WP5.2: Combination of MAR and adjusted conventional treatment processes for an Integrated Water Resources Management

Deliverable 5.2.3

Analysis of the vulnerability of bank filtration systems to climate change by comparing their effectiveness under varying environmental conditions

TECHNEAU is an Integrated Project Funded by the European Commission under the Sixth Framework Programme, Sustainable Development, Global Change and Ecosystems Thematic Priority Area (contractnumber 018320).

Introduction

While climate change is an emerging hazard to water supply, literature on the vulnerability of bank filtration (BF), a proven technique of drinking water production in Central Europe and North America, is yet scarce. The Intergovernmental Panel of Climate Change (2007) has projected a global temperature increase between 1.1 and 6.4 °C by 2100. This will affect vital factors for water supply such as precipitation regime, groundwater recharge, run-off, river discharge and raw water quality. Projections on climate change and the implications are difficult because of the uncertainties associated with climate scenarios and modelling. However, in Europe and North America where BF is in operation, the projected increase in seasonal floods and droughts has already been experienced. In addition, site-specific considerations (e.g. land use, demographic trends) are to be taken into account to evaluate the potential impacts on water supply. To fill the current gap in literature, this report provides a first overview on how changing environmental conditions may affect BF operation.

Approach

In order to assess the vulnerability of BF systems to climate change, the report aims at

(i) identifying climate-sensitive factors that affect BF performance,

(ii) assessing their relevance in moderate climate zones based on a 'dry' and 'wet' scenario and also benefiting from the TECHNEAU experience gained at BF sites in India,

(iii) illustrating by means of a case study how water suppliers relying on BF operation evaluate future challenges by climate change and other stresses.

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TKI Categorisation

Classification									
Supply Chain		**Process Chain**		**Process Chain (cont'd)**		**Water Quality**		**Water Quantity (cont'd)**	
Source		**Raw water storage**		**Sludge treatment**		**Legislation/regulation**		- Leakage	
- Catchment		- Supply reservoir		- Settlement		- Raw water (source)		- Recycle	
- Groundwater	X	- Bankside storage	X	- Thickening		- Treated water			
- Surface water	X	**Pretreatment**		- Dewatering		**Chemical**			
- Spring water		- Screening		- Disposal		- Organic compounds	X		
- Storm water	X	- Microstraining		**Chemical dosing**		- Inorganic compounds	X		
- Brackish/seawater		**Primary treatment**		- pH adjustment		- Disinfection by-products	X		
- Wastewater		- Sedimentation		- Coagulant		- Corrosion			
Raw water storage		- Rapid filtration		- Polyelectrolyte		- Scaling			
- Supply reservoir		- Slow sand filtration		- Disinfectant		- Chlorine decay			
- Bankside storage	X	- Bank filtration	X	- Lead/plumbosolvency		**Microbiological**			
Water treatment		- Dune infiltration		**Control/instrumentation**		- Viruses		**Consumers / Risk**	
- Pretreatment		**Secondary treatment**		- Flow		- Parasites			
- Primary treatment	X	- Coagulation/flocculation		- Pressure		- Bacteria	X	**Trust**	
- Secondary treatment		- Sedimentation		- pH		- Fungi		- In water safety/quality	
- Sludge treatment		- Filtration		- Chlorine		**Aesthetic**		- In security of supply	X
Treated water storage		- Dissolved air flotation(DAF)		- Dosing		- Hardness / alkalinity	X	- In suppliers	
- Service reservoir		- Ion exchange		- Telemetry		- pH	X	- In regulations and regulators	
Distribution		- Membrane treatment		**Analysis**		- Turbidity	X	**Willingness-to-pay/acceptance**	
- Pumps		- Adsorption		- Chemical		- Colour	X	- For safety	
- Supply pipe / main		- Disinfection		- Microbiological		- Taste	X	- For improved taste/odour	
Tap (Customer)		- Dechlorination		- Physical		- Odour	X	- For infrastructure	
- Supply (service) pipe		**Treated water storage**						- For security of supply	

