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# Potential Impacts of Climate Change on the Water Quality of Different Water Bodies

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**ABSTRACT.** Climate change will affect water quality and even water ecosystems, and specific effects will vary among different regions and different types of water bodies. Here we review the observed and predicted effects of climate change on different water bodies, including plain lakes, alpine lakes, rivers, costal lagoons, and estuaries, and provide a global perspective for these effects. First, the impacts of extreme weather events on the water quality are summarized. Then the influences of long-term climate change on the water quality of different water bodies are discussed, and how changes in climatic factors affect the water quality directly and indirectly by influencing the sources, migration and transformation, biochemical reactions, and ecological effects of pollutants. Furthermore, the methods used to determine the effects of climate change on the water quality, including model simulations, laboratory and mesocosm experiments, and long-term bioindicator monitoring, are subsequently addressed. Based on an analysis of the existing research advances, the related knowledge gaps are analyzed, and directions for further research on the impacts of climate change on water quality are put forward.

*Keywords:* climate change, eutrophication, salinization, aquatic species, water quality

## 1. Introduction

The global surface temperature has increased by 0.74°C during the past 100 years (1906 ~ 2005) according to the International Panel for Climate Change (IPCC) report (Rosenzweig et al., 2007). Therefore, global warming is currently an indisputable fact, and the average rate of warming over the last 50 years (0.13 ± 0.03 °C per decade) is nearly twofold higher than that observed over the last 100 years (Trenberth et al., 2007). A large number of changes in climate have been observed on both global and local scales, including long-term changes in the surface temperature, precipitation, wind patterns, radiation, and other extreme weather events, such as droughts, floods, and heat waves (Trenberth et al., 2007; Joehnk et al., 2008; Jones et al., 2010). The impact of climate change on water resources has been a widely discussed topic among scientists and the governments of all countries. The possible impacts of climate change on water resources have been widely reported. Despite progress in water quantity, research on the impact of climate change on the water quality started only recently. The Fourth Assessment Report (AR4) of the IPCC summarized that the trends of climate change in the 20th century would have adverse effects on the water quality, but the report did not provide details on how climate change would exert these impacts on the water quality (Rosenzweig et al., 2007).

Climate change can alter the water quality and even water ecosystems directly or indirectly through various biochemical processes (Dalla et al., 2007; Delpla et al., 2009). Furthermore, the specific effects will vary among different regions and types of water bodies (Whitehead et al., 2009). The knowledge of the different hydrodynamics and biochemical processes that occur in different waters is the key to understanding the relationship between climate change and water quality in different water bodies (Mooij et al., 2005; Delpla et al., 2009; Mooij et al., 2009).

This paper provides a review of the observed and the predicted impacts of climate change on the water quality in different water bodies and provides an international perspective of these impacts. First, a brief review of the effects of extreme weather events on the water quality is introduced. Then, the changes in the water quality of different water bodies subjected to long-term climate change are illustrated in detail, and our research results on the water quality changes in the Yellow River as a result of climate change are also addressed. The influence routes and mechanisms through which climate change affects the water quality are then summarized, and the methods used to quantify these effects are also discussed.

## 2. Effects of Extreme Weather Events on Water Quality

Extreme weather events including typhoons, storms, and temperature jumps mainly result in water events, such as floods

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and droughts, which may further affect the water quantity and quality (Hejzlar et al., 2003; Tate et al, 2004; VanVliet et al., 2008; Forbes et al., 2011). Some studies have reported the impacts of droughts on the water quality (Caruso, 2002; Evans et al., 2005; Ducharne et al., 2007; Monteith et al., 2007), which mainly include increased pollutant concentrations, enhanced nitrogen mineralization, and delayed recovery from acidification. During the drought period, lower flows can weaken the dilution effects of some pollutants (Zwolsman et al., 2007; Elsdon et al., 2009). For example, Van Vliet et al. (2008) assessed the impact of droughts occurring in 1976 and 2003 on the water quality of Meuse River in western Europe, and the results showed that, compared with reference years, the concentrations of chlorophyll a increased by 72.8% in 1976 and by 167% in 2003 due to decreases in the dilution effect and that the concentrations of nutrients and major elements also increased during the drought periods. Furthermore, Gómez et al. (2012) studied the effects of drying on the sediment nitrogen content in the Chicamo stream of southern Spain using a microcosms experiment and found that sediment desiccation could enhance the net nitrogen mineralization and the net nitrification and that the stream nitrogen availability after the rewetting of dried sediments depended on the duration of the desiccation period. In addition, droughts may influence the surface water recovery from acidification. Lower water tables induced by droughts have been found to promote the oxidation of previously stored sulfur compounds in Plastic Lake of Canada, and re-wetting led to the subsequent efflux of sulfate ($SO_4^{2-}$), which delayed the recovery of surface waters from acidification (Eimers et al., 2004). According to the study performed by Aherne et al. (2006) on Plastic Lake, the results simulated using MAGIC (Model of Acidification of Groundwater and Catchment) clearly demonstrated that, compared with base scenarios, the acid neutralizing capacity (ANC) would exhibit a 76.1% decrease by 2080 under variable climate scenarios.

Most studies on flood focus on the evaluation of the water flows, but only a few have investigated the impacts of floods on the water quality likely due to the difficulty in collecting data for the analysis of water quality. However, a flood event may have a significantly greater impact on the water quality than a drought. Hrdinka et al. (2012) recently reported the impacts of the 2006 flood and the 2003 drought on the water quality at the Bechyně (Lužnice River) and Varvažov (Skalice River) stations in central Bohemia, Czech Republic. Their results indicated that both the flood and the drought significantly affected the water quality compared with the reference conditions and that the flood event had significantly greater impact on the water quality than the drought even short term. During the flood, the concentrations of metals, specific organic compounds, fecal coliform bacteria, and nitrates were observed to increase by 1,760, 1,410, 146, and 121%, respectively. Hrdinka et al. deduced that these phenomena were mainly explained by high concentrations of suspended solids originating from vast alluvial washouts. In general, floods can lead to a redistribution of pollutants between contaminated sediments and soils that have not been contaminated (Hilscherova et al., 2007). In addition, the soil erosion induced by floods introduces a large number of nutrients, pathogens, and toxins into water environment (Cheng et al., 2007; Polyakov and Fares, 2007; Ficklin et al., 2009). Wallace et al. (2009) studied the sediment and nutrient concentrations in flood waters during 13 floods that occurred between 2006 and 2008 in the Tully-Murray floodplain, Australia, and found that the water discharge during floods made a large contribution (30 ~ 50%) to the marine sediment and nutrient loads.

