Securing safe drinking water supply under climate change conditions
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ABSTRACT
Water suppliers worldwide are challenged by climate variations, but so far only the qualitative change in boundary conditions has become clear but not yet the degree and impact on the water supply systems. Short-term quality changes in surface waters can, e.g. be caused by extreme rainfalls after dry periods. Longer heat periods without rain can induce middle-term quality changes in surface waters due to lacking dilution. Furthermore, unsustainable management of groundwater can lead to long-term quality changes and to water shortages, especially in times with higher water demand. Depending on the individual situation, the expected effects on the supply system differ widely, so a general adaptation strategy will not suit the individual problems. The purpose of our work is to enable water supply companies to systematically identify potential risks resulting from climate change and other external factors in a water safety plan approach, and to adapt the supply system in a most effective way by taking advantage of ongoing modernization measures and ‘no-regret’-measures. A suitable adaptation strategy should address climate change conditions as well as other external factors like changing water demand and also to take into account possible effects on every part of the supply system.

Key words | adaptation, climate change, drinking water supply, risk management, water resources management, water safety plan

NOMENCLATURE
AC activated carbon
AOC assimilable organic carbon
BAC biological activated carbon
DOC dissolved organic carbon
UV ultraviolet (light)

INTRODUCTION
In recent years, the amount of literature on climate change and its effects on the water cycle has increased significantly. Some authors describe the general impact of climate change on water resources and water quality (Delpla et al. 2009; Bonte & Zwolsman 2010), others evaluate the effects of changing raw water quality or quantity on specific water treatment technologies by drawing lessons from case studies (Hurst et al. 2004; Slavik & Uhl 2009; Sprenger et al. 2011).

All these publications show that water suppliers worldwide are challenged by climate variations, for which only the qualitative change in boundary conditions has become clear but not yet the degree and the impact on individual water supply systems. Furthermore, the unknown planning horizon is particularly challenging for the operators; planning guidelines are based on past experience, which is not likely to be a sound basis for the future, and pro-active system adaptation is lacking customer acceptance as long as clear evidence is missing.
Besides, water supply companies that are facing climate change have to adapt to dynamic conditions such as change of water demand caused by demographic change and different structure of water users (e.g. decreasing industrial water demand). It is obvious that an adaptation strategy can be sustainable only when addressing the sum of changing factors for the supply system and considering the regional water balance and, thus, the consequences for the population, economy and environment.

This paper first of all focuses on lessons learned from case studies in Germany and the Netherlands, as well as individual examination in full- and pilot-scale. Furthermore, it describes possible adaptation pathways with adaptation measures to safe drinking water supply under climate change conditions, also taking into account other external factors relevant for water supply. A systematic universal approach following the water safety plan (WSP) approach (WHO 2009) has been developed and applied to one local water supplier in order to adapt the existing assets and to boost their efficiency. The cited results have been gained from the regional adaptation project dynaktim (Merkel et al. 2010), which was embedded in a nation-wide research programme KLIMZUG.

RESULTS AND DISCUSSION

Climate-induced pressures on water supply and examples for adaptation

Water supply systems are affected by climate change and the influenced external factors (e.g. water demand) in different ways, depending on specific conditions such as regional climate conditions, raw water resources, water treatment schemes and conditions in distribution (cf. introduction). Here, five different case studies from Europe were chosen to evaluate the impacts of climate change on different water supply systems with various boundary conditions, e.g. raw water resources. From these case study applications, relevant recommendations for climate-proof water supply systems can be derived.

(1) Impact of heavy rainfalls on microbial contamination of source water and shallow groundwater. Climate change induces increased precipitation intensity. More frequent and intense extreme events can cause changes in particle and pathogen-loading in source water as well as in shallow groundwater. These effects are observed in a number of cases, especially in areas with porous and fractured underground situations as can be found in parts of Southern Germany or Luxemburg.

Case 1: As an example, extreme rainfalls, especially after longer dry periods, caused high turbidity and particle load (see Figure 1) in a shallow groundwater of a karst aquifer in Southern Germany used for drinking water supply. Based on that, microbial contamination occurred (see Figure 2). The existing ultraviolet (UV) disinfection did not reliably eliminate the resulting peak loads of Escherichia coli and coliforms due to high particle concentrations and high turbidity. As a result, the shallow groundwater could not be used for drinking water purposes during rainfall events.

To enhance safety and flexibility the existing treatment scheme was improved by ultrafiltration. The membrane process withholds particles and pathogens independent of climate effects and weather events. That is the necessary pre-treatment for reliable UV-disinfection.

