Groundwater	Massman et al., 2006	Artificial recharge pond. Change in redox conditions (anaerobic conditions) with an increase in temperature (Deutchland).
			Rainfalls	Streams	Lissemore et al., 2006	Correlations between DOC and pharmaceuticals concentrations in water.
					Oppel et al., 2004	Clofibric acid and iopromide are very mobile and could contaminate groundwaters through rivers.
Biologicals	Pathogens		Temperature and rainfalls increase	Surface waters	Charron et al., 2004; Curriero et al., 2001	Half the waterborne disease outbreaks in USA during the last half century followed a period of extreme rainfall.
					Hunter, 2003; Pednekar et al., 2005	Nearly 70% of the variability in the coliform record is due to seasonal and interannual variability in local rainfall.
	Cyanobacteria		Temperature and rainfalls increase	Lakes	Arheimer et al., 2005; Jöhnk et al., 2008; Hunter, 2003	Summer heatwaves boost the development of Cyanobacteria blooms (Nederlands and Sweden).
	Cyanotoxins		Temperature increase	Lakes	Brient et al., 2008; Wiedner et al., 2007	Cylindrospermopsis Raciborskii northern spread. Microcystin blooms during hot summers.
	Fishes, green algae, diatoms		Temperature increase	Freshwaters	Daufresne et al., 2003; Daufresne and Boët, 2007	Pollutants uptake rate increase due to an increased metabolic rate and decrease in oxygen solubility. Species predominance and abundance changes.
	Others		Temperature increase	Soils	Sardans et al., 2008	Increase enzymatic activity.

light absorbance and photochemistry and, energy and nutrient supply (Evans et al., 2005). The principal source of DOM in surface waters is soil leaching (Hejzlar et al., 2003). Furthermore, positive spatial relationships between Dissolved Organic Carbon (DOC) export and wetland areas like peatlands have been demonstrated (Evans et al., 2005). Since the 1980s, various studies have shown significant DOC increases in Northern Europe (Evans et al., 2005; Monteith et al., 2007; Worrall et al., 2004), Central Europe (Hejzlar et al., 2003) and Northern America (Monteith et al., 2007). Many potential factors (air temperature, increase in rainfalls intensity, atmospheric CO_2 increase and decline in acid deposition) have been proposed to explain these trends in DOC, although there is no scientific consensus. Evans et al. (2005) have shown that recovery from acidification and water temperature are potential drivers, since many compounds forming part of DOC are acidic. In fact, a decrease in acid deposition is observed resulting partly from a decrease in anthropogenic sulphur emissions (industries, passengers/goods transportation…) (Monteith et al., 2007; Evans et al., 2008). This could lead to an increase in soil pH and consequently to an organic acids increase permitted by new redox conditions. Nevertheless, trends in DOC are probably resulting from a combination of various factors, including acid deposition, since increasing trends have begun in a few places before reduction in acid deposition (Worrall and Burt, 2007).

According to Clark et al. (2008), a variation in stream flow can be a good indicator of changes in DOC concentration in streams draining organo-minerals soils, although the same is false for peat soils (in this case, temperature is better). Finally, Prathumratana et al. (2008) shows that COD (Chemical Oxygen Demand), used as an indicator of Natural Organic Matter (NOM), have weak to fair significant correlations with precipitations and discharge flows for the Mekong River (from 0.3 to 0.4).

Finally, Prathumratana et al. (2008) shows that COD (Chemical Oxygen Demand), used as an indicator of Natural Organic Matter (NOM), have weak to fair correlations with precipitations (0.295–0.426) and discharge flows (0.312–0.324).

2.3. Nutrients

An increase of N mineralization in soil due to an increase in mean soil temperature is expected (Ducharne et al., 2007). Moreover, droughts increase the soil extractible Total Organic Carbon (TOC) concentration in winter and warming increases extractible nitrate in summer and autumn and extractible ammonium in winter. A moderate increase in soil temperature (spring, summer and winter) could lead to a large increase in enzymatic activity. Temperature is positively correlated with nitrification process (increasing phosphatases activity and P mobilisation in soils). Changes observed in enzymatic activity are linked with direct effect of soils warming which stimulates biological activity and increases N availability (Sardans et al., 2008). Soil warming increases soil extractable nitrates concentration in summer and autumn (N losses facilitated) and concentration of extractable ammonium in winter.

