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Impact of climate change on water quality in the Netherlands

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Abstract

Impact of climate change on water quality in the Netherlands

Climate change aggravates existing problems with surface water quality in the Netherlands. New water quality problems are not expected. That is the conclusion of a literature search carried out by RIVM, focused on the expected impact of climate change on water quality, including effects on ecology, human health and some economic sectors. RIVM therefore recommends authorities not to develop new policy but to incorporate the possible impacts of climate change into existing policy. The Water Framework Directive targets may become unfeasible as a result of the additional pressure caused by climate change. RIVM also recommends stronger integration between policy areas and closer cooperation between authorities.

The first step in this project was drawing up an inventory of climate change projections. Average temperature is expected to rise and the variation within seasons is expected to increase. The next step was investigating the corresponding effects for the quality of surface water in the Netherlands. The chemical quality of surface water will deteriorate and the concentration of oxygen will decrease. Additionally, the effects of eutrophication, like algal blooms, will increase. Climate change will increase pressure on ecosystems caused by salinisation, acidification, eutrophication and fragmentation. As a result, new plant and animal species may appear in the Netherlands, having spread from the south, while other species may disappear.
Micro-organisms might cause health risks when the climate changes but the reverse might also be the case.
Higher temperatures may have consequences for public water supply because surface water may not be used as a source when temperature standards are exceeded.

Key words:
climate change, water quality, impact, ecology, human health, economy, policy options, the Netherlands

Rapport in het kort

Invloed van klimaatverandering op waterkwaliteit in Nederland

Door klimaatverandering worden bestaande problemen voor de kwaliteit van oppervlaktewater in Nederland groter. Naar verwachting leidt klimaatverandering niet tot nieuwe waterkwaliteitsproblemen. Dit blijkt uit literatuuronderzoek van het RIVM naar de verwachte invloed van klimaatverandering op waterkwaliteit, inclusief de gevolgen voor ecologie, gezondheid en enkele maatschappelijke sectoren. Het instituut raadt overheden daarom in het algemeen aan om geen nieuw beleid te ontwikkelen, maar de gevolgen van de klimaatverandering bij bestaand beleid te integreren. De doelen die de Europese Kaderrichtlijn Water stelt kunnen onhaalbaar worden door de extra 'stress' van klimaatverandering voor het milieu. Ook is het raadzaam om de onderlinge samenhang tussen beleidsterreinen te benadrukken en meer samen te werken.

Voor het onderzoek is eerst de verwachte klimaatverandering in kaart gebracht. Zo zal de temperatuur gemiddeld stijgen, waardoor de variatie binnen de seizoenen zal toenemen. Vervolgens is onderzocht wat de effecten van klimaatverandering zijn voor de kwaliteit van oppervlaktewater in Nederland. Chemisch gezien zal de waterkwaliteit achteruit gaan en de concentratie zuurstof in het water afnemen. Ook worden de gevolgen van eutrofiëring groter, zoals meer algenbloei. In ecologisch opzicht zal de klimaatverandering de bestaande stressfactoren voor het water, zoals verzilting, verzuring, eutrofiëring en versnipperde natuurgebieden, versterken. Daardoor kunnen nieuwe plant- en diersoorten uit het Zuiden naar Nederland komen en andere uit Nederland verdwijnen. Voor de mens kunnen micro-organismen in een warmer klimaat gezondheidsrisico's veroorzaken. Het is echter nog niet uitgesloten dat dergelijke risico's juist kunnen afnemen. Ook kunnen hogere temperaturen gevolgen hebben voor het drinkwater, omdat oppervlaktewater boven een bepaalde temperatuur niet voor de drinkwaterwinning mag worden gebruikt.

Trefwoorden: klimaatverandering, waterkwaliteit, gevolgen, ecologie, gezondheid, economie, beleidsopties

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Contents

Summary

This report describes the effects of climate change on water quality in the Netherlands. The report is based on a literature study and interviews with experts. The effects of a changing climate on water quality are described in terms of changing physical and chemical processes, changing ecology (micro and macro) and the influence on humans (health and economy). The report concludes with recommendations that would mitigate the consequences of a changing climate on water quality.
There is uncertainty in climate scenarios and there are gaps in knowledge of the effects of a changing climate on water systems. This makes it difficult to predict precisely the changes that will occur in water systems. Furthermore, different water systems will react differently to climate change. Therefore, we have chosen to describe a wide range of possible consequences for water quality due to climate change.

<u>Climate change and water</u>
The Dutch Meteorological Institute (KNMI) developed four climate scenarios (G/G+ and W/W+) for the Netherlands. Recent scientific developments have led to the belief that the worst-case scenario's W/W+ are most likely for the Netherlands. In the past years, average temperature in the Netherlands has increased twice as fast as the global temperature. In general, the scenarios predict milder and wetter winters, hotter and drier summers and a rising sea level. Furthermore, more extreme weather events such as heavy precipitation and heat waves are expected. These events can cause periods of intense drought or flooding.

<u>Impacts of climate change on physico-chemical water quality</u>
Climate change affects physico-chemical water quality. Climate change *directly* affects the temperature of water. *Indirectly*, physical and chemical processes related to temperature in the water column will change. Changes that are expected to occur include increased rates of (bio-) chemical processes, a decrease in oxygen concentration and changing stratification patterns.
A changing hydrology will indirectly affect the physico-chemical water quality. Heavy precipitation events will increase soil erosion, which will lead to increased nutrient and pollutant run-off to surface waters. Water systems will become more eutrophic and as a result, water transparency will decrease. Droughts, as well as a rising sea level, can lead to the salinisation of surface waters. In general, it is expected that climate change will reduce the physico-chemical water quality.

<u>Impacts of climate change on ecology</u>
Ecosystems in the Netherlands are under great pressure from eutrophication, pollution and habitat fragmentation. Climate change is expected to aggravate current problems for ecosystems.
In general, two ecological responses to climate change can be distinguished. These are a shift in the geographical range of species and a changing phenology (the timing of life-cycle events). On a *micro* scale it is expected that higher temperatures and eutrophication (an existing problem but exacerbated by climate change) will lead to increased phytoplankton blooms. In particular, nuisance cyanobacteria are expected to benefit from climate warming. Changes in the dynamics and composition of phytoplankton lead to food mismatches between zooplankton and phytoplankton. These mismatches might lead to food mismatches higher in the food chain, which would have a strong impact on the ecosystem. Harmful bacteria, such as *Clostridium botulinum* and *Legionella pneumophilia*, are also expected to benefit from climate warming.
On a *macro* scale, climate warming is mainly expected to cause changes in species phenology, physiology and species composition. Increased water temperature is an important cause of changes in aquatic species composition and diversity and lifecycle dynamics. However, changes in aquatic species

composition due to climate change are so far not well documented in the Netherlands. Extreme weather events are expected to negatively influence the diversity of macroinvertebrates. Disturbed ecosystems are more vulnerable to invasive species. Invasive species can have devastating impacts on ecosystems, and some are expected to increase due to climate change.

Impacts of climate change on humans
Changing water quality due to climate change is expected to affect social functions such as public health, recreation, agriculture and industry. Water- and vector-borne diseases might increase as a result of climate change. Drinking water supply might also be negatively affected. Recreation is expected to increase due to higher temperatures in the summer but cyanobacterial blooms in recreational waters will restrict their recreational value. Agriculture is influenced by climate change in both positive and negative ways. Crops are sensitive to direct changes (temperature, precipitation) and indirect changes (prevalence of pests, altered water quality). With regard to power plants, problems with cooling water, and therefore energy production, might occur in the future.

Impact on water policy
For policy makers it is important to bear in mind that climate change mainly aggravates existing problems. Therefore, climate change policy should focus on implementing and integrating with policy that is already in place. Water quantity problems are often related to water quality problems and these areas should ideally be considered together where appropriate. It is also recommended to prepare and implement policy measures before the effects of climate change become readily apparent. Often, precautionary measures are cheaper than measures that have to be taken when the damage is already done.
Recommendations are given for European and national policy as well as for other authorities.

1 Introduction

The aim of this report is to give an overview of the possible impacts of climate change on water quality in the Netherlands. This report is performed by order of the Ministry of Housing, Spatial Planning, and the Environment.
The report provides information about the possible impacts of climate change on the water quality of Dutch freshwaters. Water quality is investigated in both chemical and ecological terms. No concrete measures are given in this report; only possible impacts and recommendations for policy. The information for this report was gained from the literature and interviews with relevant departments and research institutes.

The Netherlands contains a lot of water. Through the centuries, the Netherlands has used water, defended itself against water and finally succeeded in living and working below sea level. Future impacts of climate change may weaken the Dutch resilience to water threats. The Netherlands is vulnerable to climate change. So far, the main focus has been on the impacts of a rising sea level and increased rainfall (water quantity). Less is known about the influence of climate change on water quality. However, policymakers need this knowledge to effectively anticipate possible changes in water quality in the future.

The report starts with observations and projections of global climate change, followed by observations and projections of the future Dutch climate. After this, the effects of climate change on physico-chemical and ecological water quality are discussed. The last two chapters deal with the consequences of a changing water quality for humans and the implications for policy, at European, national and regional/local levels.

In this report an attempt is made to visualise the possible effects of climate change on water quality and the consequences. To this end, the report contains pictures and case descriptions are also given. (Picture sources are listed in the Acknowledgements.)

2 Climate change and water

- In the past decade, average air temperatures in the Netherlands have increased twice as fast as global average temperatures.
- The Royal Netherlands Meteorological Institute developed four climate scenarios for the Netherlands. At present, the worst-case scenario (W+) is thought to be most likely for the Netherlands.
- The Netherlands harbours many shallow water bodies. Shallow water bodies are particularly sensitive to temperature increases. Increases in the temperatures of lakes has already been observed.

This chapter deals with the already observed influence of a changing climate on water. In addition, it deals with the influence of projected climate change on water. The first section deals with the global scale, the second section focuses on the situation in the Netherlands.

2.1 Global climate change

2.1.1 Observed global climate change

Changes in the climate system of the Earth have occurred regularly in the past. Glacial periods alternated with (warmer) interglacial periods. Currently, we are living in an interglacial period and the next glacial period seems far away, since climate data from the last century indicate warming of the climate system, at least on a global scale.
In the past century, global average air and ocean temperatures increased and there was widespread melting of snow and ice and global average sea level rise occurred (IPCC, 2007).
More precisely, the global surface temperature increased by 0.74 °C, in the period between 1906 and 2005, with a faster warming trend over the past 50 years (IPCC, 2007). The global average sea level rose by 1.8 mm per year from 1961 to 2003, and Arctic sea ice extent decreased by 2.7% per decade from 1978 (IPCC, 2007).
Global warming also influences the global hydrological cycle. The atmospheric water vapour content increases, precipitation patterns change, runoff of many glacier- and snowmelt-fed rivers change and warming of lakes and rivers occurs, which increases evaporation (IPCC, 2007).

2.1.2 Causes of climate change

There are natural and anthropogenic causes of climate change. According to the Intergovernmental Panel on Climate Change (IPCC) global warming is caused by human activities such as the burning of fossil fuels, deforestation and agriculture. These human activities have resulted in elevated concentrations of greenhouse gases (CO_2, CH_4, N_2O) in the atmosphere since the start of the industrial era around 1750 (IPCC, 2007). The carbon dioxide concentration in the atmosphere increased from a pre-industrial concentration of about 280 parts per million by volume (ppm) to 379 ppm in 2005. The same applies to the methane concentration (from 715 parts per billion by volume (ppb) to 1774 ppb), and nitrous oxide concentration (from 270 ppb to 319 ppb) in the atmosphere (IPCC, 2007). The 2007 assessment report of the IPCC concluded that ‘an increase in anthropogenic greenhouse gas concentrations is very likely to have caused most of the increases in global average temperatures since the mid-20th century'. However, according to other scientists, the current emphasis on the role of carbon dioxide may not be correct and the history of climate change has been insufficiently taken into consideration. They argue that changing solar activity also has a strong influence on the climate system (Van Geel et al., 1999). Van Ulden and Van Dorland (2000) investigated these opposite opinions and analysed different natural contributions to temperature change from 1882 to 1999. Their study showed that decreased volcanic activity and increased solar activity were plausible explanations for the observed global warming in the *first half* of the 20th century. A colder intermezzo from 1970 till 1995 was caused by high volcanic activity in that period. Natural factors, such as volcanic eruptions and El Niño events, have only caused short-term temperature variations over time spans of a few years but cannot explain any longer-term climatic trends (Copenhagen Diagnosis, 2009). The remaining global warming in the *second half* of the past century can be explained by anthropogenic forcing (Van Ulden and Van Dorland, 2000).

2.1.3 Projection for the 21st century

Climate models project a further increase (0.2 °C per decade) in global temperature (IPCC, 2007). Changing hydrology is predicted to cause a difference in water discharges between high-latitude areas and low-latitude areas. An increase in precipitation at high latitudes and a decrease in precipitation at low latitudes are expected (Bates et al., 2008). This will lead to an increase in river discharges at high latitudes and several wet tropical areas and a decrease in river discharges in the dry tropics and dry regions at mid latitudes (Bates et al., 2008). In many regions there is also a potential risk of flooding, due to an increase in heavy precipitation (Bates et al., 2008). Many dry areas (Mediterranean basin, western United States, southern Africa and north-eastern Brazil) will suffer in the future from a decline in water resources (IPCC, 2007). Drought-affected areas at low and mid-latitudes will expand (IPCC, 2007). Furthermore, the water quality will be affected by higher water temperatures, floods and droughts and salinisation, with consequences for human health, agriculture and ecosystems (Bates et al., 2008). For example, an increase in bacterial and fungal content due to higher water temperatures could cause diseases (e.g., botulism), which can affect humans and animals (Roijackers and Lürling, 2007).

Climate change not only involves the atmosphere. There is a strong interaction with the biosphere, most notably soils and vegetation (with a crucial and complex role for the stomata of plants where exchange between the plant and the atmosphere takes place). As a result, the hydrological and biogeochemical cycles are closely interconnected but processes like evapotranspiration are not always fully understood (Hutjes et al., 2003).