To date, most studies on the impacts of extreme weather events on water quality focus on two aspects: the effect of droughts on the concentration of pollutants and the scouring effect of floods on the surface pollutants. Because droughts and floods alter the water environment conditions, such as the sediment and water conditions, which will further affect the migration and transformation of pollutants, future studies should consider the effect of droughts and floods on the behavior and eco-environmental effect of pollutants.

## 3. Effects of Long-term Climate Change on Different Water Bodies

### 3.1. Plain Lakes and Reservoirs

Most studies on the impacts of climate change on plain lakes and reservoirs have concentrated on nutrient release, the growth of aquatic plants, eutrophication, and salinization. In deep lakes and reservoirs, the increase in the water temperature induced by climate change may expand the thermal stratification period and deepen the thermocline and further change the hydrodynamics of the water system (Kaste et al., 2006; Wilby et al., 2006; Hammond and Pryce, 2007; Jackson et al., 2007; Brooks et al., 2011). It has been observed that the stratified period has been increased by up to 20 days and lengthened by 2 ~ 3 weeks in some lakes in Europe and Northern America since the 1960s (Rosenzweig et al., 2007; Delpla et al., 2009). Recent studies have found that the exchange of bottom water and surface water has been hindered due to thermal stratification. This effect on the water exchange has led to a decrease in the dissolved oxygen concentration and excessive carbon dioxide in the bottom water, which results in the easy formation of a reductive environment (Jiang et al., 2008; Kock Rasmussen et al., 2009). In addition, the release of nutrients and other pollutants from the sediments due to bottom water hypoxia has been observed by some scientists (Carvalho and Kirika, 2003; Han et al., 2009; Beutel, 2006; Wang et al., 2008; Wilhelm and Adrian, 2008 Mihaljevi; Gantzer et al., 2009). As shown in Figure 1, a recent study on the Shimajigawa reservoir located in western Japan indicated that, compared with the base period of 1991 to 2001, the temperature would have increased by 3.8 °C in 2091 ~ 2100 under the A2 scenario. In addition, the anaerobic layer would deepen by 6.6 m and promote an upward flux of phosphorus released from sediments, which will lead to an increase in the PO4 concentration from 1.7 to 5.6 μg/L in the surface water and an increase in the chlorophyll a concentration from 7.8 to 16.5 μg/L (Komastu et al., 2007).

As primary producers, aquatic plants are of great significance to the maintenance of an ecological balance and water quality (Mihaljević and Stević, 2011; Søndergaard et al., 2011), and the growth of aquatic plants under climate change is another focus of research. Some studies have indicated that an earlier annual warming in temperate areas permits an earlier growth of algae (Joehnk et al., 2008; Xu et al., 2010). The study performed by Wiedner et al. (2007) on the growth of cyanobacterium in North German lakes showed that the rates of the population net increase of C. raciborskii, which is an invasive freshwater cyanobacterium, were mediated by temperature and that the population size would exhibit a twofold increase if the population onset was moved forward by 30 days.

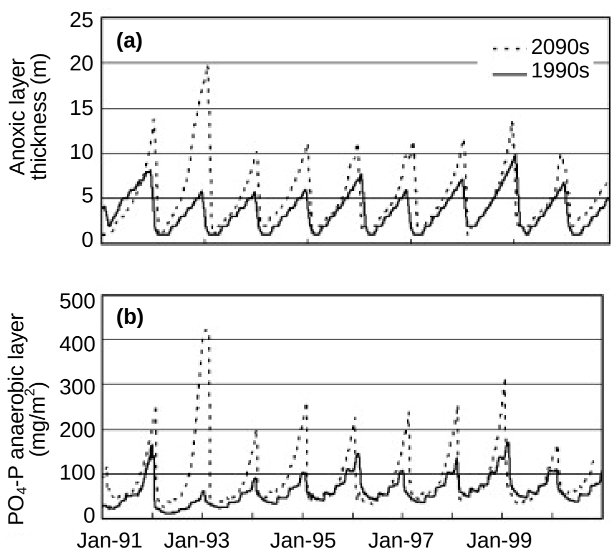


**Figure 1**. (a) Predicted thickness of the anoxic layers from 1991 to 2000 and 2091 to 2100; (b) Predicted amounts of $PO_4$-P in the anoxic layer from 1991 to 2000 and 2091 to 2100 (Source: Komatsu et al., 2007).

Furthermore, some studies have reported that climate change would facilitate the growth of phytoplankton in water environments. Trolle et al. (2011) predicted the effects of climate change on the trophic status of Lake Rotoehu in New Zealand by 2100 under the IPCC A2 scenario through the application of a one-dimensional lake ecosystem model. The simulation results demonstrated that cyanophytes would be more abundant in the future climate and would exhibit an increase of more than 15% in their contribution to the annual mean of chlorophyll a. Moreover, Cleuvers and Ratte (2002) and Lloret et al. (2008) found that an increase in the growth of phytoplankton due to climate change would weaken the light intensity in bottom water and further reduce the species and the amounts of submerged macrophytes. Furthermore, studies performed by Ren et al. (2006) and O'Farrell et al. (2011) have indicated that submerged macrophytes play an important role in the interception and the detaining of the nitrogen and phosphorus released from sediments; thus, a reduction in the submerged macrophytes would promote the growth of phytoplankton. However, a high density of submerged macrophytes has a significant influence on the facilitation of a reductive environment. Boros et al. (2011) analyzed the redox potential in a simulated shallow lake ecosystem and found that the mean redox potential was 133 ± 34 mV with a high density of submerged macrophytes and 218 ± 34 mV with a high density of phytoplankton and a low density of submerged macrophytes.