(2) Long-term shift of groundwater quality due to higher pressure from farming. Natural effects on groundwater recharge and quality are fairly less clear and understood as on surface waters. Owing to the long-term interactions between water runoff and local geologic conditions, the effects on groundwater bodies are difficult to describe and to measure. In principle, increasing winter precipitation

![Figure 1](image-url)
leads to an increase in groundwater recharge. However, this effect could be balanced out by higher evaporation associated with higher summer temperatures and by higher rainwater run-off from soils instead of percolating directly to the groundwater basin during extreme precipitation events (AWWA 2011). Climate change in Northern Europe, with higher temperatures and longer growing seasons, could also enable more intensive farming with higher irrigation needs, potentially causing the downwelling of groundwater levels and increasing nutrient (nitrate, phosphate) and pesticide loads.

**Case 2:** Using integrated water flow prediction and water quality modelling, the potential impact of different future scenarios on groundwater renewal (comparision of future periods 2021–2050 and 2071–2100 with reference period 1961–1990, different land use patterns, different soil conditions) and quality for a water supply system in Münsterland (NRW-Germany) was calculated. It could be shown that the global warming will increase the need for irrigation of farmland in the named area and different adaptation pathways (several land use patterns for different soil conditions and irrigation demands) were explored.

The model results showed that increasing irrigation especially with already nitrate polluted groundwater could lead to further cumulative nitrate concentration in ground water (see Figure 3). Moreover, the increasing irrigation demand reduces the availability of groundwater resources for other water users. Thus, a transparent allocation scheme to various water users (drinking water, agriculture, industry, cooling water) had to be explored.

(3) **Increasing salt intrusion in coastal groundwater.** Water supply in coastal regions is often based on groundwater abstraction and treatment. Climate change, with rising sea levels, can lead to a shift of salt water in the underground towards abstraction wells to the point of intrusion. In addition, a rising water demand following longer heat periods and higher temperature in general can lead to an expansion of abstraction quantity. Increasing proportions of saltwater in groundwater can force the water supplier to invest in more innovative treatment technologies.

**Case 3a:** Owing to increased abstraction of groundwater for water supply and irrigation, the upwelling of salt water into coastal groundwater was detected, e.g. in the Netherlands with increasing salt contents. To prevent salt-water intrusion into the groundwater a dune infiltration with treated surface water was installed (van Breukelen et al. 1998). This measure increased the groundwater volume and reversed the flow, shifting the fresh/salt water boundary towards the sea.

**Case 3b:** Shifting salt water frontiers towards drinking water wells is also a risk for water supply in some regions of Northern Germany. Owing to expected higher water demands from industry and intensified farming with higher average temperatures and heat periods in summer, available quantities for drinking water production could be limited. Higher water extraction is limited by the shifting salt water borders. Since reliable forecasts of the change in salt water fronts are missing, it is unclear how long drinking water can be extracted in the waterworks near the coast without further treatment with (e.g. reverse osmosis), which is a very expensive technology. To reduce the necessary water extraction for drinking water, treatment alternative water resources for industrial usage were explored, including brackish water, surface water, sea water as well as wastewater reuse after treatment.

A treatment scheme for treated wastewater reuse consisting of flocculation, ultrafiltration, reverse osmosis and stabilization turned out to be a cost-effective and resource-efficient alternative.

(4) **Flooding of catchment areas, abstraction wells and treatment plants.** Water utility infrastructure situated in low-lying coastal areas or in flooding plains of surface waters could be affected by rising sea or river levels, storm
surges, or more intense and frequent flood events. To prevent damage, these facilities may have to be redesigned to be flood-proof or even relocated.

Case 4: Following a hurricane with extreme precipitation intensity (163 l/m² in 24 h; up to 15 l/m² per hour; see Figure 4) the entire water production facility of a local water supplier in NW Germany was flooded, causing breakdown of water abstraction and microbial contamination of the raw water (coliforms: 160/100 ml, \textit{E. coli}: 20/100 ml; \textit{Enterococcus}: 48/100 ml; coliform count 22 C: 960/100 ml) and the treatment plant. The waterworks had to be switched off immediately. It took nearly 4 weeks until all parts of the supply system were disinfected and back to operation. 58 000 m³ treated water had to be discharged due to contamination. Several measures were used to increase the resilience of the entire supply system: e.g. systematic analysis of flooding risk, optimization of flooding protection at the river elsewhere and installation of emergency connections to neighbouring supply systems.