2.2 Climate change in the Netherlands

2.2.1 Observed climate change in the Netherlands

Figure 1 shows average annual temperatures in the Netherlands from 1900 until now, including the expected trend until 2020 (KNMI, 2008, 2009). In recent years, the average temperature in the Netherlands (and surrounding countries) has increased twice as fast as the global temperature (KNMI, 2008, 2009). This relatively rapid warming is probably caused by an increase in westerly winds in the winter and an increase in solar radiation in the summer.

Surface water temperatures increase with air temperature (Gooseff et al., 2005, Livingstone, 2003, Fang and Stefan, 1999, Schindler et al., 1996). The temperature of shallow waters is particularly

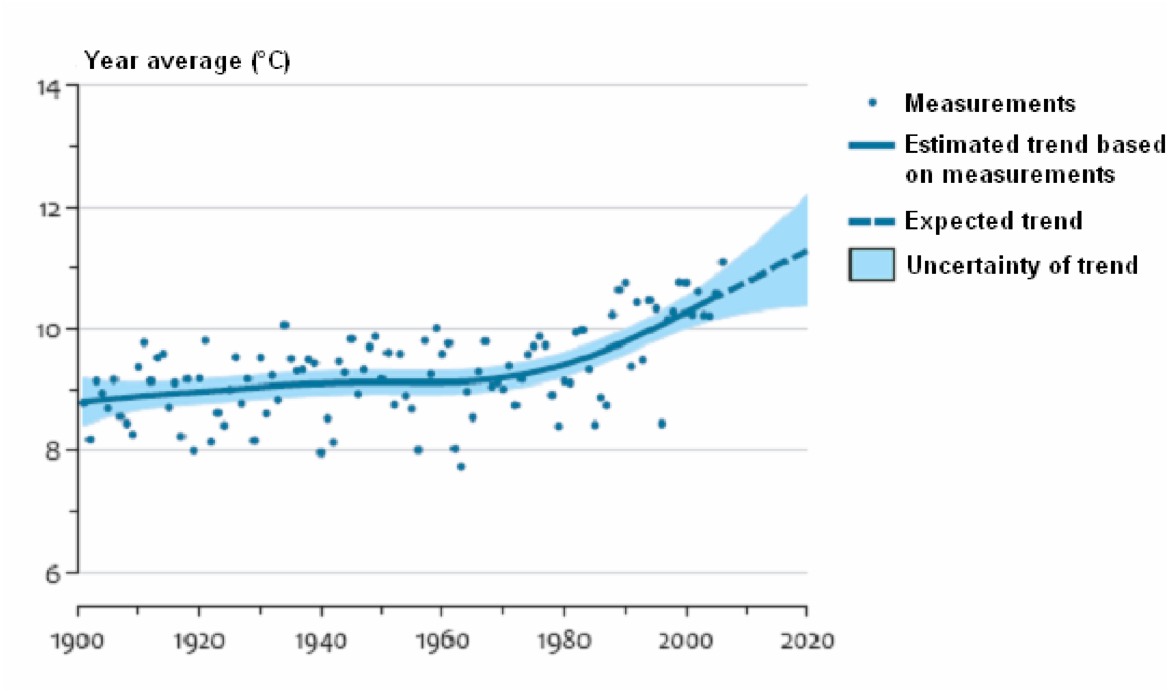


Figure 1 The average annual temperature in the Netherlands has increased by 1.7 °C since 1900, the average world temperature has increased 0.8 °C (KNMI, 2008).

closely connected with air temperature (Mooij et al., 2005). Indeed, the average temperatures of lakes IJsselmeer, Zwemlust, Veluwemeer and Tjeukemeer increased between 1961 and 2001 (Mooij et al., 2008).

2.2.2 Climate scenarios of the Dutch Meteorological Institute (KNMI)

In 2006, the KNMI (Royal Netherlands Meteorological Institute), with the aid of global and regional climate models, developed four projected climate scenarios for the Netherlands. The scenarios are possible images of the climate in the Netherlands in around 2050 (and 2100). They describe the most likely changes in climate in the Netherlands by 2050, compared to the situation in 1990 (KNMI, 2009). The W and W+ scenarios are the so-called warm scenarios and use an increase of 2 °C in 2050. The G and G+ scenarios are the more moderate scenarios and use an increase of 1 °C. In addition, the Netherlands could also be influenced by changes in atmospheric circulation, therefore the G+ and W+ scenarios are developed and indicate a change in atmospheric circulation. The four scenarios and their characteristics are shown in Table 1.

In the scenarios with a change in atmospheric circulation (G+ and W+), the winters become milder and wetter due to prevailing western winds and the summers become warmer and drier as a result of prevailing easterly winds (KNMI, 2009).

Generally, the four scenarios indicate that the sea level will continue to rise, that warming of the Netherlands will continue, winters will become wetter on average, there is little influence of climate change on the storm climate and that more extreme precipitation events will occur in summer and winter (KNMI, 2009).

Table 1 The four climate scenarios for the Netherlands developed by the KNMI in 2006

Scenario	Temperature increase in 2050 compared to 1990	Atmospheric circulation	Average precipitation in winter	Average precipitation in summer	Sea level rise
G	+ 1 °C	no change in air circulation patterns	+ 4 %	+ 3 %	15-25 cm
G+	+ 1 °C	winter: more westerly winds; summer: more easterly winds	+ 7 %	- 10 %	15-25 cm
W	+ 2 °C	no change in air circulation patterns	+ 7 %	+ 6 %	20-35 cm
W+	+ 2 °C	winter: more westerly winds; summer: more easterly winds	+ 14 %	- 19 %	20-35 cm

The rapid warming of the Netherlands, as shown in Figure 1, leads one to believe that the temperature changes of the W and W+ scenarios are likely to occur in the future (KNMI, 2009).
Besides differences between climate change in the Netherlands and global climate change, regional differences in climate within the Netherlands have been identified (KNMI, 2009). For example, it is likely that the coastal area of the Netherlands faces droughts from the G+ and W+ scenarios combined with short periods of extreme precipitation from the G and W scenarios. Overall, higher average precipitation in the provinces Noord-Holland, Zuid-Holland and Friesland is expected, compared to the other provinces (KNMI, 2009).
The development of rain-dependent raised bogs in the eastern and southern part of the Netherlands is threatened under the dry W+ scenario (Witte et al., 2009). For the low-lying part of the Netherlands, an increase of seawater intrusion is expected due to sea level rise, low groundwater levels and low river discharges in summer (Heijmans and Berendse, 2009).

2.2.3 Temperature

As discussed in section 2.2.1, water temperature increases with the air temperature. Globally, several studies have confirmed this relationship (Gooseff et al., 2005, Livingstone, 2003, Fang and Stefan, 1999, Schindler et al., 1996). This is particularly apparent in the Netherlands, since this country harbours many shallow freshwater bodies. A change in air temperature will result in a corresponding change in water temperature (Mooij et al., 2005).

An additional consequence of a temperature increase is an increase in evaporation if soil moisture is high enough and net radiation remains unchanged (KNMI, 2009). The KNMI’06 scenarios predict for 2050 an evaporation increase of 3 to 15% in summer. If this increase in evaporation is not compensated by rainfall or management actions, desiccation of the soil is possible (KNMI, 2009). This in turn could cause an extra temperature increase in summer, which could lead to more heat waves (KNMI, 2009; see also Figure 2). The W scenario predicts an increase in evaporation (mean of 10–25 mm/year) in the Netherlands in 2050. The dry W+ scenario leads to more regional changes; a substantial evaporation increase in the province of Friesland of 50–100 mm/year, and a decrease in evaporation (–25 to –10 mm/year) in the dune area along the coast (KNMI, 2009). Evaporation is also considerable for the sandy soils in the eastern part of the Netherlands (KNMI, 2009). The process of evaporation goes faster with increasing temperature, low air pressure and increasing wind (Verdonschot et al., 2007).

High temperatures also result in increased (thermal) stratification and reduced vertical mixing in deep lakes (Paerl and Huisman, 2008). Lakes will stratify earlier in spring and destratify later in autumn, due

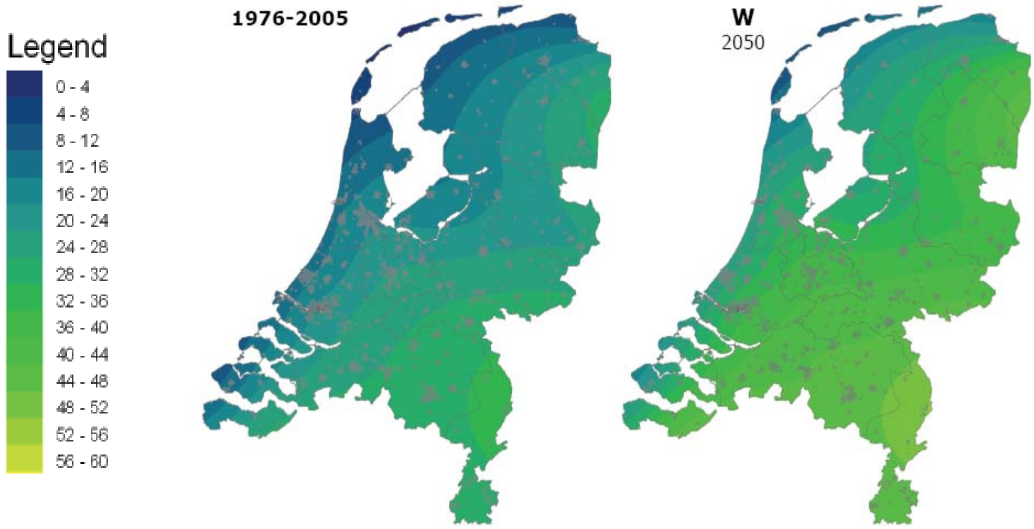


Figure 2 The average amount of summer days (≥ 25 °C) per year in the current climate (1976–2005) and around 2050 under the W-scenario. The number of summer days increases according to this scenario. The maps are based on interpolation of temperature data of the KNMI. Source: Klimaatschetsboek Nederland, KNMI, 2009.

to global warming (Paerl and Huisman, 2008). For the Netherlands, the stable water column (stratification) could easily be destroyed by the current wind speeds, according to Mooij et al. (2005).

2.2.4 Droughts

Since smaller amounts of rain in summer and increasing evaporation are predicted by the KNMI'06 scenarios, there is a risk of a long period of drought in summer. Overall, in summer, water levels will drop as well as the river discharges (Heijmans and Berendse, 2009, Bates et al., 2008, IPCC, 2007, Van Schaik et al., 2007, Roijackers and Lürling, 2007). Possible consequences are limitations for shipping, and a decreased contaminant dilution capacity, failure to meet drinking water standards and loss of biodiversity (Bates et al., 2008, Van Schaik et al., 2007, Van Vliet and Zwolsman, 2007a). There will also be a greater demand for water in dry periods (Bates et al., 2008). The worst case scenario is W+, since this scenario predicts a summer temperature increase of 3.8 °C and a summer precipitation decline of 19% in 2050 (KNMI, 2009).
Faster oxidation of peat is expected due to high temperatures and low groundwater levels in summer. As a result of this peat oxidation, CO_2 will be released from the system into the atmosphere contributing to the greenhouse gas problem. Peat oxidation may also lead to accelerated land subsidence (Van Schaik et al., 2007, Witte et al., 2009) and increased fluxes of nutrients to surface waters. Ecosystems that depend entirely on rainwater (like raised bogs), could disappear in the future (Witte et al., 2009). Small pools and streams could dry out in summer (Besse-Lototskaya et al., 2007, Loeve et al., 2006), resulting in a loss of species that depend on permanent water.

2.2.5 Floods

The average precipitation per year is expected to increase (see Figure 3). The increase in winter precipitation will lead to higher river discharges (IPCC, 2007, Bates et al., 2008, KNMI, 2009). It is

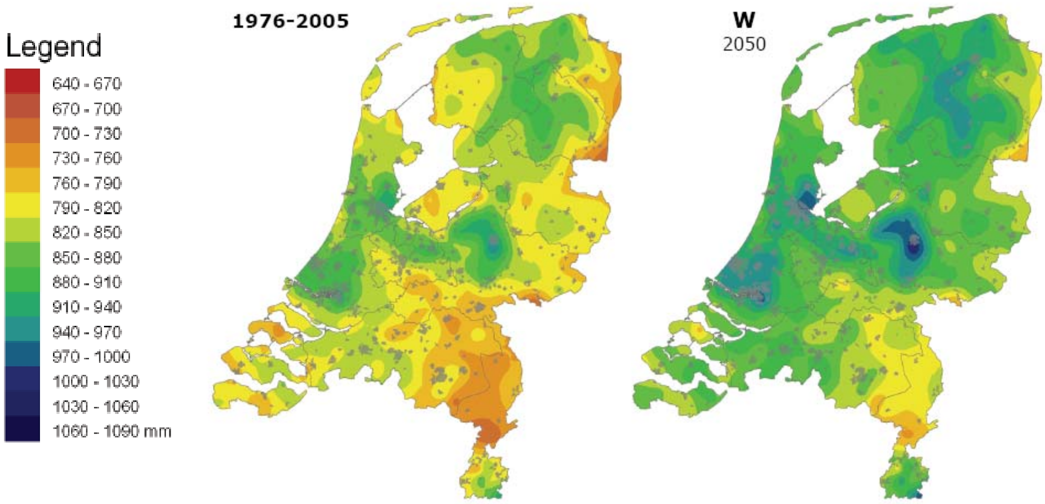


Figure 3 The average precipitation per year (mm) in the current climate (1976–2005) and around 2050 under the W-scenario. On average, more precipitation is expected. The maps are based on interpolation of precipitation data of the KNMI. Source: Klimaatschetsboek Nederland, KNMI, 2009.

expected that the winter discharges of the rivers Meuse and Rhine will increase by 3 to 10% and 5 to 20% respectively in 2050 (MNP, 2005). High river water levels and high river flow increase the probability of flooding. Long periods of rain in the stream area in winter and an increase in rainfall in the mountain area result in peak discharge for the river Rhine (KNMI, 2009). There is also an additional risk of flooding in summer due to extreme rainfall events (Heijmans and Berendse, 2009). Heavy rainfall could lead to increased run-off of nutrients from agriculture, increased erosion and a risk of sewage system overflows in urban areas (Bates et al., 2008, Van Schaik et al., 2007, Hermans et al., Heijmans and Berendse, 2009, Mooij et al., 2005). The western part of the Netherlands contains many peat areas, which could be subjected to increased flooding effects, and increased surface water salinity due to land subsidence (MNP, 2005).