Mineralization and salinization are considered as other impacts of climate change on lake water quality, and these impacts may further affect aquatic ecosystems and the drinking water security. In general, an increase in the temperature and a decrease in the precipitation will promote the mineralization and salinization of lakes. According to the results obtained by Liu et al. (2004), who studied the Hei River Basin, an increase in the temperature and a decrease in the runoff have been the major reasons for the mineralization of lakes since the early 1960s. Liu et al. (2004) deduced that the mineralization of Chaiwobao Lake and Hongjianzhuo Lake in Xinjiang Province was also associated with climate change. In addition, Bonte and Zwolsman (2010) simulated the salinization processes in Flevoland Lake and Ijsselmeer Lake in the Netherlands by 2050 using climate and water quality models under two climate change scenarios, i.e., temperature increases of 1 and 2 °C. The results, which are shown in Figure 2, indicated that a temperature increase of 2°C combined with a change in the atmosphere circulation pattern would increase the chloride contents in Ijsselmeer Lake and Markermeer Lake by 108 and 15 mg/L, respectively.

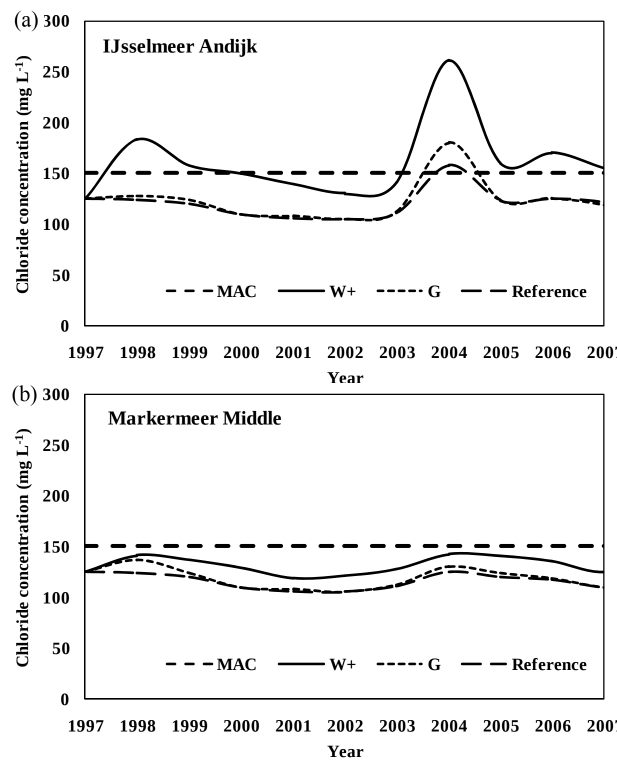


**Figure 2**. Effect of climate change scenarios G and W+ on chloride concentrations at Lake Ijsselmeer – Andijk and Markermeer Middle gaugin sites in 2050. MAC chloride = drinking water standard of 150 mg/l, scenarios G means temperature increases 1°C , W+ means temperature increases 2 °C and air circulation will change (Source: Bonte et al., 2010).

### 3.2. Alpine Lakes

Compared with other lakes at lower altitudes, alpine lakes of glacial origin are more remote and undisturbed aquatic environments. These types of lakes are much less influenced by discharged pollutants and other human behaviors and are known as sensitive indicators of global climate change (Daly and Wania, 2005; Macdonald et al., 2005; Hari et al., 2006). An increasing trend in the dissolved organic carbon (DOC) concentrations has been found in alpine lakes (Parker et al., 2008; Hruska et al., 2009). Parker et al. (2008) reported that climate change was strongly related to warmer temperatures and increased DOC concentrations in a set of alpine lakes in the Canadian Rockies. Most studies attribute this increasing trend in the DOC to changes in the chemistry of atmospheric deposition and increases in temperature and precipitation (Worrall et al., 2007; Eimers et al., 2008; Dawson et al., 2009; Hruska et al., 2009; Oulehle and Hruska, 2009; Sarkkola et al., 2009). Recent studies on alpine lakes have mostly focused on the analyses of the sediment cores from these lakes to obtain historical data that can be used to analyze the water quality trend. In addition, the changes in the biodiversity under increasing water temperature and/or increasing DOC concentrations in these lakes has also been considered. Clarke et al. (2005) analyzed diatom assemblages extracted from the sediment cores of 209 high-altitude lakes from 11 countries in Europe and found that most of the analyzed lakes exhibited an increasing trend in plankton diatom species over the past 150 years due to changes in climate. Moreover, to explore the potential biotic influence of climate change on alpine lakes, Fischer et al. (2011) used Daphnia as a bioindicator to examine its response to changing environmental conditions in Rocky Mountain alpine lakes. As shown in Figure 3, the results indicated that the mean Daphnia density (1991 ~ 2005) had a positive correlation with increases in the mean surface temperature and DOC concentration. In addition, the effect of climate change on the biodiversity in these alpine lakes has also been studied. Parker et al. (2008) found that the increased DOC concentrations induced by climate change stimulated the appearance of small mixotrophic algal species in a set of alpine lakes in the Canadian Rockies. The results reported by Čiamporová-Zaťovičová et al. (2010) also suggested that warmer conditions would cause an increase in the number of thermophilic aquatic insects in three alpine lakes in the Tatra Mountains (Slovakia) located at different elevations (the increased number of thermophilic species is typical for lakes at lower altitudes); however, the non-insect benthic macroinvertebrates would be stable. This result indicates that the sensitivity of aquatic organisms to climate change depends on the species type.