(5) Heavy rain and dry periods affect water production from a river. Unlike well-protected groundwater resources, surface waters respond directly to changing weather conditions like heavy rainfalls or prolonged dry periods.
Case 5: In this area, bank-filtrated river water from the River Ruhr (NW Germany) is the main raw water resource for water supply. Historical data show an increase of organic micropollutants caused by higher wastewater fractions during low river flows (see Figure 5) but also an increase of trace metal concentrations (Cu, Ni), bromide and salinity (Merkel et al. 2010). High river flows are associated with increasing loads and concentrations of suspended particles (turbidity can rise up to values above 200 formazine nephelometric units) and nutrients like nitrate.

At extreme weather events (heavy rainfalls, heat periods) high concentrations in the river water may occur more frequently and must be coped with in the drinking water treatment processes. Potential adaptations of existing treatment technologies (flocculation, ozonation, filtration, granulated activated carbon, UV-disinfection) and alternative treatment technologies (advanced oxidation processes, ultrafiltration/nanofiltration when indicated in combination with powdered activated carbon) were investigated (partly in pilot treatment steps), showing the potential to raise resilience of existing treatment plants (Panglisch et al. 2011).

The infiltration area at the waterworks was protected against flooding events by a surrounding clay barrier. Thus, a more than 100 000 m³ underground reservoir was created, with increased reliability of the entire supply system and higher resilience for climate change induced flooding.

**Risk management scheme for safe water supply**

To enable water supply companies to systematically raise their resilience against climate change induced pressures, a management system based on the WSP approach has been developed and applied. This entails elements of a system assessment, hazard identification (see Table 1) and risk assessment. Possible risks due to different extreme climate

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**Table 1** | Potential risks in water supply/excerpt (example: dry period/low water level; river)

<table>
<thead>
<tr>
<th>Water resource</th>
<th>Water catchment</th>
<th>Water treatment</th>
<th>Water storage</th>
<th>Water distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase of conductivity, bromide, sulphate, sodium, potassium, chloride, ammonia, nitrate, pH, temperature, DOC, nutrients, metals (resolution from the sediments), micro-organisms, turbidity</td>
<td>Artificial recharge of groundwater/ bank filtrate: increasing iron clogging of well screen section: decreasing performance and drying out of pumps, well screen section: corrosion; less removal of micro-organisms caused by a flooded aquifer</td>
<td>Performance of existing treatment insufficient (concerning quantity and quality)</td>
<td>Storage capacity insufficient to level the match between peaks in water consumption and useable raw water quantity/treatment capacity</td>
<td>Changing utilization capacity of pumps, pipes also caused by increasing max. water demands: decreasing level of efficiency</td>
</tr>
<tr>
<td>Decrease of oxygen</td>
<td></td>
<td>Increasing chemical demand for flocculation, disinfection/oxidation, increase of by-product-formation (e.g. trihalomethane, AOC, bromate)</td>
<td>Increasing deposition and biofilm growth in tanks, pumps, fittings</td>
<td>Risk for regrowth of micro-organisms caused by higher temperature and higher amounts of AOC: hygienic risks</td>
</tr>
<tr>
<td>Algal formation</td>
<td></td>
<td>Increasing demand for backwash/ flushing water (frequency and flow rates)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increasing costs of operation and waste disposal</td>
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<td></td>
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<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

AOC, assimilable organic carbon; DOC, dissolved organic carbon.
conditions, such as drought periods or strong rainfalls with floods, were identified and adaptation measures defined. The measures described in the following are part of the comprehensive risk management scheme including all steps of the water supply chain.

Adaptation measures for safe water supply

Although the climate in the western part of Germany is not expected to change dramatically, our research reveals considerable need for action with respect to adaptation and optimization of all parts of the water supply system. In some parts of the pilot region water shortages are already noticeable, due to longer heat periods with lower water levels in surface waters and increasing water demand from population, as well as from agriculture and industry.

Based on a study on regional climate change (cf. Introduction) as well as other external factors and the expected development of the regional water demand, the existing supply system can be analysed in a systematic way along the supply process.

(1) Water resources management: If changes in raw water quality or quantity are most likely going to occur, their relevance for the water supply should be estimated. As proposed seasonal shortages of water quantity are expected or already actually noticeable it is important to identify all water users of the water body. There are two possibilities to cope with possible seasonal water shortages:

A. Regional water management regulated by the responsible water authority

B. Regional water management as result of a cooperative discussion process with all water users (e.g. guided by the responsible water authority)

For both adaptation pathways, knowledge about the regional water cycle and balance as well as about all water extraction is necessary in order to find a solution that is acceptable to all stakeholders. The cooperative approach (B) was tested within the dynaklim-project by establishing a task force ‘Lippe-Groundwater’ for the River Lippe (tributary of the River Rhine in North-Rhine Westphalia), using the basic principles of a regional (water) governance. Owing to climate change, a strong decrease of the available water quantity as well as quality impairment is to be expected within dry periods.