Water bodies quality is subjected to weather seasonality which has an important impact on their nutrient patterns (Zhu et al., 2005). A warmer climate will create indirect impacts on water bodies like an increase nutrients load in surface and groundwater (Van Vliet and Zwolsman, 2008) and counteract policies effects of external nutrient loading reduction (Wilhelm and Adrian, 2008). Indeed, higher temperatures will increase mineralization and releases of nitrogen, phosphorus and carbon from soil organic matter. Moreover, an increase in runoff and erosion due to greater precipitations intensity should result in an increase in pollutants transport, especially after a drought period. Higher ammonium concentrations could be observed in rivers with a reducing dilution capacity caused by droughts (Zwolsman and van Bokhoven, 2007; Van Vliet and Zwolsman, 2008). Furthermore, release of phosphorus from bottom sediments in stratified lakes is expected to increase, due to declining oxygen concentrations in the bottom waters (Wilhelm and Adrian, 2008).

Regional and global climate scenarios and models are useful tools to produce data inputs for hydrological models in order to understand and predict the potential effects of climate change on water bodies. An increase in dry summertime frequency may lead to gradually mobilize nitrogen in soils that would be flushed into streams at the beginning of the wet season and cause higher rivers nitrate concentrations (Wilby et al., 2006). Ducharne et al. (2007) predict an increase in nitrate concentration in the Seine basin aquifer layers for the years 2050 and 2100 due to an increase in precipitations and consequently in soil leaching. Kaste et al. (2006) and Arheimer et al. (2005) respectively predict a 40–50% increase in nitrate flux by 2070–2100 in a Norwegian river basin, and an increase in phosphorus (50%) and nitrogen (20%) in a lake. Correlations between precipitations, air temperature, discharge flow and phosphates, nitrates and Total Phosphorus (TP) in the Mekong River have also been observed (Prathumratana et al., 2008). These results are in accordance with Bhat et al. (2007) who found that 73% of the total Kjeldhal nitrogen load at a forested watershed outlet was exported by surface runoff during storm events. Drewry et al. (2009) also found positive correlations between TP, total nitrogen, suspended solids and flow. It was also suggested that a major part of the phosphorus is adsorbed onto suspended solids.

For lakes, higher phosphate and ammonium concentrations in the hypolimnion are frequently observed during the warm period in temperate countries (Petterson et al., 2003). Climate change impact these ecosystems with various manners: changes in temperature, ice-cover, wind and precipitation (Mooij et al., 2005). P loading exportation, which is governed by discharges following heavy rain falls, will tend to increase with climate change and consequently have an impact on lakes (Mooij et al., 2005). Conversely, streams nitrogen concentrations are less dependent on stream discharge (Mooij et al., 2005). Increasing temperatures is supposed to decrease nitrate concentrations in lakes with an increase in denitrification rate and higher N losses in upstream-situated soil and surface waters (Mooij et al., 2005). On the contrary, the internal P loading increases thanks to microbial decomposition of lake sediments (Jackson et al., 2007). Accumulation of soluble hypolimnetic phosphorus depends on thermocline depth and hypolimnetic temperatures (Wilhelm and Adrian, 2008). Indeed, higher hypolimnetic temperatures increase both mineralization of organic hypolimnetic matter and phosphorus release from sediments. Dramatic nutrient pulses into the euphotic zone could be observed after heatwaves (Wilhelm and Adrian, 2008). Hence, alternating mixing and long stratification events threat more especially polymictic lakes than dimictic lakes (Wilhelm and Adrian, 2008). P increases in the surface layer, fueling phytoplankton growth (Jackson et al., 2007), leading to algal blooms and a deterioration of water quality (Komatsu et al., 2007). Lastly, concerning Total Phosporous (TP) concentrations, higher temperatures may impact mainly lakes with long residence times (Malmaeus et al., 2006), even though rates of change of phosphate and nitrates concentrations seem to be independent of lake morphometry (Weyhenmeyer, 2008).