3 Impact of climate change on physico-chemical water quality

- Climate change directly and indirectly affects physico-chemical water quality. The physico-chemical water quality is expected to decrease due to extreme weather events.
- Oxygen concentrations in surface water are expected to decrease.
- Climate change is expected to increase eutrophication problems in the Netherlands and may contribute to the switch of a water body from a clear to a turbid state.

3.1 Introduction

In this chapter the influence of climate change on physico-chemical water quality will be discussed. It is important to note that direct and indirect processes related to climate change affect the physico-chemical water quality. A direct process of climate change on chemical reactions in the sediment and water column is climate warming, since higher temperatures lead to higher rates of (bio) chemical reactions. For instance, nitrification and denitrification are biochemical processes directly related to temperature (Admiraal and Van der Vlugt, 1988). Changes in hydrology associated with climate change affect the physico-chemical water quality indirectly. It is expected that increased and more intense precipitation increases nutrients run off from agricultural lands to surface waters. Extreme rain events will lead to increased soil erosion and consequently the water column will become more turbid and more pollutants will be introduced (Kundzewicz et al., 2007).
Climate change will affect shallow lakes, which are numerous in the Netherlands, through a changing hydrology and climate change-induced eutrophication (Mooij et al., 2009). Often, the effect of pressure on an ecosystem is not linear; at a certain point, a switch from one stable state to another state occurs, a phenomenon called 'hysteresis'. Mooij et al. (2009) predict that climate warming lowers the critical nutrient loading at which an ecosystem switches from a clear to turbid state. This is a major problem, since high water transparency is the most important among the targets for water management and water transparency will be reduced due to climate change (Mooij et al., 2005).
The chemical water quality of Dutch surface waters has improved substantially in recent decades, particularly in the major rivers (PBL, 2008, Witmer et al., 2004). Climate change however, poses a threat to the physico-chemical quality of surface waters in the Netherlands. In the following paragraphs different parameters of physico-chemical water quality that are changing due to climate change will be discussed. These include (bio) chemical reactions, acidification, salinisation, nutrient/contaminant concentrations, stratification, light conditions and O_2 concentrations.

3.2 (Bio-) chemical reactions

3.2.1 General

The rates of (bio) chemical reactions depend on a number of factors, including the chemical nature of the reacting chemicals and the external conditions to which they are exposed. In general, higher temperatures lead to increased rates of chemical reaction. Therefore, global warming which leads to a

warmer land surface, soil and groundwater is directly associated with increased rates of (bio) chemical processes.
Sediment temperature and humidity are closely related to microbial activity. Increased temperature is expected to result in generally higher microbial activity and microbially mitigated process rates (Van Dijk et al., 2009). Higher microbial activity results in increased sediment respiration of organic material and subsequently, concentrations of dissolved organic carbon (DOC) in soils will increase. The expected increased and more intense precipitation will wash away the DOC from soils to surface waters. Light radiation is absorbed in the water column by dissolved organic matter, which results in the release of heat into the water column. Increased levels of DOC in water will result in a higher capacity to absorb light and consequently higher temperatures. Therefore, water columns with high levels of DOC will face a larger increase in temperature than water columns with low levels of DOC, when the air temperature rises (Loeve et al., 2006).

3.2.2 Nitrification and denitrification

Nitrogen is an essential nutrient in ecosystems and together with phosphorus, is the main nutrient for primary productivity. If nitrogen is present in excess, it can lead to eutrophic conditions, which adversely affect the water and habitat quality. Two biochemical processes, nitrification and denitrification, affect the processing of nitrate in water. In the process of nitrification (aerobic process), ammonium (NH_4^+) is transformed into nitrate (NO_3^-), which is used by primary producers and is therefore considered a ‘nitrate’ input process for the water. In the process of denitrification (anaerobic process), nitrate (NO_3^-) is transformed into nitrous oxide (N_2O) or nitrogen (N_2), which is ultimately released from the water column into the atmosphere and is therefore a loss of nitrate from aquatic ecosystems. Nitrous oxide is a major greenhouse gas. As these processes either contribute to or remove nitrate from the water system, they have the potential to affect water quality and ecosystem health. The rates of these two processes increase with temperature and are therefore affected by global warming (Admiraal and Van der Vlugt, 1988, Admiraal and Botermans, 1989). If concentrations of organic matter increase in the water column (e.g., as a result of erosion during heavy rainfall) the balance between nitrification and denitrification is disturbed. Micro organisms mineralise the organic matter and nitrate concentrations increase. Often, there is already an accumulation of ammonium and nitrate in environments because the nitrogen cycle has been disturbed by human activities (e.g., fertilisation).

3.3 Acidification

Most scientists agree that elevated CO_2 concentrations in the atmosphere cause acidification of the oceans (IPCC, 2007). In contrast to ocean waters, many freshwater ecosystems receive substantial amounts of carbon from terrestrial ecosystems (Van de Waal et al., 2009). This occurs mainly in the form of dissolved organic carbon (DOC). Bacterial activity mineralises the DOC into CO_2. As a result, the CO_2 concentration of lakes is usually not in equilibrium with the atmosphere (like oceans) but is related to the concentration of DOC (Van de Waal et al., 2009). Most inland waters are supersaturated with CO_2. Therefore, an increase in the atmospheric CO_2 concentration is not expected to have a significant influence on the pH of freshwater systems.
Another climate factor does have an influence on the pH of freshwater systems but makes it more alkaline rather than more acidic: increasing temperature will lead to more algal blooms. This causes an increase of CO_2 from the water uptake, which in turn causes the release of OH^- ions because of (bi-) carbonate equilibria in the water. Furthermore, pH can rise due to the extension of the phytoplankton growing season and increased erosion resulting in increased deposition of cations, causing higher alkalinity of water systems (Loeve et al., 2006). This implies that indirect effects of climate change have a positive influence on the suppression of freshwater acidification. Although Parry (2000) argues

Box 1: a ditch in the past and in the future?

A drawing of a ditch in the past.

A ditch in 2007- a more common picture in the future?

The Netherlands is famous for its polders and the numerous ditches running through them. Ditches have an important function as they transport excess water to water systems outside the polder. Ditches are used for controlling water levels and are an important infrastructural part of water management. Climate change puts additional pressure on the physico-chemical water quality. The most important factor related to climate change negatively affecting ditches is an increasing temperature (Verdonschot et al., 2007). High water temperatures will lead to oxygen depletion in the ditch and as a result, biodiversity will decline strongly. Heavy rainfall events will also negatively affect the physico-chemical water quality in a ditch. Often, ditches are in the surroundings of agricultural lands. Heavy rainfall will lead to the erosion of this land, causing eutrophication and low water transparency. Macrophytes will disappear and phytoplankton blooms and duckweed will dominate.

that climate change can result in increasing acidification of freshwater bodies, this is not likely to occur in the Netherlands, since most freshwater systems are already supersaturated with CO_2 and are therefore less sensitive to acidification due to their high buffer capacity (personal communication, Wolf Mooij).

The acidification of soils and freshwaters results mainly from acid precipitation and acid deposition. Acid precipitation is caused by the emissions from SO_2, NO_x and NH_3, mainly from traffic, agriculture and industry (Likens et al., 2007). The climate change KNMI '06 scenarios predict an increase in mean annual precipitation, which can lead to an increased input of acidifying components into the soil and surface water, depending on the amount of acidifying atmospheric compounds (Van Dijk et al., 2009).

3.4 Salinisation

The salinisation of freshwater can occur either through the intrusion of seawater or through an increase in chloride concentration in surface waters. Currently, most chloride enters Dutch water systems from French salt mines via the rivers Rhine and Meuse. The hot and dry summer of 2003 revealed that salinisation of Dutch waters is likely to become a problem in the future. The worst-case scenario of the KNMI (W+) predicts an increase in average summer temperature of 3.8 ºC and an average summer

precipitation decrease of 19%. According to this scenario, the summer of 2003 would be an average summer in 2050.
Sea level rise can contribute to the salinisation of rivers connected to the sea and groundwater in low lying areas. In hot summers, river discharges will be low and the predicted sea level rise will increase the intrusion of seawater. At the moment, saltwater intrusion has the greatest influence on the groundwater close to coastal areas, particularly in polder areas (Van Dijk et al., 2009). The coastal freshwater aquifers are the most vulnerable to salinisation by the advance of seawater intrusion (Van Dijk et al., 2009). Saltwater intrusion poses a threat to drinking water, crop irrigation and freshwater aquatic life.

3.5 Nutrient and contaminant concentrations

3.5.1 General

Extreme weather events such as heavy rainfall and heat waves influence the concentrations of nutrients and contaminants in the surface water. Increased and more intense precipitation can lead to flooding in the Netherlands. Flooding poses risks to ecosystems. Contaminated water can spread over soils and cause soil contamination. Flooded landfills can cause the spreading of toxic compounds through the water. Furthermore, ground and surface waters can be contaminated through leaching of nutrients, pesticides and heavy metals (Claessens and Van der Wal, 2008).
Extreme droughts can lead to low water discharges and dehydration events, which can affect the concentration of nutrients and contaminants. Dehydration events will cause the cessation of microbial activity, which results in an accumulation of nutrients such as nitrogen and phosphates. Biological degradation of toxicants can also be slowed down or stopped. Furthermore, periods of low discharge can cause a increase in the concentration of harmful substances, which can have negative effects on the water quality and aquatic organisms.
The bioavailability of heavy metals can change due to extreme weather events. The behaviour of heavy metals is complex and is determined by several parameters, such as pH, concentration of organic matter, minerals and redox potentials (Claessens and Van der Wal, 2008). Periodic exchanges of wet and dry periods lead to less stable forms of metal deposits and consequently, to the increased bioavailability of heavy metals (Claessens and Van der Wal, 2008).

3.5.2 Extreme events in the river Meuse

A study performed in the river Meuse proved that extreme weather events (drought and flooding) had a negative impact on the water quality (Van Vliet & Zwolsman, 2007a). In the hot summer of 2003, macro-ions such as fluoride, bromide, sulphate, sodium, potassium and magnesium increased in concentration as a result of lower dilution because of decreased discharges. Nutrient concentrations also reached elevated levels due to lower dilution. Nitrate was an exception; concentrations of this nutrient decreased. This can probably be explained by lower run-off from agricultural land and increased denitrification due to higher water temperatures. Total concentrations of heavy metals and polycyclic aromatic compounds (PAHs) showed little change during the drought of 2003 (Van Vliet and Zwolsman, 2007b). During periods of high water however, total concentrations of heavy metals and PAHs increased. In the wet year of 1995, the standards for intake of surface water for the preparation of drinking water were exceeded in the river Meuse for some substances.

3.6 Stratification

Stratification is the building up of layers in a water column (particularly in deep lakes), caused by density differences. Usually, stratification in water is caused by temperature differences but it can also be caused by density differences of salinity or oxygen. Density of pure water is a quadratic function of water temperature, with the highest density at 3.98 ºC (Figure 4). Water of lower density (in epilimnion: top layer) floats on water of higher density (hypolimnion: bottom layer); this implies that warmer water floats on colder water.
Stratification influences physical, chemical and biological properties in water systems (Bates et al., 2008). As a result of global warming, the water temperature in the epilimnion and the duration of stratification will increase, resulting in higher risk of oxygen depletion below the thermocline (transition zone between epilimnion and hypolimnion) (Alcamo et al., 2007). Strong winds are able to break stratification by mixing the water column. It is unclear whether the prevalence of strong winds will increase in the future (KNMI, 2008).
Anaerobic conditions in bottom waters increase the risk of internal phosphate (P) loading (P release from the sediment). Stronger stratification reduces water movement across the thermocline, inhibiting the upwelling and mixing that provides essential nutrients to the food web. Above the thermocline, in the epilimnion, there is risk of depletion of nutrients by primary producers. There have been decreases in nutrients in the surface waters and corresponding increases in deep-water concentrations of European lakes because of reduced upwelling due to greater thermal stability (Bates et al., 2008).
In the Netherlands, summer stratification mostly occurs in deep lakes, which were created by sand excavation. However, in shallow lakes daily stratification can occur, which disappears during the night (personal communication Wolf Mooij). Many shallow lakes are used for recreational purposes and oxygen depletion as a result of stratification will have a negative impact on their recreational value.

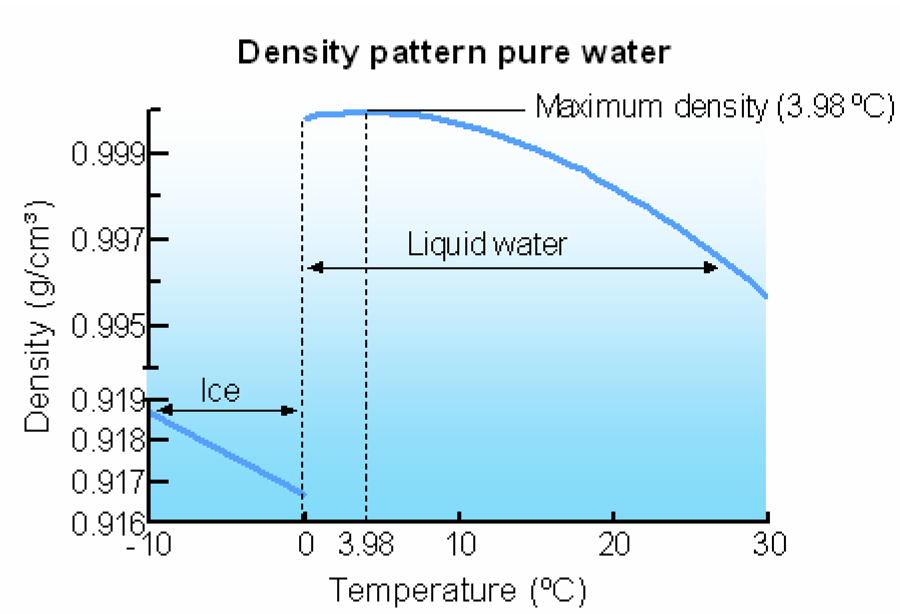


Figure 4 Density pattern of fresh water. Fresh water has its highest density at 3.98 ºC.

Figure 5 Turbid water caused by high run-off after heavy rain. More common in the future?