In addition to water supply, industrial companies and cooling systems of thermal power plants use relevant amounts of water from the River Lippe. A group was successfully established, and is working on measures for a consensual management of the regional water resources and implementation of technical measures to reduce water consumption (e.g. in farming and industrial applications). If water extraction cannot be reduced by measures like water saving or storage, a prioritisation of the usage is necessary. Especially during dry periods with increased water demand, drinking water supply has to be treated with priority in order to secure water supply for the population.

(2) Water treatment: If analysis of historical data shows correlations between predicted climate effects or extreme events and raw water quality, the performance of the water treatment scheme under critical conditions should be examined. Performance testing is an established method to find out about reactions of technical plants under stress situations. If tests at the technical scale are not possible, tests at pilot or laboratory scale can show critical points of the existing treatment scheme under the expected external changes and extreme conditions. Furthermore, modelling of different treatment steps can be helpful to consider reactions on, e.g. changes in operation or water quality.

Water supply companies are the main responsible actors for a suitable drinking water quality. However, if pollution of the water is caused by third parties (e.g. industries, waste water plants, hospitals) it could be reasonable to ensure direct elimination at the source, applying the polluter-pays-principle (OECD 1992). In many cases (e.g. for surface waters) it is much more economically efficient and ecologically reasonable to eliminate pollutants at high concentrations directly at the source than to emit them into the environment for removal at the downstream water treatment plant. This is particularly relevant when concentrations of substances are nearly constant at the source but dilution (e.g. in a river) varies across a high range due to precipitation or other climate effects. This effect can be detected in the River Ruhr for micropollutants such as carbamazepine or amidotrizoic acid. With lower run-offs the concentrations of the substances increase severely (see Figure 5).
Water treatment technologies usually perform best with a defined and more or less constant flow rate and mass concentration of substances that should be removed. Under climate change conditions, the range of concentrations may widen and the frequency of extreme values may increase. Therefore, performance testing under extreme conditions is very important to find boundaries for acceptable water quality. In most cases adaptation of the existing treatment technologies is possible, e.g. by increasing dosage of flocculants or ozone (see Table 2). Monitoring of raw and drinking water quality as well as between treatment steps is very important in every case to verify the efficiency of the implemented measures.

(3) Water distribution: Depending on the individual situation, measures to secure safe drinking water quality such as water treatment, planning and operation of water distribution and monitoring water quality can be implemented at different processes. To prevent microbiological regrowth and hygienic problems in the distribution system and to mitigate temperature increase of the drinking water in the pipes, a reduction of the assimilable organic carbon (AOC) within water treatment is very effective (Blokker & Pieterse-Quirijns 2013; Van der Kooij & Van der Wielen 2014). This can be achieved very effectively by biological filtration processes, especially granular activated carbon adsorption (Langlais et al. 1999). When ozone is applied, two downstream filtration stages are usually needed to achieve an appropriate AOC-removal to values under 10 µg/l (Liu et al. 2001). Furthermore, the use of chemical disinfection with depot effect (e.g. booster chlorination) can be suitable if concentration of AOC cannot be lowered enough. By using high chlorine dosages, the formation of chlorination by-products and tastes has to be taken into account.

Adapted planning and operating of water distribution systems can also be suitable to react to higher temperatures in drinking water due to climate change. That means, e.g. minimization of stagnation by appropriate flushing regimes and optimized planning with prevention of ‘dead-end’ pipes and sectors with low water velocity. Pipe diameters should be selected according to the expected water demand, ensuring a sufficient water flow-through. If water demand has decreased and water velocity is low in some sectors of the distribution network, these parts should be prioritised for renewal. Newly installed pipes should be