In addition to the use of bioindicators in the sediment cores of alpine lakes, heavy metal contaminants and conductivity have also used to demonstrate the effect of climate change on the water quality (Kirk et al., 2011). An increase in the temperature due to climate change may influence rock weathering and glacier melting (Jing and Chen, 2011), which would, in turn, affect the alpine water quality. For example, Thies et al. (2007) found that the melting of glaciers in the Alps induced the dissolution and thus the release of heavy metal ions, such as calcium, magnesium, and nickel (Figure 4), leading to an 18-fold increase in the water conductivity in Rasass See. Similar processes occurred at the higher elevation of Lake Schwarzsee ob Solden, where the electrical conductivity exhibited a 3-fold increase during the past two decades. Moreover, Klaminer et al. (2010) studied the lead (Pb) contamination of subarctic lakes using a Pb isotope tracer and demonstrated that a warmer climate has simulated the transport of heavy metals from the soil to the arctic surface waters.

### 3.3. Rivers

Recent studies on the impacts of climate change on rivers have mostly emphasized nutrient loads and sediment transport (Wilby, 2006; Chen et al., 2007; Kaushal et al., 2008; Tong et al., 2007; Han et al., 2009; Tu, 2009; Hamilton, 2010; Desortová and Punčochář, 2011; Lee et al., 2010; Wilson and Weng, 2011). A recent study performed by Zhang et al. (2012) simulated the impacts of climate change on the streamflow and non-point source pollutant loads in the Shitoukou reservoir catchment, China. The results indicated that the annual $NH_4^+$-N load into the Shitoukoumen reservoir would exhibit a significant downward trend with a decreasing rate of 40.6 t per decade under the A2 scenario. Nõges et al. (2011) reported that an increase in the winter precipitation in the Ticino river basin of southern Europe was likely to increase the nutrient loadings in the lakes and contribute to eutrophication. Moreover, considering both point sources and agricultural diffuse sources, Martínková et al. (2011) used SWIM (Soil and Water Integrated Model) to simulate changes in the nitrate load from the Jizera catchment (Czech Republic) under the A1B scenario. Although the results varied in the different simulated periods, the nitrate loads of most periods were positively correlated with the water discharge and precipitation. Similarly, Arheimer et al. (2005) simulated changes in the nutrient loads and algae growth in the Leonard River system in Southern Sweden using water quality and ecological models under the A2 and B2 scenarios and concluded that an increase in the temperature, would result in a 50% increase in the total phosphorus, a 20% increase in the total nitrogen, and an 80% increase in cyanobacteria.

In addition, Whitehead et al. (2009) simulated the impact of climate change on the sediment delivery in River Lambourn in the UK using a combination of weather patterns downscaled from the Global Climate Model (GCM) and the INCA-SED (Integrated Catchment-Sediment) models under the B1, B2, A2, and A1F1 scenarios. These researchers concluded that climate change would lead to an increase in the sediment delivery during spring and autumn by 2050 and that this increase would be induced by an increase in storms and river flows. Moreover, Verhaar et al. (2011) simulated the sediment transport during 2010 ~ 2099 in three tributaries of the Saint-Lawrence River, Canada, under climate change with various scenarios. The results showed that the sediment transport volume would exhibit increases of 209, 286, and 134% in the Batiscan, Richelieu, and Saint-Francois Rivers, respectively, under the HadCM3-B2 scenario compared with the base scenario.

Moreover, the relationships between climate change and the major ion contents have been studied. Prathumratana et al. (2008) found negative correlations between the ion contents and

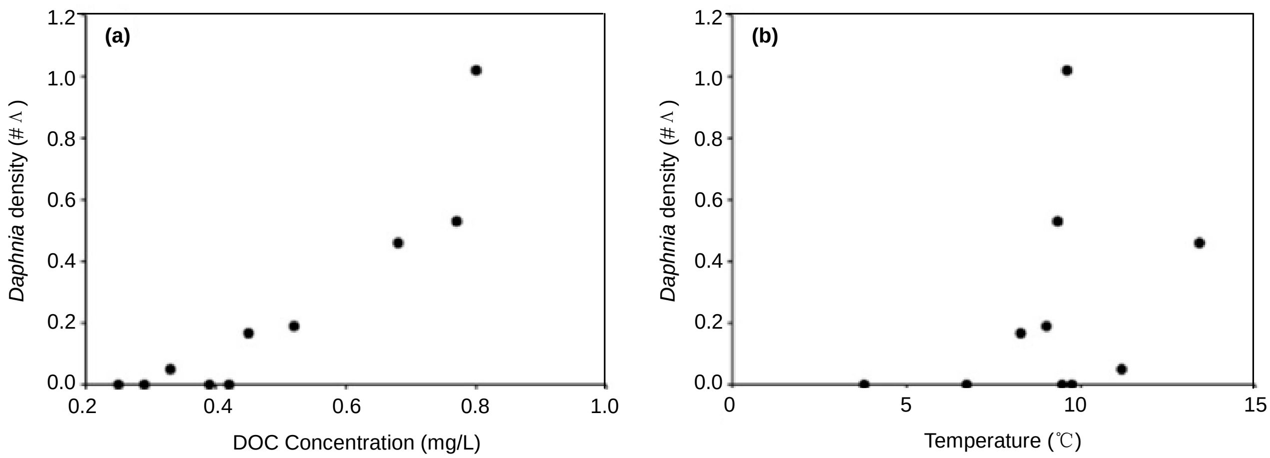


**Figure 3**. Relationships between D. middendorffiana density and DOC concentration (a) and surface temperature (b) in Banff and Yoho National Parks Lakes (Sources: Fischer et al., 2011).