3.7 Light conditions

Climate change can reduce the availability of light in surface waters. More intense precipitation will lead to the increased erosion of soils and consequently, to the increasing turbidity of the water column (see Figure 5). Climate warming is predicted to reduce the critical nutrient loading at which a water body switches from a clear to a turbid state (Mooij et al., 2009). There are several factors responsible for this prediction, especially the higher growth rate of phytoplankton and increased availability of phosphorus, caused by higher mineralisation and release (Mooij et al., 2007). Thus, climate change reduces the transparency of water bodies in several ways: it increases particulate matter and nutrient loading (soil erosion) and decreases the critical nutrient threshold value at which a system switches from a clear to a turbid state.
Turbidity reduces the light availability in the water column and negatively influences aquatic organisms, phytoplankton and macrophytes. Furthermore, the transparency of water plays an important role in the targets of the Water Framework Directive.

3.8 Oxygen concentrations

Oxygen is an essential chemical compound for life in aquatic environments. Oxygen is used for breathing and biodegradation by aquatic organisms. The primary sources of dissolved oxygen are the atmosphere and photosynthesis (Kalff, 2000). Dissolved oxygen concentrations of 5 mg/l or more are acceptable for most aquatic life, concentrations below 2–3 mg/l are considered hypoxic and result in the suffocation of most aquatic species (Ficke et al., 2007).
Global warming affects the concentration of oxygen in water systems. The amount of oxygen that can dissolve in water decreases with temperature (Kersting, 1983). In other words, higher water temperatures lead to decreased concentrations of dissolved oxygen. At the same time, the aerobic

metabolic rates of most cold-blooded aquatic organisms and respiration by bacteria increase with temperature, so an increase in temperature both decreases the dissolved oxygen-supply (through lower solubility) and increases the biological oxygen demand (Ficke et al., 2007). Aquatic organisms exposed to an increase in water temperature can face an ‘oxygen squeeze’, where the decreased supply cannot meet the increased demand. Reduced oxygen concentrations tend to alter biotic assemblages and biochemistry, reduce biodiversity and the overall productivity of lakes and streams (Bates et al., 2008). In general, species that prefer anoxic conditions will be favoured.

4 Impact of climate change on ecology

- Climate change is expected to aggravate current problems for ecosystems, such as eutrophication, pollution and habitat fragmentation.
- Climate change causes a shift of geographical species distribution in a northerly direction. As a result, new species may invade the Netherlands.
- Climate change causes changes in the timing of the life-cycle events of flora and fauna. Consequently, food mismatches may occur.
- Shifts in the species composition of micro-organisms and macrophytes communities are expected. Cyanobacterial blooms are expected to increase.
- The number of invasive species is expected to increase.
- The ecological effects of extreme weather events are largely unknown.

4.1 General ecology

4.1.1 Introduction

Flora and fauna are under heavy pressure in the Netherlands. The remaining size of plant and animal populations in the Netherlands is now 10–15% of the potential diversity that would have been present in an undisturbed, optimal natural situation (PBL, 2008). What remains, however, is valuable from an international perspective because of its unique character, owing to the country's position in a delta (PBL, 2008). Examples of unique Dutch ecosystems are wet heath lands, dunes, streams, swamps, brackish environments and salt marshes. These ecosystems are under pressure as a result of acidification, eutrophication, pollution, dehydration and habitat fragmentation. Climate change will constitute an extra pressure on the ecosystems, exacerbating current problems.

In this chapter, the influence of climate change on the aquatic ecology will be discussed in three parts. In this first section, the general responses of biota to climate change will be discussed. In the following sections of this chapter, the influence will be discussed more in detail, at the level of micro- and macroecology.

Common responses of organisms to global warming can be distinguished, including a northward shift of species to higher latitudes (and altitudes) and an earlier start of life-cycle events like emergence, flowering and bird migration (Daufresne et al., 2009, Walther et al., 2002, Heijmans and Berendse, 2009, Loeve et al., 2006, Van den Hoek and Verdonschot, 2001, MNP, 2005). Another suggested ecological response to global warming is a reduced body size among cold-blooded organisms (Daufresne et al., 2009). Daufresne et al. (2009) observed a negative effect of global warming on the body size of fish and plankton, from the individual to the community level.

In this chapter, the two most common responses of organisms to global warming (shift of species and earlier start life-cycle events) are explained, followed by a description of some indirect effects of climate change (mainly changes in the hydrological cycle) on organisms.

4.1.2 Species shifts

Species have a tolerance for maximum and minimum temperatures. Due to increasing temperatures, boundaries shift northwards and especially northern species are forced to shift along (Nijhof et al., 2007).

For many taxonomic groups, a worldwide upward shift of species ranges occurred during the 20th century (Walther et al., 2002). For instance, many butterfly species in North America and Europe moved 200 km northward over 27 years due to increased temperatures. Another example is the increasing abundance of warmth-preferring zooplankton and fish species along the Californian coast (Walther et al., 2002). Conversely, some species ranges decreased, like that of the Arctic fox (Walther et al., 2002).

In general, species with a northern distribution in Europe (with the Netherlands as the southern boundary) can disappear from the Netherlands in the future. Species with a southern distribution in Europe (with the Netherlands as the northern boundary) can appear or expand northwards in the Netherlands, due to improved climatic conditions (Nijhof et al., 2007). Many warmth-preferring bird, insect, fish and plant species already show a northward shift and enrich (or alter) the Dutch flora and fauna (MNP, 2005, Heijmans and Berendse, 2009). Figure 6 shows a graph of increases and decreases of warmth- and cold-preferring species in the Netherlands.

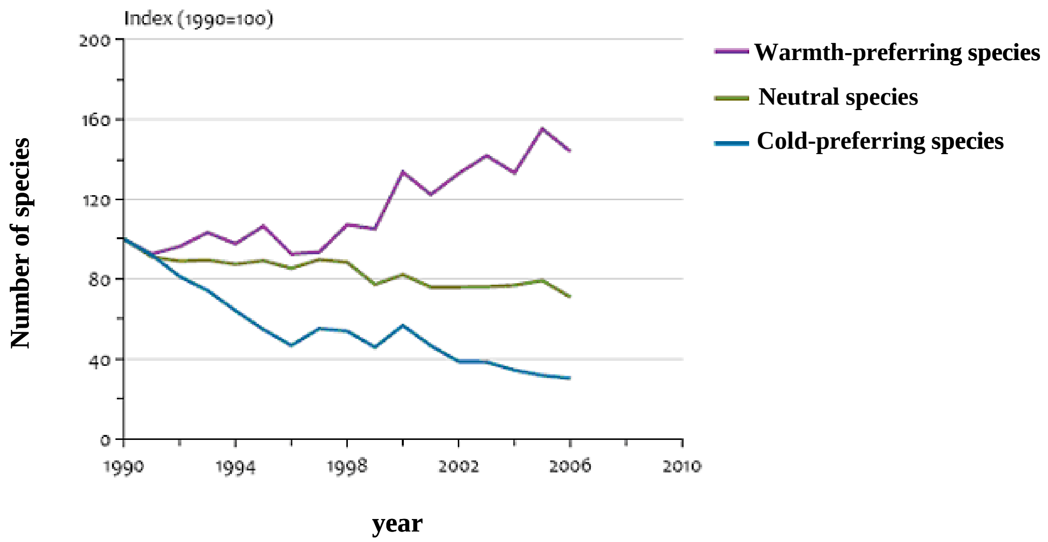


Figure 6 Cold-preferring species have declined, warmth-preferring species have increased and neutral species have remained more or less stable in the past few years in the Netherlands (adapted from PBL, 2009).

Examples of species that have increased in the Netherlands are the Comma butterfly (*Polygonia c-album*), the bird species common kingfisher (*Alcedo atthis*), and the little egret (*Egretta garzetta*), the bee orchid (*Ophrys apifera*) and the scarlet dragonfly (*Crocothemis erythraea*) (MNP, 2005, Heijmans and Berendse, 2009). Subsequently, species that could disappear from the Netherlands are the dragonfly *Leucorrhinia rubicunda*, and the Moor frog (*Rana arvalis)*. These are species with a northern distribution (MNP, 2005, Heijmans and Berendse, 2009, Van den Hoek and Verdonschot, 2001). Species shifts of fishes in the North Sea are already observed, species with a southern distribution showed a small increase (Hiddink and Ter Hofstede, 2008, Perry et al., 2005). In the river Rhône in

France, southern, thermophilic fish and invertebrate taxa have gradually (in 20 years) replaced more northern, cold preferring species due to climate warming (Daufresne et al., 2004).

For faunal species in stream ecosystems in the Netherlands, it is predicted that 12% of the species disappears, 17% arrives and 71% remains unchanged due to climate change (Van den Hoek and Verdonschot, 2001). Freshwater fish species that could benefit in the Netherlands from higher temperatures are *Cypriniformes* like the European Chub (*Squalius cephalus*) and sunbleak (*Leucaspius delineatus)*, and catfishes (Verdonschot et al., 2007).
A risk of high winter temperatures in the Netherlands is an increase of exotic species, which can become invasive and damage whole ecosystems (M. de Lange, personal communication). This subject will be discussed in more detail in the following sections.

4.1.3 Timing and processes

Besides shifts in geographical ranges, a common response of biota to global warming is a change in phenology (timing of life-cycle events). Because of the increasing temperatures, spring events start earlier. Spring activities like flowering, the appearance of butterflies and migratory birds in Europe and the United States have occurred earlier since the 1960s (Walther et al., 2002). In Europe, the flowering and leaf-unfolding of numerous plant species have occurred 1.4 to 3.1 days per decade earlier in the past 30 to 48 years (Walther et al., 2002).
Earlier spring activities can lead to food-mismatches between different components of the food web (Daufresne et al., 2009, MNP, 2005, Heijmans and Berendse, 2009). For instance, some birds like the Pied Flycatcher (*Ficedula hypoleuca)* lay their eggs too late to coincide with the caterpillar peak (Visser and Rienks, 2003). Others, like the Blue Tit *(Cyanistes caeruleus*) lay their eggs increasingly earlier in the year, so this species has adjusted to the early spring (MNP, 2005). In aquatic ecosystems, early phytoplankton blooms could lead to a food-mismatch with some zooplankton species (Verdonschot et al., 2007). In Lake Washington (USA), warming of the lake since the 1960s has caused earlier thermal stratification and an early spring diatom bloom. This has resulted in a temporal mismatch with *Daphnia* populations, which have showed a long-term decline (Winder and Schindler, 2004a).
Furthermore, the growing season is prolonged owing to the early spring and late autumn. The growing season for plants in the Netherlands have increased by on average one month since the end of the 1980s (Van Vliet, 2008).
Since all aquatic organisms besides birds and mammals are cold-blooded, a temperature increase implies an acceleration of physiological processes like growth, reproduction, metabolism and emergence (Van der Grinten et al., 2007, Verdonschot et al., 2007). For instance, the rate and moment of insect emergence is determined by temperature, although this is very species-specific. Other observed responses of water insects to increased temperatures are early egg deposition (*Hyllella azteca)*, changes in sex ratios (*Lepidostoma vernale*) and a lacking diapause (Verdonschot et al., 2007). Warming of shallow lakes in the Netherlands during 1971–2006 led to an earlier start (3 weeks) of growth in bream (Mooij et al., 2008). Most fish species in temperate regions do not grow in winter because of the low temperatures. However, higher winter temperatures in the future could make growth and development possible for these fish (Verdonschot et al., 2007).

4.1.4 Indirect effects of climate change

Other climate-related events like floods and droughts could also affect aquatic biota (Besse-Lototskaya et al., 2007). High river discharges combined with a high stream flow result in the relocation of sediments. The result is that some biota will wash away to unsuitable habitats and some organisms will become buried in the sediment. Macrophytes, invertebrates, attached algae and fish eggs could be

crushed by moving sediment (Besse-Lototskaya et al., 2007). However, the supply of new materials can create new habitats for other organisms (Besse-Lototskaya et al., 2007).
Long periods in summer without precipitation lead to low river discharges and even to the complete drying out of streams. When water levels are low, certain bank habitats like macrophytes become unreachable for aquatic organisms that depend on the macrophytes for reproduction, food and shelter. Furthermore, organisms will be more concentrated when water levels are low, resulting in more biological interaction. When a stream completely dries out, species without special adjustments (diapause, mobility) will die in large numbers (Besse-Lototskaya et al., 2007). When small pools and ditches dry out, a loss of species occurs, only some midge, fly and beetle species survive (MNP, 2005).

4.2 Microecology and macrophyte ecology

4.2.1 Introduction

In this section, the influence of climate change on various groups of micro-organisms (viruses, bacteria, protozoa, algae) and macrophytes in Dutch freshwater ecosystems is discussed. Climate change is likely to affect microbiological water quality but it is as yet unclear in what way. Aspects related to climate change that are expected to influence microbiological water quality are temperature, the concentration of carbon dioxide in the atmosphere, run-off from land, storm water overflow, flow rate of the surface water and extreme weather events (Schijven and De Roda Husman, 2005). Pathogenic microorganisms of human and animal faecal origin enter surface waters by wastewater discharges and by run-off from the land (Schijven and De Roda Husman, 2005). They include viruses (e.g., noroviruses, enteroviruses, hepatitis A and E viruses), bacteria (e.g., *Campylobacter*, *Salmonella*, *E. coli* 0157) and parasitic protozoa (e.g., *Cryptosporidium*, *Giardia*) (Schijven and De Roda Husman, 2005). Extreme weather events, such as flooding, contribute to increasing numbers of these micro-organisms in surface waters.
The effect of warming, a rising atmospheric carbon dioxide level and a changing hydrology on viruses, bacteria, protozoa, algae and macrophytes will be evaluated.
First, the influence of an increasing temperature and carbon dioxide level on these organisms will be described. Second, the influence of a changing hydrology will be discussed. The chapter ends with a consideration of cyanobacterial blooms.