Internal plumbing		- Service reservoir				Water Quantity		**Risk Communication**	
- Internal storage		**Distribution**						- Communication strategies	
		- Disinfection				**Source**		- Potential pitfalls	
		- Lead/plumbosolvency				- Source management	X	- Proven techniques	X
		- Manganese control				- Alternative source(s)	X		
		- Biofilm control				**Management**			
		Tap (Customer)				- Water balance	X		
		- Point-of-entry (POE)				- Demand/supply trend(s)	X		
		- Point-of-use (POU)				- Demand reduction			

TKI Categorisation (continued)

Contains		Constraints		Meta data					
Report	x	Low cost	x	*Iris Huelshoff, Janek Greskowiak & Gesche Grützmacher*					
Database		Simple technology	x	*KompetenzZentrum Wasser Berlin*					
Spreadsheet		No/low skill requirement	x	*Iris Huelshoff*					
Model		No/low energy requirement	x	*iris.huelshoff@kompetenz-wasser.de*					
Research		No/low chemical requirement	x						
Literature review		No/low sludge production	x	*SINTEF*					
Trend analysis		Rural location							
Case study / demonstration	X	Developing world location							
Financial / organisational									
Methodology									
Legislation / regulation									

Colophon

Title
Analysis of the vulnerability of bank filtration systems to climate change by comparing their effectiveness under varying environmental conditions

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Glossary

Aerobic	denotes metabolic processes in the presence of dissolved oxygen
Ambient groundwater	synonymous with natural, landside-, inland-, background groundwater
Anaerobic	denotes metabolic processes in the absence of dissolved oxygen or nitrate (NO_3^-) using sulphate as electron acceptor
Anoxic conditions	environment in which both O_2 and NO_3^- are absent and neither sulphate reduction nor methanogenesis occur (Fe(III)- and Mn(IV)-reducing environment)
Bank filtration (BF)	the infiltration of water from a river or lake into a groundwater system induced by water abstraction from wells adjacent to banks
Combined sewer overflow	discharge of untreated stormwater and sewage into rivers during storm events
Deep anoxic conditions	environment in which both O_2 and NO_3^- are absent and sulphate reduction and/or methanogenesis occur
Evaporation	process by which water changes from the liquid to vaporous state
Interception	process by which water is retained by the vegetation surface and finally evaporated
Groundwater recharge	herein defined as the natural replenishment of groundwater resources by infiltration of precipitation
River discharge	volume of water transported by a stream in a certain amount of time
Run-off	water originating from rain, snowmelt or irrigation that flows over surfaces and eventually reaches the stream or surface water
(Sub-)oxic conditions	environment in which O_2 and/or NO_3^- are present

Upconing	vertical upward movement of saline water as response to local reduction in the freshwater head

Contents

1 Introduction

Within the European project TECHNEAU ("Technology enabled universal access to safe water"), work package WP5.2 ("Combination of Managed Aquifer Recharge (MAR) and adjusted conventional treatment processes for an Integrated Water Resources Management") investigates river bank filtration (BF) and adjusted post-treatment as a MAR technique to provide sustainable and safe drinking water. Given the manifold implications of climate change on the hydrological cycle and water supply, the present report aims at assessing the vulnerability of BF systems. A general expectation for moderate climate zones is an overall rise in temperature. In this context, the TECHNEAU experience gained from BF sites in Delhi, India can help understanding how BF performance in Central Europe and North America may become impaired.

The change of climate is regarded one of mankind's major challenges in the 21st century for which risk evaluation is carried out by the Intergovernmental Panel on Climate Change (IPCC). According to the IPCC, the impacts comprise increasing temperatures, weather extremes and evapotranspiration, leading to freshwater resources and land deterioration, desertification as well as inundation of populated areas. In the Fourth IPCC Assessment Report (2007), a mean global surface temperature rise by 1.1 to 6.4 °C and a mean global sea level rise by 18 to 59 cm until 2100 were projected. As a result, small island states with land area 3 to 4 m above present mean sea level (e.g. the Bahamas, the Maldives) and many coastal areas (e.g. The Netherlands) are threatened by inundation. Floodings put human settlements at risk for destruction enforcing the displacement of tens of millions and impairing water-supplying infrastructure (e.g. desalination plants), freshwater reservoirs or agricultural land. Not only seaside floodings but an increased number of inland floodings is expected to occur where riverine systems transport snowmelt from higher altitudes such as the Himalaya in Asia or the Alps in Europe.