2.4. Inorganics micropollutants

In Western Europe, metal concentrations in rivers have greatly decreased in the past decades with industrial and urban wastewater treatment efforts. Nevertheless, droughts may have impacts on river water quality (Zwolsman and van Bokhoven, 2007; Van Vliet and Zwolsman, 2008), depending on the compound properties that could be as well either negative or positive. First of all, significantly higher concentrations for barium, selenium and nickel were observed in river Meuse during the drought of 2003 (Van Vliet and Zwolsman, 2008). Conversely, significantly lower concentrations of total lead, chromium, mercury and cadmium were measured within the same period. These differences are mainly due to dissimilarities between adsorption capacities by suspended solids but discrepancies exist between studies. Indeed, in the Rhine river, it was observed that droughts have a negative impact on metal concentrations of cadmium, chromium, mercury, lead, copper, nickel and zinc which were higher during the 2003 drought than during reference periods (Zwolsman and van Bokhoven, 2007).

Thies et al. (2007) have studied high alpine lake waters (Alps) response to climate warming and observed a solute release from an active rock glacier ice. Surface waters over metamorphic rocks were affected by the rising export of ions and heavy metals from meltwater. They predicted that high mountain freshwater will thus become increasingly affected by climate warming.

Furthermore, a strong complexation of some metals by DOC could lead to a transport of dissolved lead, titane and vanadium in peatland systems after a stormflow (Rothwell et al., 2007). A seasonal change in dissolved metal concentrations was also observed for various trace elements (Fe, Mn, Al, La, U, Th, Cd and As). An increase of organic carbon content and a decline in redox conditions seem to be related with a trace elements release. A positive correlation is also found between storm events and trace element concentrations in streams (Olivie-Lauquet et al., 2001). In fact, organic and inorganic colloids could play an important role in trace elements mobilisation in soils and water (Pédrot et al., 2008).

2.5. Organics micropollutants

Surface waters are the main receptors for pesticides contamination from the agricultural use. Bloomfield et al. (2006) observed that changes in rainfall seasonality and intensity and increased air temperatures are the main climate drivers for changing pesticides fate and behaviour, although effects of climate change are likely to be variable and difficult to predict.

Lennartz and Louchart (2007) has studied the physico-chemical interactions between soil organic matter and herbicidal compounds (diuron and terbuthylazine) after drying and rewetting cycles to examine impacts of climate induced soil water status variations. Results show that variations in soil water contents modify the soil organic matter structure, which hinder diffusion and trap pesticides. An increase in extreme events with climate change will probably counteract pesticides reduction measures. Probst et al. (2005) simulate pesticides entries into streams and found, with a heavy rainfalls scenario (precipitation increase from 10 to 20 mm/day), that isoproturon and bifenox could potentially present a greater risk due to their ecotoxicity.

For pharmaceuticals, in a Southern Ontario watershed, Lissemore et al. (2006) found significant correlations between DOC and some active substances frequently detected in water (monensin and carbamazepine), with concentration variations of monensin, lincomycin, sulfamethazine, trimethoprim and carbamazepine depending on flow rate and precipitation amount. Furthermore, clofibric acid and iopromide are found to have an important leaching potential which could represent a long term risk for groundwater contamination from river water through sediment and subsoil (Oppel et al., 2004), especially in case of heavy rainfalls events.

2.6. Pathogens

Waterborne pathogens could be spread within the freshwater after a contamination by animal or human waste due to heavy rainfall discharge in combined sewer systems (CSS). When the flow exceeds the CSS capacity, the sewers overflow directly into surface water body (Charron et al., 2004). Pednekar et al. (2005) have studied coliform load in a tidal embayment and shown that stormwater coming from the surrounding watershed is a primary source of coliform. Moreover, higher water temperatures will probably lead to a pathogen survival increase in the environment, although there is still no clear evidence (Hunter, 2003).

Floods often led to a contamination of groundwater and additional disease outbreaks like *Acanthamoeba keratitis* in Iowa (USA) in 1994 (Hunter, 2003). According to Curriero et al. (2001), half of the waterborne disease outbreaks in the US during the last half century followed a period of extreme rainfall. Even though the risk of diseases outbreaks linked to mains drinking waters is low in developed countries, private supplies would be at risk (Hunter, 2003). In addition, an increase in temperature threats water quality with regard to waterborne diseases especially cholera disease in Asia and South America (Hunter, 2003). Lastly, it was shown that with increased UV radiation due to ozone layer depletion, NOM trap higher levels of UV energy and breaks down to more bioavailable organic compounds, minerals and micronutrients. All these processes could stimulate bacterial activity in aquatic ecosystems (Soh et al., 2008).