4.2.2 Temperature

4.2.2.1 Microbes

Primary producers capture much of the energy that flows through freshwater food webs and microbes such as bacteria, viruses and protozoa are responsible for the bulk of the biogeochemical processes (including decomposition and nutrient recycling) in aquatic systems (Dodds, 2002). The ecology of primary producers is much better understood than that of microbes. Therefore, it is hard to predict what the effects of a changing climate will be on the ecology of microbes. Studies addressing the sensitivity of the microbial community to environmental changes have not presented a consistent pattern. Climate change is likely to alter environmental conditions that are present within an ecosystem. As microbial communities are presented with new environmental conditions, shifts in community composition may occur as different sets of organisms outcompete others for available resources in the new environment (Waldrop and Firestone, 2006).
Although it is hard to predict if and what kind of changes may occur in microbial community composition, predictions about bacterial productivity can be made. Climate change induced eutrophication will promote phytoplankton production. In general, increased phytoplankton abundance

will lead to increased decomposition by bacteria, when the phytoplankton starts to decay. This effect was observed in an experiment where in nutrient enriched treatments, high autotrophic growth rates were observed, followed by increased heterotrophic bacteria production (Andersson et al., 2006). Climate change induced eutrophication and warming are likely to increase respiration by bacteria. Increased respiration puts a higher demand on the oxygen availability and can deplete the oxygen in a water system, leading to anoxia.
Some bacteria exhibit higher growth rates with increasing temperature. An example is the bacterium *Clostridium botulinum* type C. *Clostridium botulinum* type C causes botulism among wild animals in fresh waters. Botulism is fatal to water fowl and other aquatic animals but these bacterial strains are not pathogenic to humans (Mooij et al., 2005). Besides high temperatures (> 20 °C), this bacterium prefers anoxic conditions. Therefore, climate change may promote this bacterium in the future. So far, outbreaks of botulism among wild waterfowl in the Netherlands have occurred mainly in hot summers (Mooij *et al*, 2005). Other bacteria, like *Campylobacter*, die off at elevated temperatures and increased sunlight (Koenraad et al., 1997, Thomas et al., 1999).

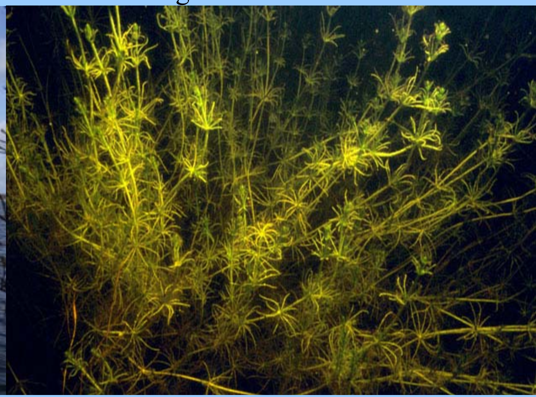
Another large group of microbes in aquatic ecosystems are the viruses. Viruses are not really organisms because they cannot survive without a host and are not capable of basic metabolic function (Dodds, 2002). Due to the selective and parasitic nature of viruses, viral and host abundances are expected to co-vary (Fuhrman, 1999). Planktonic viruses have bacteria and algae as hosts. Viral population dynamics have been reported to be closely linked to microbial and algal population dynamics in aquatic environments (Tijdens et al., 2008). In general, viral abundance increases with increasing productivity of water systems (Filippini et al., 2008). This suggests that climate induced eutrophication may lead to an increase in viral abundance. However, there is still little knowledge on the ecology of viruses in freshwater environments (Tijdens et al., 2008).

4.2.2.2 Primary producers

Algae are primary producers in aquatic food webs. The influence of a temperature increase on algal communities can be shown by changes in primary productivity (photosynthesis), growth rate and species composition.
In principle, warming increases primary production. At very high temperatures, a reduction of primary production may take place but this is not expected to occur in Dutch freshwaters, where water temperatures should remain below 30 ºC (Kerkum et al., 2004). Several studies showed an increased productivity in phytoplankton communities due to temperature elevation (Kerkum et al., 2004). However, Verdonschot et al. (2007) expect that the direct effects of a temperature increase on primary production of algae will be limited. They suggest that higher temperatures will demand higher light intensity for photosynthesis, which is often not available in natural situations. In natural situations light conditions are often suboptimal because of turbid water or shading by macrophytes (Verdonschot et al., 2007).
From laboratory experiments it seems that growth rates of algae respond directly to elevated temperatures, if nutrients and light are not limiting and the temperature does not exceed the temperature optimum of the particular species (Verdonschot et al., 2007). The optimum growth rate of many algae species ranges from 20–25 °C. Some species reach their optimum growth rates at higher temperatures (Verdonschot et al., 2007). These species could benefit from higher water temperatures and alter the species composition and diversity of the phytoplankton community. A temperature increase favours cyanobacteria directly through increased growth rates (Jöhnk et al., 2008, Mooij et al., 2005). Since the growth rate of these primary producers is restricted below 20 °C, they would benefit from a temperature increase (Jolanda Verspagen, personal communication).

Box 2: a lake can switch to a turbid state as a result of climate change.

Lake Botshol



Chara hispida, a common plant in clear lakes.

According to the concept of alternative stable states, lakes can be locked in either a macrophyte dominated clear water state or a phytoplankton dominated turbid state. In the Botshol Nature Reserve (near Abcoude, West Netherlands), the two shallow lakes often switch after wet winters from a macrophyte dominated clear state to a phytoplankton dominated turbid state. In wet winters, phosphorous and humic acid run-off from land caused by high groundwater levels, result in increased phytoplankton density and consequently, low water transparency. An important and desired macrophyte species in the Botshol are the Characeae. Populations of Characeae are strongly reduced after wet winters (Rip et al., 2007). The predicted warmer and wetter winters result in more nutrients run-off, increasing phytoplankton density and reducing water transparency. This will increase the instability of the Characeae populations.

Cyanobacteria and green algae dominate the phytoplankton community at water temperatures of 20 °C and higher, where silicate, nitrogen or light is limited. Conversely, diatoms dominate in waters that contain a lot of silicate and nitrogen and less phosphorus, and where the water temperature is 14 °C or less. In general, cyanobacteria dominate in waters with temperatures above 25 °C (Verdonschot et al., 2007). De Senerpont Domis et al. (2007) performed a microcosm experiment, which showed that cyanobacteria responded more strongly to rising temperatures than green algae and diatoms. The elevated temperature resulted in a high growth rate, followed by a peak abundance of cyanobacteria. In general, the dominance of phytoplankton communities by cyanobacteria is likely if climate change continues (Paerl and Huisman, 2008, Pires, 2008, De Senerpont Domis et al., 2007, Mooij et al., 2005). Also for phytobenthos, the benthic algal community, higher temperatures seem to favour cyanobacteria over diatoms (Van der Grinten et al., 2005). Changes in algal communities that occur due to a temperature increase, affect higher trophic levels like zooplankton and fish (Verdonschot et al., 2007). The previously mentioned advantage of cyanobacteria due to warming together with human activities like shipping increases the risk of invasions of exotic cyanobacteria. The subtropical filamentous cyanobacterium *Cylindrospermopsis raciborskii* was first reported in France in 1994 and is currently recorded in several temperate areas, including the Netherlands (Briand et al., 2004, Mooij et al., 2005). This recent migration to mid-latitudes possibly results from a combination of its wide tolerance to climatic conditions, including warming, which makes the environmental conditions for its growth ideal at mid-latitudes (Briand et al., 2004). This species prefers high water temperatures (> 20 °C) and high nutrient levels. The rapid spread of this cyanobacterium is cause for concern because it produces the very harmful toxins cylindrospermopsin and saxitoxin (Briand et al., 2004, Mooij et al., 2005).

Although *C. raciborskii* is not yet common in the Netherlands, it could cause damage to the ecology, health and economy in the future and if it manages to establish itself here.

4.2.2.3 Macrophytes

Temperature influences photosynthesis, reproduction, morphology and development of macrophytes (Verdonschot et al., 2007). In many cases, a temperature increase has a positive effect on photosynthesis unless the temperature optimum of the particular species is exceeded (Verdonschot et al., 2007). Earlier flowering, higher growth rate, a larger amount of leaves and larger-sized leaves are effects of elevated temperatures on macrophytes. However, these effects are species specific. Effects of elevated temperatures were observed for *Nymphoides peltata* (larger-sized leaves) and *Equisetum fluviatile* (earlier growth) in different field studies (Verdonschot et al., 2007). For certain pondweeds (*Potamogeton* and *Chara)* temperature elevation results in a decline in plant cover. *Potamogeton* species even disappear when the water temperature is higher than 25 ºC (Kerkum et al., 2004).
Besides physiological effects, higher temperatures can also affect the composition of macrophyte communities. Macrophytes that have a temperature-dependent dormant period (e.g., seeds) could emerge earlier due to warmer springs. This can result in a competitive advantage in comparison with macrophytes that have a day length-dependent dormant period (Verdonschot et al., 2007).
It is expected that the number of successful establishments of invasive macrophytes will increase due to increasing globalisation and climate change. The main route for establishment is via human activities such as gardening and pond and aquaria installation (De Lange et al., 2008). Recently introduced macrophytes include *Myriophyllum heterophyllum*, *Elodea spp*. and duckweed species (De Lange et al., 2008).
Currently, many problems are caused by floating pennywort (*Hydrocotyle ranunculoides).* Floating pennywort is a tropical plant that now has a worldwide distribution and has been present in the Netherlands since 1994. In Dutch eutrophic waters this macrophyte is able to overgrow entire water bodies, inhibiting light penetration into the water below, which finally results in oxygen depletion. Therefore, water managers combat this macrophyte but this is difficult and expensive. As a result, floating pennywort also causes economic damage. The costs in 2007 for the removal of this plant by the water boards were approximately 2 million euros. Because floating pennywort can grow into a new plant from a small fragment of material, suppression of this macrophyte is difficult (Van der Meulen, 2009).

4.2.3 Carbon dioxide

It is difficult to assess the direct influence of higher atmospheric CO_2 concentrations on aquatic ecosystems. First of all, the concentration of carbonate and bicarbonate in the water does not change linearly with atmospheric CO_2 concentrations because of many processes taking place in the water that influence the inorganic carbon pool. Secondly, higher inorganic carbon concentrations in the water only increase the primary production of algae or macrophytes in case of carbon limitation. However, growth rates can vary widely among species, thereby changing ecosystem composition. Thirdly, different groups of species react differently to changing inorganic carbon concentrations in the water. In general, algae have a higher affinity for inorganic carbon than macrophytes and among macrophytes significant differences occur because some can only take up CO_2 while others can also take up HCO_3^- (Schippers et al., 2004a). Because of the large difference between (groups of) species, conflicting information can be found in the literature (Van de Waal et al., 2009, Verdonschot et al., 2007, Schippers et al., 2004b, Jolanda Verspagen, personal communication).
Many lakes are supersaturated with CO_2 because they receive organic matter from the catchment, which decomposes in the lake (Van de Waal et al., 2009). In these systems an increase in productivity due to elevated CO_2 in the atmosphere is not expected. However, as a result of human activity, the input of nitrogen and phosphorus to the global biochemical cycle exceeds that of the C-input by several

orders of magnitude (Schippers et al., 2004b). As a consequence, nutrient-rich and C-limiting freshwater systems will be more common in the future. Schippers et al., (2004b) suggest that in these systems increased atmospheric CO_2 may boost phytoplankton blooms, which are already causing major water quality problems.
Although it is difficult to assess the effects of higher atmospheric CO_2 concentrations on aquatic ecosystems, changes in species composition can be expected (Schippers et al., 2004).

4.2.4 Hydrological cycle

4.2.4.1 General

Predicted increases in precipitation amounts will have a large influence on micro-organisms and macrophytes. Many micro-organisms enter the surface water via waste water discharges and run-off from the land (Schijven and De Roda Husman, 2005). Increased precipitation leads to an increase in run-off from the land and sewage system overflows. Consequently, more micro-organisms like enteric viruses and protozoa are introduced, leading to peak concentrations of these micro-organisms in surface waters (Schijven and De Roda Husman, 2005). The bacterium *Clostridium botulinum* is expected to become more abundant in fresh waters due to increased precipitation and storms. Rainfall and storms enhance resuspension of the sediment that the bacterium inhabits (Mooij et al., 2005).

4.2.4.2 Primary producers

Extreme weather events such as storms affect primary producers in the water column.
Strong winds can prevent surface blooms of phytoplankton through mixing of the water column, and consequently reduce the competitive advantage of buoyant cyanobacteria (Mooij et al., 2005). Strong winds also increase the turbidity of aquatic systems, which prevents the establishment of submerged macrophytes (Mooij et al., 2005). However, it is not certain that more wind will occur in the future (KNMI, 2009, Mooij et al., 2005).
Nevertheless, summer droughts and intense precipitation (in summer and winter) will further enhance the dominance of cyanobacteria in freshwater ecosystems (Paerl and Huisman, 2008). Due to low water levels in summer, nutrient levels will be more concentrated resulting in more eutrophication, which promotes cyanobacterial blooms (Paerl and Huisman, 2008).
This also applies to heavy rainfall events, which cause increased eutrophication due to the earlier-mentioned increased nutrient run-off from the land to surface waters (Paerl and Huisman, 2008, Roijackers and Lürling, 2007, Mooij et al., 2005).
In addition, salinisation can also favour cyanobacteria, because several cyanobacteria, like *Microcystis* species from the Delta area, are quite salt tolerant (Paerl and Huisman, 2008, Jolanda Verspagen, personal communication).
Macrophytes are also influenced by changes in the hydrology. For example, droughts influence macrophytes. Some plants depend on temporary droughts for germination (Loeve et al., 2006) but droughts can also have negative effects. After the dehydration of small pools in the dry and hot summer of 1976 for example, nuisance plant species like water pennywort (*Hydrocotyle vulgaris*) expanded very quickly in the newly filled pools (Loeve et al., 2006).

4.2.5 Cyanobacterial blooms

In the sections above, three climate factors were discussed, along with their effects on microecology and macrophytes. Cyanobacteria are able to take advantage of all three of these factors.
As previously stated, factors like temperature increase, salinisation, and eutrophication all favour the dominance of cyanobacteria. These factors result, in combination with a more stable water column (due to enhanced stratification), an earlier and prolonged growing season and increasing water residence times, in blooms of cyanobacteria (Paerl and Huisman, 2008) (Figure 7).