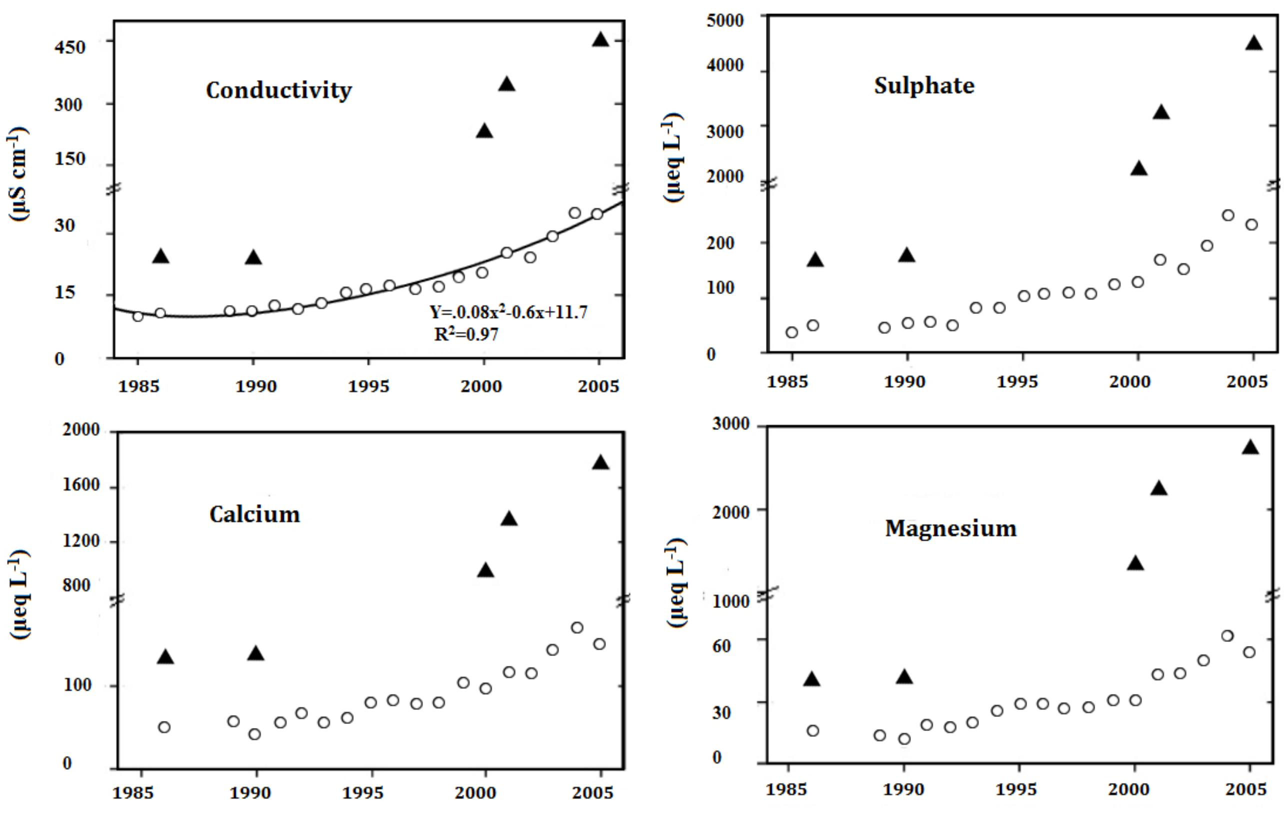


**Figure 4**. Conductivity, sulfate, calcium, and magnesium in lake water of Rasass See (RAS, black triangles) and Schwarzsee ob So¨lden (SOS, open circles) (1985-2005) (Source: Thies et al., 2007).

the precipitation in the Mekong River by comparing climatic data with water quality data during the period of 1985 to 2004. We also studied the relationship between the natural river runoff and the major ion contents of the Yellow River during the period of 1960 to 2000 (Wu et al., 2014). Three hydrological stations were selected as the study area; these were the Lanzhou Station, the Huayuankou Station, and the Lijin Station, which are located in the upper, middle, and lower reaches of the river, respectively. Monthly water quality and quantity data from 1960 to 2000 were retrieved from the Yellow River Conservancy Commission (YRCC). The M-K tests performed indicated that the concentrations of total ions, $Ca^{2+}$, and $Mg^{2+}$ in the Yellow River exhibited increasing trends from 1960 to 2000, and this increase was especially obvious in October at the Huayuankou Station

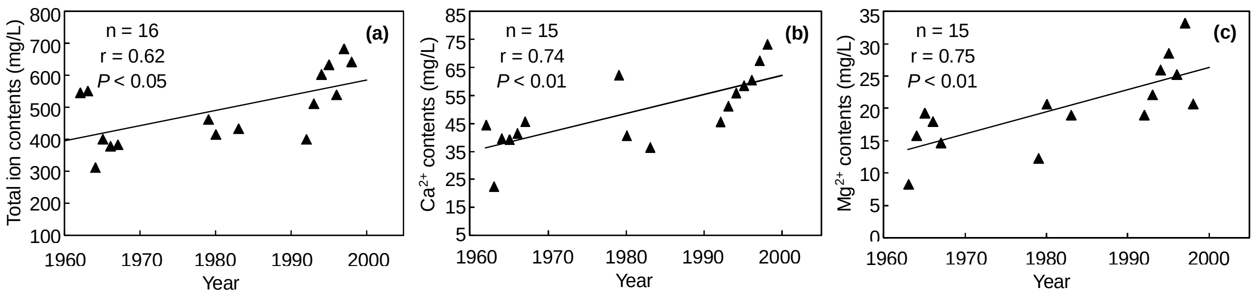


**Figure 5**. The variation trend of total ion, $Ca^{2+}$ and $Mg^{2+}$ contents in October at the Huayuankou Station of the Yellow River.