2.7. Cyanobacteria and cyanotoxins

Competition between phytoplankton and cyanobacteria could be switch in favor of cyanobacteria in a warmer climate (Arheimer et al., 2005) and could also increase their dominance. A higher phosphorus flux in the epilimnion can promote phytoplankton growth in the euphotic layer and lead to an evolution from a macrophyte-dominated clear water state to a phytoplankton-dominated turbid state. Increase in water temperatures and nutrient concentration causes massive cyanobacteria bloom in many waterbodies (Hunter, 2003). Summer heatwaves could also boost the cyanobacteria development in lakes through reducing vertical turbulent mixing and increasing growth rates (Jöhnk et al., 2008). Moreover, new cyanobacterium species as *Cylindrospermopsis raciborskii* have colonized northern habitats due to effects of rising temperatures. This tropical cyanobacterium, known to produce Cylindrospermopsin, is now detected in South and Western Europe freshwaters (Italy, Spain and France) (Brient et al., 2008) and has been detected in German lakes (Wiedner et al., 2007). Moreover, an earlier annual warming in temperate countries permits an earlier and more important growth of this alga (Wiedner et al., 2007). Lastly, other cyanobacteria, like *Microcystis* which can produce microcystin, could become invasive with climate warming (Jöhnk et al., 2008).

2.8. Water quality indicators

Fishes, green algae and diatoms are often used as water quality indicators. Daufresne and Boët (2007) observed an increase related to global warming in total abundance and in proportions of warm-water species and size-structures changes in fish communities in French rivers. Southern thermophilic fish species progressively replaced northern cold water species in the upper Rhône River (Daufresne et al., 2003). Furthermore, high temperature and low turbulent diffusivities in lakes could suppress the population abundances of green algae and diatoms (Jöhnk et al., 2008). High temperatures seem to favor the cyanotoxins dominance, as *Microcystis*, over diatoms and green algae (Jöhnk et al., 2008).

2.9. Synthesis

The climate change impacts on surface water quality can be summarized in Fig. 1, which consider the effects (droughts and floods) of the two main factors (temperature and rainfalls). These impacts depend on natural or man built environment, and the consequences can be different according to water body type (rivers, lakes, dams, ponds, wetlands...) and characteristics (water residence times, size, shape, depth…). For streams, the main parameters affected are DOM and nutrients meanwhile pathogens and cyanobacteria/cyanotoxins are more related to lakes. In between, micropollutants, inorganic or organic are also frequently affected.

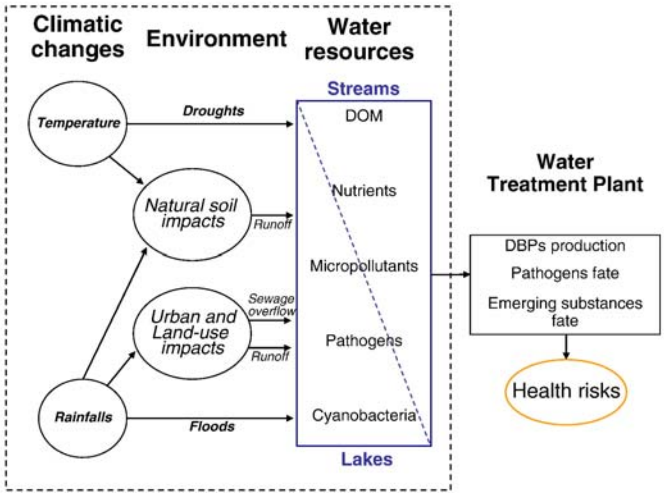

Fig. 1. Impacts of climate change on water resources and drinking water quality.

3. Expected impacts on drinking water production

Research undertaken in the 1970s, indicated the presence of disinfection by-products (DBPs) in drinking water (Rook, 1974; Symons et al., 1975). Special attention was given to the concentration of trihalomethanes (THMs) because of their potential carcinogenic effects (Singer, 1993). The study on the occurrence of DBPs in drinking water distribution systems has increased in the recent years, focusing firstly on natural organic matter transformation. Concerning emerging DBPs linked to pharmaceuticals and new pesticides, very few studies have been published in order to understand their formation and fate during water treatment. For pharmaceutical by-products, most of studies are limited to parent's pharmaceutical products (PPs) (Fent et al., 2006; Mompelat et al., 2009).