In these eutrophic systems, nutrients are present in excess and light is limited. According to Jöhnk et al. (2008), buoyant cyanobacteria like *Microcystis* will dominate in these systems because they can increase their own access to light (buoyancy) and are better competitors for light than other, non-buoyant phytoplankton species. There are many (harmful) consequences of surface blooms, which can affect higher trophic levels. Initially, cyanobacteria are low-quality food for their consumers. Cyanobacteria contain no or little unsaturated fatty acids that are essential for zooplankton species and zebra mussels (Mooij et al., 2005, Marieke de Lange, personal communication).
Decomposition of the blooms results in oxygen depletion, which can ultimately kill fish. Fish and birds can also be killed by the produced cyanobacterial toxins, which are also a threat to humans, cattle and pets (Paerl and Huisman, 2008, Jöhnk et al., 2008). Furthermore, blooms suppress the occurrence of macrophytes and this results in a loss of habitat for invertebrates and fish (Paerl and Huisman, 2008, Jöhnk et al., 2008).
In the Oostvaardersplassen, an important bird sanctuary in the Netherlands, dense surface blooms of cyanobacteria have occurred together with mass mortalities of birds (especially ducks and geese) (Jöhnk *et al*, 2008).

Figure 7 Water in Nieuwegein contaminated with cyanobacteria.

4.3 Macroecology

4.3.1 Causes of changes in species composition

Climate change will change the composition of macro invertebrate species through a number of mechanisms. These mechanisms include increasing temperature and increasing number of invasive species, changing hydrology and sea level rise. These will not necessarily operate independently and synergy or interactions between them is probable (Ficke et al., 2007). For the purpose of clarity however, they will be discussed separately. Furthermore, the importance of site specificity and deviations in local climate imply that specific predictions on the effect of climate change can only be made with a specific ecosystem and a specific region in mind (Mooij et al., 2005). In this chapter however, we will describe general processes associated with climate change that will cause a change in composition and diversity of macro invertebrates.

4.3.2 Increasing temperature

Aquatic organisms (except birds and mammals) are cold-blooded, which means that their body temperature is equal to the surrounding temperature. Global warming has a direct effect on water temperature and water temperature has a direct effect on aquatic organisms. Therefore, water temperature influences growth, metabolic rates, reproduction, emergence and dispersal of macro invertebrates (Verdonschot et al., 2007). Increased water temperature is an important cause of changes in aquatic species composition and diversity (Daufresne et al., 2004).
Laboratory and field experiments have shown that increased temperatures resulted in physiological changes in macro invertebrates, such as higher growth rates, reduced survival and reduced egg production, increased generations per season and earlier emergence (Elliot, 1987, Hogg & Williams, 1996, Cereghino et al., 1997). Field observations from lakes and rivers that have been warmed by cooling-water from industry show similar physiological changes in macro invertebrates (Verdonschot et al., 2007). Observations from undisturbed natural freshwater systems showing physiological changes in macro invertebrates caused by global warming are generally lacking and are so far predicted by models. Braune et al. (2008) developed a population dynamic model that predicts an increased development speed under global warming, an extension of the northern range limit and changes in the phenology of the dragonfly *G. vulgatissimus*.
The model of Braune et al. (2008) predicts an extension of the northern range limit of the dragonfly species. Shifting of geographical ranges can occur as a result of rising temperatures, which lead to new suitable habitats. Northern extensions of the geographical ranges of aquatic macro invertebrates have already been observed. A study on long-term changes in aquatic communities in the upper Rhône River showed that thermophilic fish species as well as downstream, thermophilic invertebrate taxa progressively replaced northern, cold-water fish species and upstream, cold-water invertebrate taxa (Daufresne et al., 2004). These patterns were significantly correlated with thermal variables, suggesting that the shifts were the consequences of climatic warming.
Long-term changes in aquatic communities caused by global warming have not been studied in the Netherlands so far. There are however predictions. It is expected that with a temperature rise of 1.5–4.5 ºC, geographical ranges will shift hundreds of kilometres in a northern direction and there will be an increase in southern species (Besse-Lototskaya et al., 2007). Species that prefer ‘cold-water’ habitats might lose suitable environments as a result of global warming and disappear from the Netherlands. Dragonflies probably best reflect climate change in the Netherlands, as there is a strong increase in southern thermophilic species and a reduction of species with a northern distribution (Roos and Woudenberg, 2004). However, acidification, eutrophication and habitat fragmentation are also major causes for the reduction of dragonfly species with a northern distribution (Roos and Woudenberg, 2004).
The phenology (i.e., life cycle events) of aquatic organisms can change in response to global warming. When phenological responses to climate change differ across trophic levels, mismatches within food webs can occur (Pires, 2008). On the micro scale, mismatches between zooplankton and phytoplankton have already been observed (see section 4.2). On the macro scale, food mismatches have not yet been documented, which does not mean they have not yet occurred.
Global warming can lead to rapid oxygen depletion in the water column, as described in chapter 3. Anoxic conditions reduce habitat availability and is a problem for slow moving and sessile organisms. Reduced oxygen availability has been identified as the cause of increased fish mortality (Pires, 2008).

4.3.3 Changing hydrology

Extreme weather events, such droughts and heavy rainfall (floods) are predicted to become more frequent in the future (KNMI, 2009). Examples of extreme weather events in the Netherlands are cold wet springs, very mild winters or extremely long hot periods in summer. Aquatic organisms are adapted to a certain level of hydrologic variability within the ecosystem they live. Changes in these

hydrological conditions due to extreme events could have negative effects on aquatic populations (Ficke et al., 2007). The ecological effects of extreme events have been identified as one of the main gaps in our knowledge of community ecology (Heijmans & Berendse, 2009). Weather extremes are rare and therefore hard to relate to changes in community structure (Vos et al., 2007). However, it is likely that an increased frequency of extreme weather events will have negative effects on aquatic organisms.
Floods or exceptionally large seasonal pulses can displace adults and displace or injure juveniles and larvae (Ficke et al., 2007). Furthermore, they can change habitat structure, the availability of food and nutrients for organisms via transport or deposition of sediment, organic matter and nutrients (Besse-Lototskaya et al., 2007). Drought or prolonged dry spells can cause population declines and altered species composition. As a result, increasing extreme weather events could select for generalist species or those with the ability to rapidly colonise depleted habitats and possibly lead to a loss of locally adapted (specialist) species (Ficke et al., 2007). Fragmented ecosystems are particularly vulnerable to extreme weather events (Pires, 2008). Ecosystems in which the frequencies of disturbances (e.g., extreme weather events) are increased are more easily invaded by invasive species (Moles et al., 2008).

4.3.4 Invasive species

Invasive species are species that arrive at locations where they were never recorded before (Mooij et al., 2005). At the moment, there are 55 alien macro invertebrate species recognised in the Netherlands (De Lange et al., 2008). Most of these alien species reached the Netherlands via the Main-Danube canal, ballast water or escapes from garden ponds and aquaria (De Lange et al., 2008). Climate change, especially global warming, acts in two different ways on the permanent establishment of alien species (De Lange et al., 2008):

1. expansion/shifting of the geographic range of species (natural adaptation to climate change);
2. facilitation of permanent establishment after colonisation by other transport routes (e.g., ballast water transport ship or escapes from garden ponds).

The first process, climate change induced establishment, is a natural process. The second process is induced by human activities. Alien species introduced by the second process find a suitable habitat due to climate change. For example, the six macrophytes that proliferate (and are actively controlled) in the Netherlands all have their origin in (sub) tropical climates (De Lange et al, 2008). These species cannot tolerate frost but the rareness of harsh winters has promoted the establishment of these tropical species. The success of macro-invertebrates, mainly coming from Eastern Europe, will also depend on their chances of survival in winter (Loeve et al., 2006). Chances of successful establishment will increase with mild winters.
Invasive species form a problem when they explosively expand and change the ecosystem. This happens when there is a lack of natural enemies or when they are competitively superior to endemic species for food recourses and habitat. The successful invasive Chinese crab damages banks and shores in the Netherlands and cuts the sprouts of juvenile macrophytes (De Lange et al., 2008). Another example of an invasive species causing problems is the crayfish. It is thought that this species is responsible for the decimation of fish stocks, damage to vegetation and decreased transparency of the water column (Van Emmerik & De Laak, 2008).

4.3.5 Sea level rise

As a result of sea level rise and decreased river discharges, saltwater intrusion will increase in river estuaries (Loeve et al., 2006). For the lower parts of the Netherlands it is expected that the salinisation of ground and surface waters will increase (Heijmans & Berendse, 2009). Aquatic organisms currently living in estuaries are probably not able to cope with increased salt concentrations and will disappear from these ecosystems. Brackish environments will probably increase in number. Brackish environments are generally poor in their number of species; however they contain specialised species that do not occur in other places (Heijmans and Berendse, 2009).

4.3.6 Effects on fish

Fish are cold-blooded organisms, which means that their body temperature equals the temperature of the surrounding environment. Growth, reproduction and behaviour depend on the temperature of the water (Van der Grinten et al., 2007). Fish in temperate ecosystems, such as the Netherlands, undergo 90% of their annual growth in the summer months because food availability tends to be highest and water temperatures approach growth optimums (Ficke et al., 2007). Therefore, a slight increase in water temperature could be beneficial to the overall productivity of fisheries because the growing season is extended and overwintering stress is decreased (Ficke et al., 2007).
However, fish are dependent on oxygen availability, which is expected to decrease due to climate change (see physico-chemical water quality). Most fish can maintain adequate levels of oxygen uptake at dissolved oxygen concentrations above 5 mg/l. When concentrations drop below 5 mg/l, many species employ physiological and behavioural adaptations to maintain adequate rates of oxygen uptake but as dissolved oxygen concentrations drop below 2–3 mg/l, most species will perish (Ficke et al., 2007).

Climate warming is expected to weaken the resilience of the macrophyte-dominated clear water state (Mooij et al., 2009). Furthermore, it is expected that climate warming will lower the critical loading at which the system switches from a clear to a turbid state (Mooij et al., 2009, see also chapter 3). In addition, with the predicted climate-induced shift towards cyprinid and percid dominance in fish assemblages in northern temperate lakes, higher disturbance of sediment is to be expected leading to increased turbidity of the water column (Mooij et al., 2009). Fish that depend on vision for feeding and reproduction will be harmed most under these scenarios.
In warmer waters, fish are more susceptible to infections, diseases and parasites (Van der Grinten et al., 2007). In temperate regions, winter temperatures are a major limiting factor on the standing stock of parasites and warmer winters could allow the possibility of year-round infection and multiple generations of parasites in one year (Ficke et al., 2007). Changes in fish composition brought about by individual species range shifts will probably alter the composition of the parasite fauna of specific systems. Fish migrating from warmer regions may serve as hosts or vectors for parasites and diseases that are novel for species in the receiving environment (Ficke et al., 2007).

Box 3: More fish deaths in the future?

The future picture for the Netherlands?

In the summer of 1994 there was a massive number of fish deaths in Lake IJssel. It was thought that cyanobacterial blooms were responsible for this massive mortality. However, there were no clear links found between liver damage in the fish and the concentration of cyanotoxins in the livers and the phenomenon was explained by the presence of multiple stress factors, including anoxia, high water temperature, pH values, concentration of ammonia (NH_4 becomes NH_3, which is toxic for fish) and the presence of parasites during blooms of cyanobacteria (RIZA, 2004). Nevertheless, the contribution of cyanotoxins to the mass deaths could not be excluded. It is important to note that all these factors are enhanced by climate change.

Effects of cyanobacteria can also be found higher in the food chain. In the summers of 2002 and 2003, a high number of bird deaths occurred in Lake Volkerak-Zoom (approx. 5,000) and the Oostvaardersplassen (approx. 10,0000). There were strong indications that cyanotoxins contributed to the death of the birds.

5 Impact of climate change on humans

- Some health risks may be increased by climate change.
- Droughts and higher water temperatures could cause problems for the drinking-water sector in the Netherlands.
- It is expected that rising temperatures, a changing hydrology and salinisation could damage agriculture in the Netherlands.
- Recreation in surface waters may become less attractive.

5.1 Human health

5.1.1 Introduction

In 2005, the Netherlands Environmental Assessment Agency (then called MNP), argued that it is not probable that climate change would make a large contribution to water-borne diseases in the Netherlands. However, in 2009, the same agency (now called PBL) expected for the period after the year 2040 that the introduction, distribution and growth of pathogenic micro-organisms in water will increase and consequently, the number of human infections with these pathogens but no quantitative data are available to build these conclusions on.
In general, health effects caused by cyanobacterial blooms, botulism, pathogenic amoebae and vector-borne pathogens are expected (MNP, 2005). In addition, drinking water production can be affected by high water temperatures and high concentrations of toxic substances caused by low river discharges. One can distinguish two types of diseases related to water: either caused by pathogens in water or caused by vectors (such as mosquitoes) that carry pathogens; in that case, the vectors usually need water for their life cycle. These two types are discussed below.

5.1.2 Water-borne diseases

In the near future, experts from the Laboratory for Zoonoses and Environmental Microbiology will publish a report on the projected effects of climate change on the occurrence of water-borne diseases. The report will be called ‘Climate change and recreational water-related infectious diseases (RIVM report 330400002/2010)’. The authors are AM de Roda Husman and FM Schets. Readers are referred to the forthcoming report for information on water-borne diseases.

5.1.3 Vector-borne diseases

Many pathogens are not waterborne themselves but develop in vectors that, for at least part of their life, live in water. A well-known example of a vector-borne disease is malaria. The mosquito *Anopheles* (Figure 8) is the carrier of the protist *Plasmodium*, which causes malaria. The mosquito itself is a nuisance but harmless. Humans are infected by a bite from an infected female mosquito. *Anopheles* lives in fresh or brackish waters throughout its larval and pupal life stage. Changes in climate such as temperature and rainfall can influence the life cycle of both the vector and the protist. Temperature and rainfall affects the distribution of the vector. In general, the PBL (2009) expects a more northerly

Figure 8 Picture of a malaria mosquito.

distribution of southern vectors in the period after the year 2040 due to climate change, with associated infections and diseases.

With specific regard to malaria, disagreement exists as to whether malaria infections will increase due to climate change. Malaria has occurred in the Netherlands during the first part of the 20th century. It disappeared from the Netherlands in 1970 thanks to improved health care, the improved housing of cattle, limitations of brackish water and the specific characteristics of the Dutch *Plasmodium vivax* strain. Currently, the only malaria cases in the Netherlands are those that have been imported from areas in which malaria is endemic (Van Ierland et al., 2001).