**Table 1.** Correlations of River Runoff and Major Ion Contents of the Yellow River at the Lanzhou and Huayuankou Station (Source: Wu and Xia, 2014)

| Parameters | Runoff of Lanzhou Station | | | Runoff of Huayuankou Station | | |
|---|---|---|---|---|---|---|
| | August | September | October | August | September | October |
| $Ca^{2+}$ contents (Aug.) | -0.338* | | | -0.302 | | |
| $Ca^{2+}$ contents (Sep.) | | -0.133 | | | -0.237 | |
| $Ca^{2+}$ contents (Oct.) | | | -0.007 | | | -0.668** |
| $Mg^{2+}$ contents (Aug.) | -0.250 | | | -0.324 | | |
| $Mg^{2+}$ contents (Sep.) | | -5.44** | | | -0.447* | |
| $Mg^{2+}$ contents (Oct.) | | | -1.25 | | | -0.597** |
| Total ion contents (Aug.) | -0.419* | | | -0.364 | | |
| Total ion contents (Sep.) | | -4.12* | | | -0.461* | |
| Total ion contents (Oct.) | | | -0.074 | | | -0.672** |

*Correlation is significant at the 0.05 level.
** Correlation is significant at the 0.01 level.

(Figure 5). There were two probable reasons for the increase in the major ion concentrations in the Yellow River. One explanation is that the increasing temperature caused by climate change enhances rock weathering, which leads to higher major ion concentration in the river water. The other reason is that the decreasing trends of the river runoff weaken its dilution effect in the major ions in the river water, which results in increases in the concentrations of the major ions; the detailed correlations are shown in Table 1.

### 3.4. Costal Lagoons and Estuaries

To date, research on costal lagoons and estuaries has focused on the monitoring of the rising water temperature, nutrient loads, and eutrophication (Knowles and Cayan, 2002; Yunev et al., 2007; Davies et al., 2009; Drewry et al., 2009; Whitehead et al., 2009; Kirilova et al., 2011). Preston (2004) reported that the water temperature of the Chesapeake Bay estuary in the United States had increased by 0.8 ~ 1.1 °C since the mid-20 century, and Fulweiler and Nixon (2009) also reported that the mean water temperature in Narragansett Bay of the United States had increased by 1.7 °C during the last 30 years. Li et al. (2011) studied the nutrient input to the Yamen estuary in South China using the Soil and Water Assessment Tools (SWAT) model and found that a temperature increase of 3 °C would result in an increase in the load of sediment, inorganic nitrogen, and inorganic phosphorus of approximately 13, 40, and 5%, respectively.

In their analysis of the effect of climate change on eutrophication, Miller and Harding. (2007) found that winters with more frequent warm or wet weather patterns are followed by a greater phytoplankton biomass in the subsequent spring, i.e., this greater biomass covers a larger area and extends into the estuary. Higher rates of primary production have also been observed in the Hudson River estuary in the USA during dry summers (Howarth et al., 2007). Lloret et al. (2008) attempted to identify the role of climate change in the eutrophication of the Mar Menor costal lagoons in Spain using a photosynthesis model and conducting experiments. The results demonstrated that the rise in the sea level induced by climate change would lead to increases in light attenuation and cause a high decrease in the amount of light reaching the water bottom, which would be accompanied with a loss of macroalgae and a rapid growth of phytoplankton.

Solar UV radiation can penetrate to ecologically significant depths in aquatic systems, and some evidence has shown that UV radiation affects aquatic species, especially those in estuaries, by inducing phototoxicity of some pollutants, such as PAHs, to aquatic organisms (Häder et al., 2007; Schiedek et al., 2007). Laboratory studies performed by Lyons et al. (2002) have shown that the toxicity of both pyrene and benzo(a)pyrene was enhanced when the exposures were conducted in the presence of UV light, i.e., under ultraviolet radiation (UVB = 6.3 ± 0.1 $\mu W/cm^2$, UVA = 456.2 ± 55 $\mu W/cm^2$), 1 μg/L benzo(a)pyrene and 1 μg/L pyrene concentrations caused the percent of abnormal oyster embryos, which is a marine invertebrate, to increase from approximately 20 to 85% and from 11 to 73%, respectively.

### 3.5. Seas

The sea environment is the largest water system and exhibits the richest biodiversity and greatest productivity. To date, studies on the impacts of climate changes on the sea water quality have mainly focused on marine biodiversity, ocean acidification, and salinity changes. Several studies have reported that climate change can influence marine pelagic species by affecting their life period and biodiversity (Cheung et al., 2009; Hicks et al., 2011). Edwards and Richardson (2004) quantitatively investigated the effect of climate warming on the ecological community by analyzing long-term data of 66 types of phytoplankton. These researchers found that the increase of 0.9 °C in the summer sea surface temperature from 1958 to 2002 collectively moved the seasonal peaks of meroplankton as secondary and tertiary producers by 27 d and that of copepods as secondary producers by 10 d. Cheung et al. (2009) simulated the global patterns of a sample of 1,066 exploited marine fish and invertebrates in 2050 under the SRES A1B scenario using a dynamic bioclimate envelope model and demonstrated that climate change may result in the extinction of numerous local species in the sub-polar region and an intense species invasion in the Arctic Ocean. These research results demonstrate that marine species are sensitive indicators for the analysis of the effect of climate change on oceans. In addition, the acidification of the oceans due to increased carbon dioxide has been studied by some researchers (Barry, 2010; Ferrari et al., 2011; Galaz et al., 2011). Some studies have shown that an increase in the carbon dioxide in the surface water would not only lead to changes in the seawater chemistry process but also reduce the pH by 0.14 ~ 0.35 units by 2100 under the “business-as-usual” scenario (Raven et al., 2005; Barry et al., 2007; Carere et al., 2011). The acidification and warming of oceans may have negative impacts on the development of marine species (Ferrari et al., 2011). However, a series of studies conducted by Byrne et al. (2009, 2010a, 2010b) on the effect of acidification and warming on the fertilization of echinoids in Austria, which is a representative marine species, indicated that the fertilization of these organisms is robust to temperature and pH fluctuations. These results also indicated that further studies on the potential impacts of ocean changes on marine species should focus on more vulnerable embryonic and larval stages that spend a long time in a water environment. Doo et al. (2011) conducted a simulation experiment and found that a decrease in the pH or an increase in the $CO_2$ could significantly reduce the percentage of normal larvae of Centrostephanus rodgersii, which is a habitant-modifying species from eastern Australia. The detailed results showed that a decrease in the pH from 8.1 to 7.6 would decrease the normal percentage of larvae from approximately 95 to 75%.