This part aims at reviewing the main known determinants on DBPs formation under usual water treatment conditions. Then we consider the expected impacts of climate change on these parameters and the degradation of drinking water quality. Lastly, we present some further monitoring needs for a better knowledge.

3.1. DBPs determinants

Several factors such as temperature, dissolved organic carbon (DOC), pH, bromide concentrations, and operational factors or chlorine doses and contact time were reported to significantly affect the formation of DBPs (Nikolaou et al., 2004; Teksoy et al., 2008). Temperature and organic matter matrix, influenced by climate change, are considered hereafter.

Concerning the influence of the water temperature on the DBPs formation, the general trend shows that for natural surface water temperatures (5–30 °C), increased temperatures promote the DBPs formation rate. Some studies (Rodriguez and Serodes, 2001) showed that THM concentrations vary significantly (from 1.5 to 2 times, depending on the utility) between drinking water plant and tap (the most distant). When water temperature exceeds 15 °C, spatial THM variations are particularly high (from 2 to 4 times, depending on the utility). In the same way, others authors reported that increasing temperature (10–33 °C) generally increased the formation of bromoorganic DBPs (Zhang et al., 2005). However, this general trend should be moderated for certain unstable DBPs. Indeed, Yang et al. (2007) studied the formation of DBPs after 3 days of chloramination with monochloramine (NH_2Cl) at three temperatures (10 °C, 20 °C and 30 °C). They showed that chloroform formation increases with temperature from 10 to 30 °C. However, for more unstable DBPs as dichloroacetonitrile (DCAN) and 1,1-dichloro-2-propane (1,1-DCP), this general trend should be moderated, since their decomposition could increase with temperature.

In terms of water quality, it has been established that fulvic and humic constituents of organic matter constitute important precursors for THMs (Christman et al., 1990). Total organic carbon (TOC), as well as UV absorbance, have been used as indicators of the presence of organic matter in drinking water (Thomas, 2007). Some authors pointed out that the minimum effective alum dose shows a strong stoichiometric relationship with DOC concentrations in model waters (Shin et al., 2008). Moreover, several studies have mentioned that dissolved organic carbon (DOC) concentration in alum or iron treated water was directly related to the THM formation potential (van Leeuwen et al., 2005; Uyak and Toroz, 2007). Some research projects based on laboratory bench-scale and field data have shown that the higher values are for these parameters, the higher the concentrations of THMs formed (Rodriguez et al., 2000; Golfinopoulos et al., 1998; Garcia-Villanova et al., 1997; Montgomery, 1993). For DBPs formation, the determinant factor could be the aromatic part or hydrophobic fraction of NOM and molecular weight distribution (Randtke and Jepsen, 1981; Bose and Reckhow, 1998; Croue et al., 1999; Singer, 1999). Moreover, some studies have already showed that for waters that are not governed by sweep flocculation, coagulant doses are determined by the concentrations of both NOM and particles, silica being the dominant factor for coagulant demand at high particle concentrations (>100 mg/L) (Shin et al., 2008). Consequently, mineral-bound humic substances increase the intrinsic complexation properties of mineral substances for organic and inorganic pollutants (Murphy and Zachara, 1995) and directly impact on DBPs formation potential.

3.2. Potential impacts

Concerning climate change issues on DBPs formation, past investigations have already observed that the occurrence of THMs in chlorinated water may vary significantly according to season and geographical location in the distribution system (Williams et al., 1997; Garcia-Villanova et al., 1997; Arora et al., 1997; Singer et al., 1995; Clark, 1994). These temporal and spatial variations are due to changes in raw and treated water quality as well as in operational parameters (pH, chlorine dose, contact time…) related to chlorination.