Table 2 | Treatment technologies affected by changing raw water qualities and possible adaptation measures (examples)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Affected treatment technologies</th>
<th>Impacts on water treatment</th>
<th>Adaptation measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidity</td>
<td>Filtration, flocculation, membrane technology</td>
<td>Increase flushing water demand, increase demand for chemicals</td>
<td>Adaptation of flushing strategy and chemical dosage</td>
</tr>
<tr>
<td>DOC</td>
<td>Filtration, flocculation, ozonation, AC-adsorption</td>
<td>Increase in ozone attrition and demand, inappropriate DOC-removal</td>
<td>Adaptation of ozone dose adjusted to raw water quality; adapted dosage of flocculants</td>
</tr>
<tr>
<td>Organic compounds</td>
<td>Ozonation, AC-adsorption, gas exchange (volatile compounds)</td>
<td>Increase in ozone attrition and demand, shortened periods between</td>
<td>Optimized oxidation processes (ozone, AOP), selected AC for specific compounds removal,</td>
</tr>
<tr>
<td>(e.g. diethylene triamine</td>
<td></td>
<td>reactivations, increase in AC-demand</td>
<td>BAC</td>
</tr>
<tr>
<td>pentaacetic acid,</td>
<td>Gas exchange, sedimentation, filtration, flocculation, membrane technology, ozonation,</td>
<td>Increasing water viscosity, risk for regrowth of micro-</td>
<td>Increase flushing water amount to reach necessary flushing velocity; booster</td>
</tr>
<tr>
<td>carbamazepine, amidotrio</td>
<td>disinfection</td>
<td>organisms in storage/distribution</td>
<td>chlorination; minimize AOC-discharge</td>
</tr>
<tr>
<td>acid)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>Soil passage, filtration, flocculation, membrane technology, ozonation, disinfection</td>
<td>Hygienic risk for water quality</td>
<td>Adaptation of disinfection (c-t-value) adjusted to raw water quality, booster</td>
</tr>
<tr>
<td>Micro-organisms</td>
<td></td>
<td></td>
<td>chlorination</td>
</tr>
</tbody>
</table>

AC, activated carbon; BAC, biological activated carbon.
buried at sufficient depth and not below roads and paved areas to reduce the influence of higher soil temperatures.

To ensure safe water quality, temperature regimes in drinking water should be defined and controlled in operation, especially in sensitive sectors, e.g. with low water velocity or under paved areas. Monitoring of microbiologically assimilable substances (AOC, biodegradable dissolved organic carbon) can help assessing the actual risk for microbiological regrowth and can be a control parameter for the function of water treatment. It could be demonstrated that the bacterial species E. coli, Klebsiella pneumoniae, Pseudomonas aeruginosa and Legionella pneumophila as opportunistic pathogens can be absorbed independent of the temperature by drinking water biofilms on materials that are relevant for the drinking water supply. They can persist at least for several weeks in the biofilm and represent a reservoir for the pathogens and a possible source of drinking water contamination. A microbiological monitoring for hygienic relevant micro-organisms on the surfaces (biofilms) has shown potential for an effective early warning monitor for hygienic parameters within the network (Grobe et al. 2012).

CONCLUSIONS

Climate change already affects the regional water cycle in most parts of the world. Owing to changing air temperatures and precipitation frequency, amount and seasonal allocation, water supply companies all over the world are affected by climate change and furthermore by other external factors, e.g. changing water demand in the supply system.

There are two possible pathways for water supply companies to adapt to climate change conditions and to secure water supply:

(a) Reactive adaptation after water shortage or damage.
(b) Risk-based adaptation strategy considering on-going modernization measures

To define a useful and sustainable adaptation strategy in a first step, (1) knowledge about the external factors has to be built up (e.g. modelling regional precipitation and climate change, study on regional water demand). Based on this information, (2) the vulnerability of the region as well as the specific system can be examined by analysis of capacity and performance of existing infrastructure under climate change conditions, analysis of flood risk for existing infrastructure and assessment of regional vulnerability. In every case, responsible water authorities are important players, especially concerning regional water demand and balance as well as defining the regional vulnerability.

By developing and implementing a roadmap for ‘Regional Climate Adaptation’, the dynaklim-region will receive a framework of reference for a future, regional adaptation strategy that connects previously isolated individual topics, coordinates goals and activities of regional administration, politics, economy and society, and identifies and coordinates priorities with relevant regional actors (Hasse et al. 2012; Schultze et al. 2014). The large-scale adaptive process in the metropolitan area will provide major experience to the world-wide efforts on climate change adaptation strategies.

Investigated experiences from several suppliers show that a reactive adaptation after water shortage or damage will likely result in (a) higher costs, (b) longer downtimes for water supply, and (c) negative image effects. On the contrary, risk-based adaptation strategy enables the water supplier to integrate adaptation measures in, e.g. ongoing modernization measures and to implement ‘no-regret-measures’. In many cases, this strategy seems to be the more efficient way to adapt to changing conditions. And if other external factors are taken into account by risk analysis and strategy development, even more synergies can be generated.

The results show the need for an individual analysis of the supply system incl. regional modelling of climate change in the water catchment area, effects on existing water utility infrastructure and performance testing of existing processes. A systematic risk management scheme (e.g. based on the WSP approach) should be used to include all possible risks and necessary adaptation measures. With a widespread approach, taking into account the whole supply system, a highly cost- and time-effective adaptation strategy can be developed, and by implementing the adaptation measures water quality and supply can be secured also under changing conditions.

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