A change in the salinity will be another effect of climate change on the sea water quality. Helm et al. (2010) calculated the effect of a salinity change on the ocean density from 1970 to 2005 using global datasets of in situ observations and found a global pattern in which the ocean salinity increased near the upper-ocean salinity-maximum layer (average depth of ~100 m) and decreased near the intermediate salinity minimum (average depth of ~700 m). These researchers hypothesized that these salinity changes were correlated with increased precipitation at high latitudes and decreased precipitation in the subtropics. Moreover, Melki et al. (2009) found a decrease in the surface water salinity in the Gulf of Lion in southwest Europe during the last 28 kyr and hypothesized that the negative salinity anomaly was either due to a strong local freshwater input and an increase in the western Mediterranean precipitation-minus evaporation (P - E) budget or due to inflowing North Atlantic surface waters with lower salinities. Regardless of whether the salinity increases or decreases, recent studies have reported that changes in the salinity could influence the biodiversity of marine species (Allinson et al., 2011; Boyle et al., 2011; Fukunaga et al., 2011; Hicks et al., 2011). Moreover, a reduction in the salinity and a higher water temperature would lead to an increased toxicity of certain heavy metals but would also reduce the toxicity of organic phosphate (Allinson et al., 2011; Nel et al., 2011). Dalla et al. (2007) and Lamon et al. (2009) suggested that the solubility of heavy metals and persistent organic pollutants (POPs), such as PAHs, depends on the salt concentration in the water environment.

Similarly to other climatic factors, wind may influence the sea water quality (Ma et al., 2010). Chung et al. (2009) studied the Salton Sea using water quality models, and the simulation results showed that the sediment resuspension induced by wind in the Salton Sea is the most important nutrient transport process. In addition, the temperature was correlated with the sea level pressure, which is a key factor in the control of cyclones and anticyclones. Changes in both the temperature and the large-scale wind system may be associated with changes in the sea water quality; however, few studies have been conducted on this topic.

### 3.6. Effect Mechanisms of Climate Change on Water Quality

According to research advances on the impacts of extreme weather events and long-term climate change on the water quality, climate change can influence the sources, distribution, migration, and transformation of pollutants in different types of water bodies. Changes in precipitation play an important role in influencing the water quality of rivers. The intensity of the precipitation determines the soil and water erosion, which can influence the elution of contaminants from the soil and ground surface. For example, frequent storms could release the chemical matters stored in the soil and transport these to a water environment via land runoff, which would result in the formation of nonpoint source pollution. Furthermore, water loss and soil erosion can lead to an increase in the sediment concentration in surface water, and strong precipitation can result in the resuspension of sediments. Both of these processes would change the water and sediment conditions, which would influence the migration and transformation of pollutants in the water environment. In addition, the precipitation will affect the river runoff and thus influence the water self-purification.

The increase in the temperature induced by climate change will promote the biochemical reaction rate of pollutants and will thus influence the biochemical processes in the water system. In addition, the increasing temperature will extend the period of thermal stratification and deepen the thermocline in the water of lakes and reservoirs, which would lead to hypoxia in the bottom water and thus induce the release of pollutants, such as nitrogen and phosphorus, from the sediments. Moreover, both the increasing temperature and the increasing nutrients released due to hypoxia in the bottom water will promote the growth of phytoplankton, which would result in intensified eutrophication. Furthermore, the increasing evapotranspiration induced by the increasing temperature will contribute to the mineralization and salinization of lakes.

Changes in the wind velocity can affect the volatilization of pollutants. In addition, changes in the wind velocity and patterns will influence the water circulation and the water flow velocity, which will further influence the volatilization and migration of pollutants. Changes in radiation can not only influence the photodegradation and phototoxicity of pollutants but also affect the growth of aquatic species.

Different types of water bodies can be influenced by climate change, including short-term extreme weather events and long-term changes in precipitation, temperature, and other climatic factors. Different impacts will be reflected due to the diverse hydrogeological conditions and the destiny of pollutants in specific water bodies. This finding has been demonstrated by many studies, as mentioned in the above sections. However, few studies have noted the key processes through which climate change impacts the water quality in different water bodies. In addition, a universal impact pattern of climate change on different water bodies should be introduced through an in-depth study.

## 4. Methods for the Quantification of the Impacts of Climate Change on Water Quality

The integration of GCM or Regional Circulation Models (RCM) with water quality and ecological models is considered a useful tool for the study of the impacts of climate change on the water quality and the ecosystem. To date, these integrated models can be divided into two types. One type is used for the analysis of the impact of climate change on the sources of pollutants in water bodies. For example, Marshall and Randhir (2008) used the SWAT model to predict non-point source pollution in the Connecticut River Watershed of New England under changes in the precipitation and temperature, which were the simulated outputs from two IPCC GCMs. The other type of integrated model is used to analyze the impact of climate change on the migration and transformation of pollutants in a water environment. Komatsu et al. (2007) used the output data of the GCM under the A2 scenario as the input for water quality and ecological models to predict the concentrations of nitrogen, phosphorus, biomass, and iron in the surface water of a reservoir. However, there are few models that study both the sources and the transformation processes of pollutants. Thus, additional water quality and ecological models should be developed to study the effects of climate change on both of these aspects. In addition, all of the model predictions are uncertain to some degree. As a result, the characterization and reduction of this uncertainty is one of the priorities of future research.