Rainstorm events lead to elevated levels of turbidity and organic matter found in river waters which cause deterioration in treatment performance. However, it has been shown that this effect is not uniform. This could be due to a combination of lower water temperatures and a change in the nature and increased concentrations of NOM in the natural water (Hurst et al., 2004). This could also explain why these authors observed that seasonal differences have a significant impact on process robustness, independent of the raw water turbidity. Rodriguez and Serodes (2001) showed that when water temperature is lower than 15 °C, THMs in treated water will not be higher than initial THM concentration, even if these ones are high (60 µg/L). The latter situation may be typical in spring or fall, when the organic content of raw water and treated water tends to increase following rain or field runoff. For typical summer water temperatures (>18 °C), the THM concentration within the system treatment may rise from 2 to 4 times, depending on the utility (Rodriguez and Serodes, 2001).

DOC nature and concentration are not the only parameters which drastically change during rainstorm events and the biological compartment contribution should be taken into account too. Chen and Zhang (2008) globally showed that algae contributed much more to the HAA (haloacetic acids) formation than the THM during the summer and autumn blooms. During these special events, when the algal concentration is 20–80 million per liter, the DBP precursors originating from algae would account for about 20% to 50% of the total formation potential.

Variations of temperature, pH and aqueous composition occurring during climate change could also have an influence for contaminants on their sorption on mineral phases. When assessing the leaching behaviour of anthropogenic compounds, the influence of the properties of soils has to be taken into account (Oppel et al., 2004; Yu et al., 2009). Moreover, especially during rainfall events, mineral particles leaching could lead to high concentrations in natural waters, having a direct impact on coagulant demand during water treatment as seen before (Shin et al., 2008) and on DBPs formation.

Concerning the occurrence and fate of micropollutants with respect to drinking water treatment, the main (recent) studies are related to pharmaceuticals. Actually, studies on pharmaceuticals are principally linked to wastewater treatment, the efficiency of which may affect the quality of water resources downstream a treated effluent discharge. Even if they are partially removed, residual quantities may remain in treated water, and have been found in drinking (tap) water (Al-Ahmad et al., 1999; Hernando et al., 2006). The efficiency of pharmaceuticals removal varies with treatment processes and also with temperature and weather (Choi et al., 2008). For instance, diclofenac showed largely different elimination rates between 17% (Heberer et al., 2002), 69% (Ternes et al., 1998), and 100% (Thomas and Foster, 2004) depending on these two last parameters. Finally, for pesticides elimination in conventional physi-cochemical drinking water treatment processes, such as flocculation, sedimentation, filtration, or lime softening, only certain lipophilic substances are removed adequately (Baldauf, 2006).

Natural micropollutants, mainly represented by cyanotoxins may also have a huge impact on drinking water treatment. Chlorination, micro-/ultrafiltration and especially ozonation are the most effective water treatment procedures in destroying cyanobacteria and in removing microcystins (Hitzfeld et al., 2000). During cyanobacterial bloom events, ozonation may be an appropriate process to eliminate peptide toxins like microcystin-LA and-LR (Rositano et al., 1998, 2001; Brooke et al., 2006). Lots of studies concerning removal of cyanobacterial toxins from water showed that the effectiveness of the oxidation process is not only dependant on the reactant concentration, but also on temperature, pH, ionic composition (Rositano et al., 1998; Shawwa and Smith, 2001) and NOM concentration (Al Momani et al., 2008). Although very few studies reported the relationship between algae and DBPs precursors, some authors pointed out the algal contribution to some DPBs formation (Chen and Zhang, 2008). Some studies tried to improve new by-products identification for cyanotoxins (Rodriguez et al., 2007; Merel et al., 2009). However, DBPs formation has largely not been investigated.

3.3. Monitoring and modeling of impacts

Face to the previous expected impacts on the degradation of (drinking) water quality, several monitoring tools are proposed.

The first way is to incorporate on-line TOC (or DOC) measurements into coagulation control algorithm for pH control and coagulant dose to prevent uncontrolled variation especially during storm/raining events (Hurst et al., 2004). In the same area, the development of field monitoring procedures or system may be useful for improving DOM knowledge in order to evaluate bulk properties mainly influencing disinfection by products formation such as biological activities (algal contribution, photosynthetic evolution…) or molecular polarity. Fluorescence analysis could help in the assessment of DOM sources by spectral signatures related to waters affected by microbial activity, either by wastewater influence or by autochthonous processes and could correlate some of these data with DOC for instance (Parlanti et al., 2000; Jung et al., 2005; Rosario-Ortiz et al., 2007).