According to Pires (2008), there is too little evidence for a link between malaria and climate change and there is very little chance that malaria will reappear in the Netherlands before 2050. However, the large water surface in the Netherlands and the presence of the malaria vectors *Anopheles atroparvus* allow for local transmission of *Plasmodium vivax* during the summer months (Van Ierland et al., 2001). The MNP (2005) also reported that in the future, the risk of a local outbreak of malaria in summers caused by *Plasmodium vivax* will increase but is still close to nil (Kuhn et al., 2003). Furthermore, is it possible that human infections with the dangerous malaria parasite *Plasmodium falciparum* will occur in the future, due to the spread of the Mediterranean *Anopheles labranchiae* mosquito to Central and Western Europe (MNP, 2005; Van Ierland et al., 2001).
Still, the risk of a large-scale malaria epidemic in the Netherlands due to climate change seems very small, thanks to good health care and preventive measures (MNP, 2005; Van Ierland et al., 2001).

Common symptoms of dengue are severe headache, muscle pain, fever and rash. The West-Nile virus mainly infects birds but is also known to infect humans. The virus can cause different symptoms, including meningitis. In the Netherlands, potential vectors of the West-Nile virus are endemic. The reason why no epidemic of the West-Nile virus has hit northern Europe is unknown. In conclusion, the presence of a vector does not automatically mean that there is also pathogen present. Even if both are present, the transmission cycle of the virus between endemic birds and mosquitoes might not be sustained. In 1996, a West-Nile virus outbreak occurred in Romania, with 393 people infected and 17 deaths. Recently, outbreaks of the West-Nile virus have been seen in Italy. Outbreaks also occurred in Russia and Israel.

5.1.4 Cyanobacterial blooms

The frequently mentioned cyanobacterial blooms may pose a serious threat to human health, as several cyanobacterial species can produce a variety of toxins (Lürling en van Dam, 2009, Roijackers and Lürling, 2007). Cyanobacteria that produce toxins include the genera *Anabaena*, *Aphanizomenon*, *Cylindrospermopsis*, *Lyngbya*, *Microcystis*, *Nostoc* and *Planktothrix* (Roijackers and Lürling, 2007). Dermatoxins that cause skin and eye irritations are produced by many cyanobacteria. Microcystins, produced by *Microcystis*, accumulate in the liver, where they cause major damage. Saxitoxins, produced by the invasive species *C. raciborskii* block neuronal transmission, which leads to muscle paralysis. Cylindrospermopsin, also produced by *C. raciborskii*, causes necrosis (death of cells) in the liver, kidney, thymus, spleen, intestine and lungs and displays mutagenic activity (Lürling and Van Dam, 2009, Roijackers and Lürling, 2007). The most frequent health complaints that occur after contact with or consumption of cyanobacteria are skin irritations, diarrhoea, stomach and intestinal complaints and even larger health problems. In 2002, a teenager from the USA died 48 hours after contact and consumption of the cyanobacteria *Anabaena flos-aquae*, which produces the fatal toxin anatoxin-a (Lürling and van Dam, 2009).

In the Netherlands, the danger comes from the surface scums, which can be driven by the wind to the bathing areas of recreational waters. In these scums, the toxin concentration is high. The ability of many frequently occurring cyanobacterial genera (*Anabaena spp.*, *Aphanizomenon spp.*, *Microcystis spp.*) to form scums implies an elevated toxin concentration by a factor of 100 (see Figure 9). These scums may signify a high health risk for people swimming (Roijackers and Lurling, 2007, Lürling and Van Dam, 2009). The risk becomes even higher when the wind directs the scum to a small surface area near the shore (see Figure 9).

Table 2 summarises the influence of climate change on the occurrence of several diseases. Note that the literature is sometimes ambiguous.

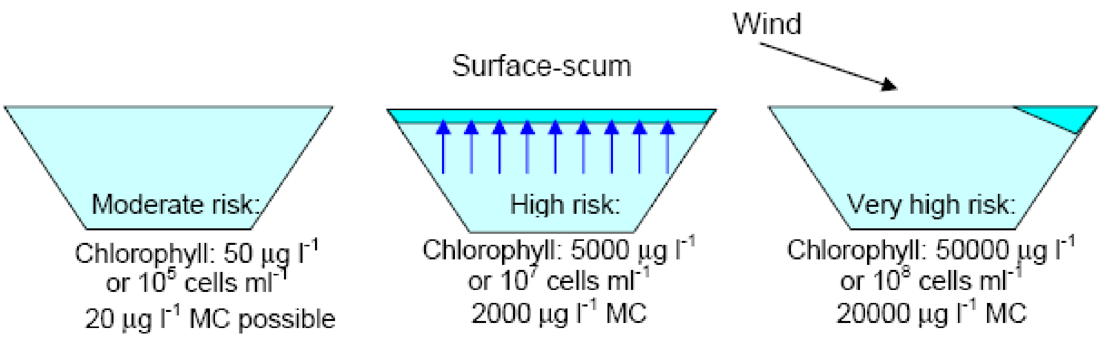


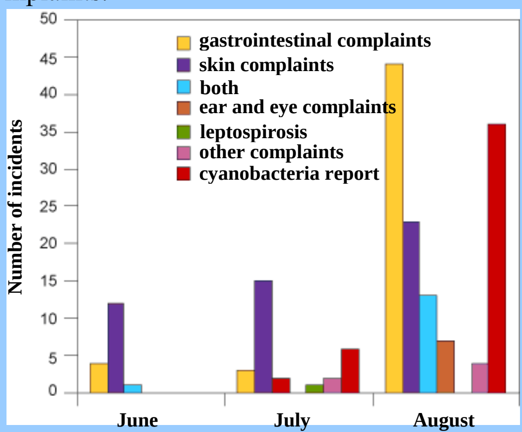
Figure 9 Schematic illustration of scum formation changing the cyanotoxin risk for adverse health effects from moderate (left), via high (middle) to very high (right). A concentration of cells from a 4 m water column into a 4 cm surface layer implies a 100-fold accumulation to a high risk level (left to middle). A 1000-fold accumulation occurs when wind sweeps scums from 100 m to 10 m from the shore. Source of picture and text: Roijackers and Lurling, 2007.

Table 2 Overview of pathogens that form a risk to humans in the future in the Netherlands, as a result of climate change. – = decreased risk; + = slightly increased risk; ++ = increased risk. Note 1: from Roijackers and Lurling, 2007, note 2: from Schijven and De Roda Husman, 2005; note 3: Braks, personal communication

Organism	Disease	Vector	Risk for humans
Bacteria			
Legionella pneumophila	Legionnaires' disease	Free-living	+[1]
Leptospira icterohaemorrhagiae	Leptospirosis (Weil's disease)	Rats	+[1]
Mycobacterium avium	Lung damage	Animals, humans	+[1]
Vibrio cholerae	Diarrhoea	Free-living	+[1]
Clostridium botulinum	Paralysis	Birds	++[1]
Protozoa			
Cryptosporidium parvum	Diarrhoea	Mammals	+[1] / –[2]
Giardia duodenalis	Diarrhoea	Animals, humans	+[1] / –[2]
Naegleria fowleri	Meningitis	Free-living	+[1]
Plasmodium spp.	Malaria	*Anopheles*	++[1]/–[3]
Viruses			
Human adenovirus	Upper respiratory tract	Humans	+[1]
Coxsackievirus	Gastro-enteritis	Humans	+[1] / –[2]
Echovirus	Gastro-enteritis	Humans	+[1] / –[2]
Hepatitis A	Jaundice	Humans	+[1]
Hepatitis E	Jaundice	Humans	+[1]
Dengue virus	Dengue	*Aedes aegypti*	++[1]/+[3]
West-Nile virus	West-Nile virus	Mosquitoes	+[1]

Box 4: Health complaints in the summer of 2003

The summer of 2003 was extremely warm in the Netherlands. This summer counted 48 warm days (max. ≥ 25 °C), and 11 tropical days (max. ≥ 30 °C). However, according to the W+ scenario, this would be an average summer in 2050. The hot summer resulted in increased recreation in shallow bathing waters (Schets and De Roda Husman, 2004). The increased recreation together with an increased number of water-borne pathogens, could affect human health. To gain insight into the health problems connected with recreation in surface water, the RIVM records the health complaints at the end of each bathing season (Schets and De Roda Husman, 2004). The RIVM records by means of surveys of the GGD (Municipal Health Services) and the provinces. Municipal Health Services and provinces reported a total of 134 incidents in which at least 535 people were involved in the summer of 2003 (Schets and De Roda Husman, 2004). An incident was defined as a cluster of health complaints isolated in place and time. This number (134) was higher than in previous years. In the years 2000, 2001 and 2002 the number of incidents was 21, 54 and 101, respectively (Leenen and De Roda Husman, 2004). Most incidents were reported in August, when the highest temperatures occurred (Figure 1). In addition, the presence of cyanobacteria in bathing waters was considerable in this month. Among the incidents, gastrointestinal and skin complaints were common in all months (see bar chart). Probably, the warm surface water in August offered optimal conditions for the (cyano) bacteria that were the cause of the gastrointestinal and skin complaints.



The frequency of incidents per category of health complaints and the occurrence of cyanobacteria in bathing water during the summer months of 2003 (after Schets and De Roda Husman, 2004).

A picture of swimmers itch. Source: RIVM.

5.2 Drinking water

The drinking water supply will probably be negatively affected as climate change continues (Figure 10). This is an important issue because drinking water is an essential requirement for the human population. Especially droughts form a risk to the drinking water supply (Van Vliet and Zwolsman, 2007, Van Bokhoven and Zwolsman, 2007, Zwolsman and Van Vliet, 2007, Loeve et al., 2006).
The influence of droughts on the drinking water supply has already been observed in the Netherlands, especially in the summer of 2003. Van Vliet and Zwolsman (2007) measured the effect of the summer

drought of 2003 on the drinking water production from the river Meuse. More than 6 million people from the Netherlands and Belgium depend on drinking water from this river. During this dry period, the river discharge was very low and the concentrations of many macro-ions, which are relevant substances for drinking water production increased in the river. Zwolsman and Van Vliet (2007) concluded that concentrations of chloride, fluoride, bromide and sulphate (the relevant substances for drinking water production) are inversely related to the river discharge, which means that a low discharge results in a high concentration of these substances. The explanation is that a low discharge results in a reduced dilution of these substances.

Figure 10 This sign may become more common in the future.

Another consequence of a reduced dilution is extra pollution with unknown substances from industry and communal sources. The collection of water from the Meuse stopped for 2 months in the summer of 2003 because a high concentration of an unknown substance was detected in the inlet water (Van Vliet and Zwolsman, 2007).
Negative effects were also observed for drinking water production from the river Rhine. It is expected that the river Rhine will in the future become totally dependent on rainwater, where it is now a combined rainfall/snow-melt river (Pfister et al., 2004). In the summer of 2003, the chloride concentration in the Rhine exceeded the drinking water standard of 150 mg/l (Van Bokhoven and Zwolsman, 2007). There are two types of drinking water standards for chloride: one for the drinking water itself (150 mg/l) and one for the surface water used as source. This latter standard depends on the type of water treatment installed and is either 150 or 200 mg/l.
At a concentration of 200 mg/l chloride, the surface water intake has to be stopped because the water is then unsuitable for the preparation of drinking water. The limit of 200 mg/l chloride will probably often be exceeded in the future because Rhine discharges are predicted to drop further due to climate change. Under the extreme climate scenarios, this river changes into a rain-fed river, which further enhances the chance of low discharges (Van Bokhoven and Zwolsman, 2007, Loeve et al., 2006). Additionally, low river discharges in combination with the predicted salinisation, reinforces the risk of too high chloride concentrations (Loeve et al., 2006).
Besides low river discharges, elevated surface water temperatures are also a risk for drinking water production (Van Bokhoven and Zwolsman, 2007). Both surface water used for the production of drinking water as well as the drinking water itself need to comply with a temperature of 25 °C. The maximum temperature in the river Rhine at Lobith has exceeded these values quite regularly in recent years (Van der Grinten et al., 2007). Besides global warming, another cause of elevated water temperatures are the heat discharges of power plants and other thermal emissions. Thus, there are two discrete pressures on water temperature.
Increased surface water temperature leads to more microbial activity and consequently, an increased risk of microbial infections in drinking water (Van Bokhoven and Zwolsman, 2007, Van Schaik et al.,

2007). An example is the thermophilic bacterium *Legionella pneumophila*, which causes Legionnaire's disease. As mentioned in section 4.2, this pathogen can increase due to warming because it thrives at temperatures above 25 °C (up to 60 °C). When the bacterium is present in the pipes of the water supply system, humans can become infected through water vapour, by the inhalation of aerosols. The disease varies from a cold to a strong flu and in the worst cases, to pneumonia and even death. A well-known outbreak of Legionnaire's disease in the Netherlands occurred in Bovenkarspel in 1999. Two hundred visitors of a flower exhibition were infected and 32 people died (Roijackers and Lürling, 2007). Van Schaik et al. (2007) noted that there is also an increased risk of more vigorous growth of *Aeromonas* bacteria in the pipes of the water supply systems due to high water temperatures. *Aeromonas* bacteria can cause gastro-enteritis in humans.
In conclusion, climate change could exacerbate problems with drinking-water production and increase health risks for humans.

5.3 Economy

Changes in water quality due to climate change influence society. Sectors such as recreation, agriculture and industry are influenced by a changing water quality. In this section, the direct and indirect effects of climate change on these sectors will be discussed.

5.3.1 Recreation

Climate warming is expected to increase temperatures in summer and prolong the recreational season. However, climate warming and especially summer heat waves, will reduce the quality of recreational waters. A temperature rise, particularly in shallow waters, increases potential health risks. With rising temperatures the chances of the occurrence of pathogenic micro-organisms increase. The occurrence of cyanobacteria has for some years already caused the closure of Dutch recreational waters in the summer. In Table 2, the most important organisms that pose a risk for bathers in the Netherlands are listed. In addition, their most important characteristics and the increased risk of infection as a result of climate change are indicated.
There is no reliable information on the relationship between the future climate and exposure to water. People may wish to swim more but will maybe want to stay inside (air-conditioned) buildings.
For policy making, it is sensible to anticipate an increased exposure.
Climate warming will also have a negative effect on recreational fishing, due to the declining quality of fish stocks.