In addition to combining climate models with water quality and ecological models, sediment core analyses and mesocosm experiments are also used to study the impact of climate change on the water quality of different types of water bodies. Sediment cores maintain historical data of the water environment quality and are less disturbed by human behaviors. Particularly in the region where water quality data are sparse, sediment analysis can be the best approach to obtain historical water quality data and to study the impacts of climate change on a water environment. For example, Kirilova et al. (2011) studied the relationships between climatic factors and diatom assemblages in the Sacrower See in NE Germany by analyzing laminated sediments and determined the sensitivity of diatom assemblages to meteorological changes. Moreover, Boros et al. (2011) studied the impact of temperature changes on the redox potential around the sediment-water interface in lakes through a mesocosm experiment. Gomez et al. (2012) also used a microcosm approach to study the effects of drying on the nitrogen contents of sediments. Therefore, sediment analyses and mesocosm experiments are useful tools for the analysis of the impacts of climate change on water quality.

In addition, the long-term field monitoring of bioindicators, such as phytoplankton and zooplankton in water bodies, can also afford evidence of the impacts of climate change on water quality. For example, Fischer et al. (2011) used Daphnia as a bioindicator to examine its responses to changing temperature in alpine lakes. However, studies on the impacts of climate change on water quality using these methods are very few. Thus, further investigations should strengthen the long-term monitoring of bioindicators in water bodies.

However, different study methods may have different effects on the impact assessments. Microcosm and mesocosm experiments can explore the mechanism through which climate change affects the water quality. The analysis of the sediment core and some bioindicators affords historical evidence on how climate change affects the water quality in different water bodies, and these results are more accurate and specific. In contrast, model simulations provide predictions under different scenarios of climate change, and these results are unverifiable, especially under scenarios that are introduced based on some assumptions. Compared with the other methods, model simulation, as a more macro approach, provides information for better water resource management under climate change and is beneficial for the suggestion of preventive measures against the effects of climate change.

In addition, the identification of the impacts of climate change, human activities, and/or other factors is a key process for the quantification of the impacts of climate change on the water quality. In general, human activities include pollution discharge, land use, dam construction, and water withdrawal from the surface water and groundwater. Correlation and regression analyses have been the most common approach used to quantify the impacts of climate change and anthropogenic behaviors on the water quality in recent years (Palmer et al., 2011; Veríssimo et al., 2013). Özkan et al. (2012) studied the impact of water chemistry, lake morphology, land use, and climate on the phytoplankton richness in 195 Danish lakes and ponds using the ordinary least squares (OLS) multiple regressions method, and the results indicated that the water chemistry and the lake morphology had a strong influence on the phytoplankton richness and that the climate and land use exhibited only a slight contribution to the phytoplankton richness. Another method used to assess the impacts of climate variability and human activity is the combination of the climate elasticity method and the hydrological model (Ma et al., 2010; Hu et al., 2012); however, this method is more often used to analyze changes in the water quantity. Therefore, additional methods for the identification of the impacts of climate change and human activities on the water quality should be developed and improved in the near future.

## 5. Conclusions

This review is part of an ongoing process to improve the understanding of the potential impacts of climate change on water quality. Global climate change has many potential impacts on the biogeochemical processes that occur in different types of water bodies. The most important impacts are listed as follows: (1) Eutrophication, salinization, and nutrients release are both the observed and the predicted effects of climate change on the water quality of plain lakes. (2) Alpine lakes are facing problems due to the transport of heavy metal melting from soils to the water environments and the decreasing biodiversity of the local species. (3) Rivers and estuaries may exhibit increasing nutrient loads under climate change. (4) A decrease in the marine biodiversity and changes in the salinity are the potential threats to oceans under climate change.

However, there are scientific consensuses and disagreements regarding the impacts of climate change on the water quality of different water bodies. First, because climate change exhibits significant regionalism, the changes in the water quality in different regions exhibit significant variability. Moreover, the changes in the water quality are regulated by multiple factors. Most studies choose to focus on one or some of these driving factors to determine the effect of climate change on the water quality and assume that the other factors remain unchanged, resulting in different conclusions. Furthermore, even in the same region or similar environmental conditions, the results might exhibit differences due to the different scenarios, indicators, and data processing methods used in the study. In a future study, all of the possible factors should be taken into consideration, and the methods should be standardized to obtain comparable results and/or the global-scale response of the water quality to climate change.

Future studies should be conducted in the following aspects. To quantify the impacts of climate change on water quality, there remain two questions that should be considered. First, it is important to determine whether the impacts of climate change on the water quality found by the models or the laboratory and mesocosm experiments will actually occur in a complex environment. Second, for the long-term field monitoring of bioindicators, it is important to improve the method used to identify the effects of climate change from other confounding factors, such as pollution and land use changes. Therefore, further work should focus on the methods used to quantify the impacts of climate change on water quality.

In addition, research on the effects of climate change should be extended, and mechanism-based studies and experimental approaches are needed. For example, there have been some studies on the effects of precipitation and temperature on the nutrient and sediment loads. However, few studies have elucidated the effect of climate change on the transformation of nutrients. Some research studies have shown that variations in the suspended sediment concentration in river water will exert significant influence on organic pollutant biodegradation and nitrogen compound transformation (Xia et al., 2004, 2006, 2009). Because climate change will lead to variations in the suspended sediment concentration, it is necessary to study the effect of climate change on the transformation of nutrients and other organic pollutants. In addition, most studies have used models to simulate the impacts of climate change on the water quality, but there is a lack of experimental evidence that supports the conclusions drawn by these studies. Moreover, the studies that have investigated the effect of climate change on the aquatic organisms in different types of water bodies focused on the population or the life duration of the aquatic species. Thus, additional studies should be conducted on the effects of climate change on the development of aquatic species and their interaction with pollutants.

Furthermore, measures for the adaption to climate change in different water bodies should be taken into consideration to guarantee the balance of the demand and supply of water. Climate change, in combination with human activities, affects the water quality of different water systems. The quantification of the impact of climate change on water quality is key for the introduction of efficient adaption measures. Moreover, a water quality and ecological model that analyses both the sources and the transformation processes of pollutants in water bodies should be developed and used to study the integrative impacts of climate change, land use change, and pollutant discharge on water quality and ecosystems.

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