Another solution is the prediction of the occurrence or fate of some physico-chemical parameters through modeling. Uyak and Toroz (2007) have proposed a model for the concentration estimation of THM and HAA in chlorinated raw water of surface water supplies for instance. Other models have already been developed that relate coagulant dose to the concentration and character of organics present in natural waters. These models enable prediction of inorganic coagulant doses that maximize removal of organics at a particular coagulation pH (van Leeuwen et al., 2005). As we have seen before, model development studies taking into account temperature should be continued. The complexity of DBP formation reactions makes it difficult to develop universally applicable models. This research field should however be considered with special attention for the future.

A last point to consider is the analytical development for emerging substances and by-products. Concerning pharmaceuticals and pesticides, there is a real need for identification and toxicity assessment on the degradation byproducts formed during water treatment. The removal of pharmaceuticals and other polar micro-pollutants can only be assured using advanced techniques such as ozonation, activated carbon or membrane filtration (Ternes et al., 2002) or eventually UV treatment (Canonica et al., 2008). However, developing only the best available treatment techniques to remove these substances without taking into account DBPs formation is not the actual challenge. Comparison on emerging substances consumption (such as pharmaceuticals) and occurrence in water based on a reference methodology, health and ecotoxicological risk assessments should be developed in parallel with analytical methods permitting identification and quantification of by-products.

3.4. Synthesis

The climate change impacts on drinking water treatment issues can be summarized in Fig. 2. Remind that climate change may cause at the resource level (surface water), huge hydrologic variations, water temperature rise and increases of pollution load (chemical and microbiological). For treatment plants, considering that all remediation actions have been made (pollution source reduction, run off limitation, fertilizers and pesticides reduction management, etc.), adaptation measures must be envisaged for a better efficiency, particularly with regards to extreme events (heavy rainfalls and droughts). These measures integrate complementary treatment steps and process control even for small water supply systems. Moreover, water quality monitoring with analysis of micropollutants among which emerging substances and treatment by products must be carry out, as well as health risk assessment (following the water safety plan procedure). Obviously, in case of severe floods, transportation of bottles or tanks may be the only solution for safe drinking water supply.

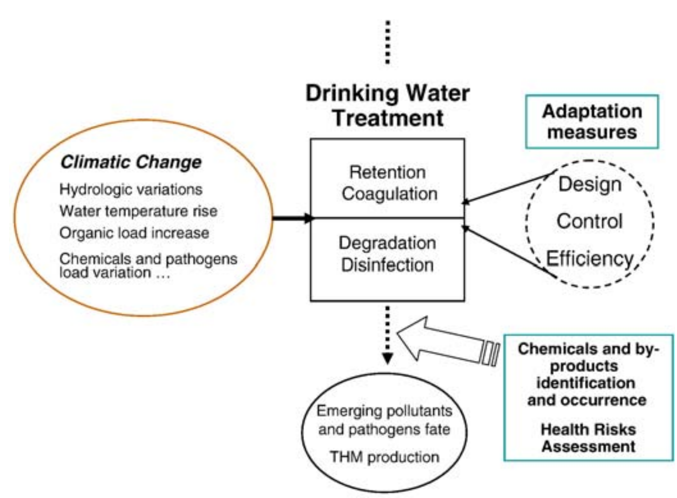

Fig. 2. Climate change impacts and drinking water treatment issues.

4. Conclusion

The main outcome of this literature review on climate change impact on surface water quality (from resources to tap) is that there is a degradation trend of drinking water quality leading to an increase of at risk situations with regard to potential health impact, mainly during extreme meteorological events. Among water quality parameters, dissolved organic matter, micropollutants and pathogens are susceptible to rise in concentration or number as a consequence of temperature increase (water, air and soil) and heavy rain falls in temperate countries.

Another conclusion is the lack of information on micropollutants occurrence and fate with regard to climate change impacts and treatment efficiency, including potentially association and transportation with natural organic matter. Disinfection by products of micropollutants not removed during treatment and of residues must be identified and their toxicity assessed. Last conclusion concerns water borne diseases potentially highly linked to climate change impacts but still rarely studied at least for temperate countries. Finally, there is a huge need for water quality monitoring and predictive tools as models and decision support systems mainly with the aim of health risks assessment and remediation and adaptation actions.

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