5.3.2 Agriculture

In the Netherlands, different kinds of agriculture are conducted, including cattle breeding, (greenhouse) horticulture and arable farming. Direct effects due to rising temperatures and changing hydrology and indirect effects as result of new plagues and diseases, are expected for agriculture in the Netherlands. As a result of increasingly wet springs and autumns, the sowing and harvesting periods may come under increasing pressure (RIZA, 2005). During wet periods, problems are expected to occur on clay and peat agricultural soils, mostly situated in the western part of the Netherlands. On the sandy soils in the eastern part of the Netherlands, fewer problems are expected because water can infiltrate more easily in these soils. Increased wet periods can result in crop damage. Intense periods of drought can also result in crop damage.
In the western part of the Netherlands, the increasingly salty seepage water, due to sea level rise, will cause problems for agriculture and particularly (greenhouse) horticulture. Horticulture is most sensitive to high chloride levels in water. In summer, increased chloride levels in the water used for irrigation

may cause problems for agriculture throughout the Netherlands. In Figure 11, the sensitivity to chloride concentration of most cultivated crops in the Netherlands is given. A possible increase in the frequency of storms (hail storms) also poses a threat to (greenhouse) horticulture and fruit culture.

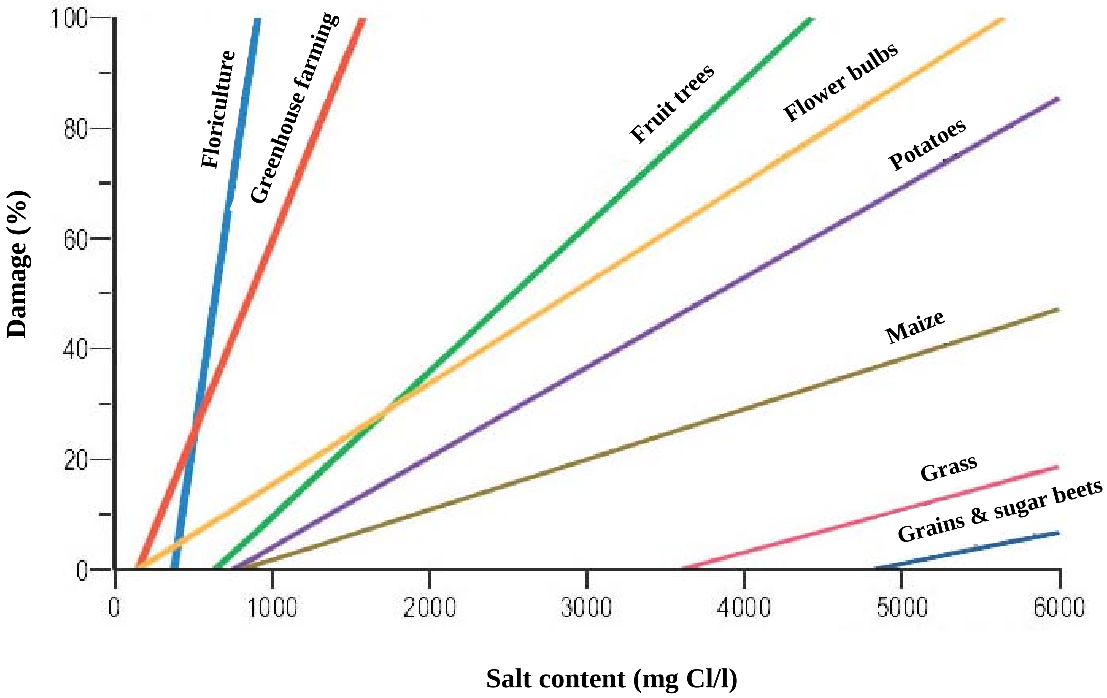


Figure 11 Relationship between salt tolerance and yield loss of crops (Roest et al., 2004).

An indirect effect of climate change on agriculture is the arrival of new diseases and plagues. This may lead to increased use or use of new pesticides, which can form a problem for water quality. An example of a possible new threat is the western corn rootworm (*Diabrotica virgifera virgifera*). This species is advancing in Europe and was first reported in the Netherlands in 2004. At the moment, the Netherlands is at the border of its geographical range but with increasing temperatures it may move northwards and invade the country. The species can account for 6.5 to 13% of harvest loss (PBL, 2005).

5.3.3 Industry/shipping

Industry and in particular power plants, will face problems as a result of restrictions on cooling-water discharges. During long-lasting dry and hot periods, there will be a shortage of cooling-water because cooling-water discharge is restricted by maximum water temperature standards (28 ºC). These standards have been implemented to protect aquatic organisms and drinking water production. Power plants is the main group using cooling-water in the Netherlands. At the moment, a shortage of cooling-water occurs every two or three years, mainly in plants along the Amsterdam-Rhine canal and the

North Sea canal (RIZA, 2005). Shortage of cooling-water is likely to become more frequent in the future.
Low water levels increase the chance of damage to aquatic life (mainly fish) by industry and shipping, because factories have a higher intake of water and the chance of damage by ship propellers is greater (RIZA, 2005). This probably resulted in the high mortality of eels in the River Rhine in 2003 (RIZA, 2005).
Changing hydrology and changing river dynamics will increase mud deposition. Consequently the dredging costs of shipping transport routes and harbours will increase (RIZA, 2005).

5.3.4 Insurance sector

Insurance premiums will increase as a result of climate change. Claims will increase as a result of the greater frequency of extreme weather events, such as flooding and heavy storms. Insurance company Munich Re states that the number of natural disasters has doubled in Europe since 1980. The observed increase in economic losses is due to various factors, including increases in wealth and infrastructure and more frequent extreme weather events. Both economic losses and the number of extreme weather events are likely to increase with a changing climate.

6 Implications for water policy

- Climate change does not introduce many new problems but mainly aggravates existing ones. Therefore, it is recommended to integrate climate change policy with existing policy. The danger of systems 'flipping states' should be kept in mind.
- Climate change is likely to have an influence on the goals set by the Water Framework Directive. The recent CIS Guidance Document needs discussion in the Netherlands.
- Policy areas should be integrated to a greater extent than they are now (e.g., water quantity and quality but also spatial planning and nature policy).
- Water managers should be prepared for new and more severe management problems.

6.1 General aspects

In the previous chapters, the possible effects of climate change were discussed in *scientific* terms. This chapter aims to highlight *policy areas* where additional policy instruments can be applied. While in the previous chapters the information was grouped according to effects, here the grouping is based on policy areas.

Generally speaking, climate change does not introduce many 'new' problems but mainly aggravates existing ones. The good news is that it is therefore often possible for climate-change policy to chime in with policy that is already in place. The bad news is that many natural systems do not react linearly to stress factors but, at a certain moment, flip to another state (Janse, 1997, Scheffer et al., 2001). Since many Dutch natural systems are already under great stress, the chance that climate change, together with all other existing stress factors, will cause such flips is not hypothetical but real.
Another complex aspect of climate change is that the effects are only partly visible so far. However, given the conclusion of the IPCC panel that 'Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations' (IPCC, 2007; GHG=Greenhouse Gas), RIVM recommends to prepare and maybe take policy measures before these effects become more visible. This definitely puts demands on interaction and communication with stakeholders, because to the public it may not seem logical to take measures without visible effects.

In the past, there was a tendency to believe that man could shape his physical environment according to his needs without restriction. In general, this belief has lost some credit. Climate change will most likely enhance this tendency because we are currently facing the limits of what we can change in our physical environment.

In recent decades, a lot of attention has been given to the possible consequences of climate change in relation to water *quantity* (mostly regarding flooding but to a lesser extent also droughts). The expected problems for water *quality* caused by climate change, are often related to water *quantity*. Therefore, these areas should ideally be considered together where appropriate. Given the already existing pressures on water quality, the aim should ultimately be to achieve more robust and therefore less vulnerable water systems. An important step would be to put more emphasis on the relations between surface water and groundwater. This requires the closer cooperation of ministries, provinces and water boards.

It is important to be aware of the many cross-links that exist between the effects of climate change. An example: due to climate change some diseases may occur more often or new diseases may be introduced here. A consequence can be that more or new medicine will be used, which may partly end up in surface water. Other consequences of climate changes like algal blooms and botulism also target surface water. At the same time, hot summers can lead to more people wanting to swim in the surface water, where they can be exposed more than before to medicine residues and algal blooms.

6.2 Policy recommendations

6.2.1 European level

At the European level, debates are ongoing about climate change and its consequences for various policy areas. The outcome of these debates potentially has a strong influence on the boundary conditions of Dutch policy. Very recently, a guidance document about climate change was published (EU, 2009) as part of the Common Implementation Strategy of the Water Framework Directive (WFD). The document focuses on the second and later planning cycles of the WFD and so not on the first cycle for which River Basin Management Plans should be established in December 2009. For the WFD, eleven so-called ‘guiding principles’, grouped under five steps are mentioned. They are summarised here.

1. When performing the Risk Assessment according to article 5, take care to include possible additional pressures caused by climate change.
2. When setting up the monitoring programmes,
   a. make sure to keep or build long-term monitoring series;
   b. include reference sites in the programme or sites that give information about reference conditions;
3. Objective setting.
   a. Climate change should not be used as a general ‘excuse’ for not meeting the objectives and therefore applying exemptions. Instead, the possibilities that the WFD offers for applying exemptions should be followed closely. Article 4.7 offers options for applying exemptions under certain conditions.
   b. It is possible to attribute a different type to a water body.
   c. It is possible to incorporate the effects of climate change on reference conditions (important for the description of the Good Ecological Status) but only when well-founded. This has a link to the requirements for long-term monitoring.
4. When making assessments of future water use, possible changes caused by climate change should be taken into account.
5. For the Programme of Measures, it is recommended to take into account the robustness of measures under different climate conditions. In addition, measures considered for other purposes (e.g., hydropower development to reduce emissions of CO_2), should be analysed on their effects on water.

The RIVM recommends thorough discussion of the implications of this guidance document.
The WFD contains provisions about consequences for downstream countries (article 4.8). This is an essential element in the WFD since water management under the WFD is organised not on a national

level but on the basis of river basins. The implication is that in selected situations the Netherlands can ask neighbouring countries to implement additional measures. Up to now, these provisions have not been used by the Netherlands even though there have been opportunities, e.g., for the temperatures of large rivers. It is important to recognise the opportunities that the WFD offers to improve water quality in the Netherlands. This issue is also mentioned in the EU guidance document (EU, 2009, page 43).

6.2.2 National level

For many policy areas, the choice has been made to sketch the outlines of policy on a national level and at the same time decentralise the administration. This combination always creates some tension. Speaking about the possible effects of climate change on water, this tension is probably more severe (PBL, 2009). This increases the importance of cooperation between authorities. (Note that during the final stage of preparation of this report, the first series of River Basin Management Plans was published. There was no time to study these plans thoroughly but at first glance, it seemed that some of our recommendations had already been adopted.)

6.2.2.1 Environmental policy

- For toxic substances, higher concentrations can be expected during droughts. It is recommended to re-assess the allowable emissions of substances in this context. Also, more or new medicine and personal care products (e.g., suntan lotion) can be expected to end up in surface waters. In addition, the risk of accidents with chemicals due to flooding should be evaluated.
- Due to new or more severe pests in agriculture, new or more pesticides may be used. It is recommended to anticipate this in the policy for the admission of new pesticides or in the regulations for the use of existing ones.
- For nutrients, more run-off to surface water can be expected due to high rain intensities. Currently, there is policy in place to reduce the emissions of nutrients to surface waters. This policy may need more emphasis.
- For drinking water, it is recommended to re-assess the locations where surface water is extracted for drinking water production in the context of:
  - expected higher chloride concentrations in rivers;
  - expected higher temperature of surface waters;
  - expected higher concentrations of toxic compounds in surface waters (both existing as well as new substances).

  The partition of surface water and groundwater as sources for drinking water might be re-assessed in this context.
  Water-saving policy may need to be enhanced.
- Locations of bathing waters should be re-assessed in combination with locations of heat emissions, in view of the possible risks of infection diseases. More monitoring or surveillance could be considered.
- For the Water Framework Directive, the yardsticks for natural waters need to be re-evaluated and possibly adjusted. Policy developments at the European level may have an influence on this need.
- It is recommended to re-assess the entire infrastructure of water supply in the Netherlands in the context of expected or possible climate change.
- In the future, the image of water may be negatively influenced, e.g., when bathing waters temporarily have to be closed or in case of odour problems. This could have consequences for public support for policy.

6.2.2.2 Spatial planning

Traditionally, spatial planning is a field that is used to look ahead to a greater extent than many other fields. In the recent past, a lot of attention has already been given to the relationship between spatial

planning and climate change, e.g., water quantity. For water *quality*, this relationship should be enhanced (see several aspects mentioned above under ‘environmental policy’).
In view of the limits of the manipulability of the physical environment, changing the (land) use of certain areas might be considered.

6.2.2.3 Nature policy

Nature policy and water policy should be integrated more, not only for aquatic nature but also for land-based nature (in view of droughts). This should include further integration of policy for the Natura-2000 areas with implementation of the WFD.

6.2.2.4 Agricultural policy

Agriculture will face different conditions in the future (weather, water availability and composition). The choice of crops may need to be adjusted, for instance, crops that are sensitive to salt may have to be moved. However, new crops may be grown that could not be grown in the past.

6.2.2.5 Energy policy

The locations of planned power plants may need to be reconsidered.

6.2.3 Other authorities

- Water quality problems in urban areas should be anticipated (smell, death of fish). Especially here the image of water could be negatively influenced. There may be a negative impact on housing prices.
- Traditionally, rainwater was transported together with sewage water. In the recent past, more and more rainwater is kept separate from sewage water and infiltrated. This reduces emissions by storm overflows. This development should be encouraged and enhanced. However, the infiltration of rainwater may cause soil and groundwater quality problems if the water becomes polluted with metals or PAHs (Ekkelboom, 2009). Therefore, diffuse sources of these substances need to be tackled even more.
- Water systems need to become more solid and more natural than they are now. The way some water systems are currently structured makes them vulnerable to climatic extremes.
- Water boards need to re-evaluate and maybe adjust the yardsticks for heavily modified and artificial water bodies under the Water Framework Directive.
- It can be anticipated that some invasive species will proliferate. This will require increased vigilance on the part of water managers and involve higher costs.
- Droughts may increase the demand for the intake of water from other areas. If the quality of the new water is worse than that of the original source, problems such as eutrophication may increase. This is not a new problem but it may be aggravated by climate change.

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