Notwithstanding the remaining uncertainties regarding the character, magnitude and rate of climate change, global warming has been suggested to induce an altered precipitation regime and increased evaporation rates resulting in the reduction of freshwater resources. The 11 warmest years on record have occurred in the past 13 years. In many regions, water supply is already challenged by a growing population and rising agricultural or industrial water demand. This development coincides with the pollution of available freshwater resources (municipal and industrial discharge, run-off from agricultural surfaces). Moreover, intense land use (e.g. agriculture, livestock farming, mining and urbanisation) competes with water management considerations such as catchment protection and natural replenishment.

The above summarised impacts on the hydrological cycle illustrate the challenges that water supply is facing in the 21st century. Climate change affects the demand for water, the reliability of raw water resources as well as the sustainability of water supply and treatment infrastructure (Arnell & Delarney, 2006). The future development of precipitation, groundwater recharge, river discharge and run-off regimes as well as water demand needs to be assessed before shortages can occur. In many European countries, the water consumption per capita will decrease as the result of a declining population and water savings efforts. In the last decades, water saving has been encouraged by water-economic technology and water price policy. In newly-industrialised countries such as India or China, the growing population, agriculture and industry will cause an on-going rise in water demand despite the increase in costs. In many developing countries, available freshwater resources already fall short of meeting the needs of the growing population and the situation is expected to worsen. Africa was identified to be the continent the most susceptible to climate change. Vegetation and wildlife are already under threat from population pressures, land deterioration and water depletion. The majority of African countries is classified as either water-scarce (1,100-1,700 m^3 per capita/annum) or water-stressed (<1,100 m^3 per capita/annum). It has been estimated that by the year 2025, two-third of the world's population will live in water-stressed conditions (UNEP, 1999).

Where the traditional way of water abstraction and use will prove unsustainable or show deficiencies (e.g. groundwater depletion in South-East Asia), alternatives are sought. A holistic approach would comprise (i) the education of consumers on the importance of safe water, sanitation and source water protection, (ii) the operation of waste and drinking water treatment, (iii) the implementation of protective legislation as well as water price policy and (iv) the identification of alternative schemes for drinking water production. While considerations (i) to (iii) promote the responsible and sustainable use of available freshwater resources, the consideration (iv) aims at finding technically feasible alternatives to traditional approaches.

The conventional approach is to either abstract surface water or groundwater and subject the source water to treatment for drinking water purpose. A range of alternatives has been studied in Australia which ranks as the driest inhabited continent on Earth. Traditional water supply relies on water storage in dams which were demonstrated to be highly vulnerable to the prolonged periods of droughts experienced in recent years. Potential approaches to address water shortages include stormwater management, water recycling for potable and non-potable use and the operation of desalination plants (Rathjen *et al.*, 2003). However, in low-income countries, high-tech solutions such as desalination plants may be not affordable. Water supply schemes have to meet local needs. Subsurface storage of freshwater, for instance, may prove unsuitable in areas where saline groundwater and soil are prevalent (e.g. in Australia) (Dillon *et al.*, 2002; Pearman, 1988).

Bank filtration (BF), i.e. the induced infiltration of surface water into the subsurface and abstraction by wells, is a sustainable and suggested low-cost technique that is established in North America and Europe for drinking water production. Due to its efficiency to remove relevant contaminants from surface water and its freshwater storage capacity, it has been advocated as useful technique to developing and newly-industrialised countries (Huelshoff *et al.*, 2009). Where bank filtration is in operation (still predominantly in moderate climate zones), it is important to understand the manifold implications that climate change may have on system performance. Experience from BF sites in warm climate zones (e.g. from India) may help to assess the vulnerability of BF systems to climate change. A first assessment and overview is herein provided to fill the current gap in literature. The present report therefore aims at (i) identifying the climate sensitive factors influencing BF performance and (ii) assessing their relevance under the common climate change scenarios.

2 Vulnerability of bank filtration systems to climate change

2.1 Climate-sensitive factors influencing BF performance

The change of climate is regarded a future hazard to water supply (Beuken *et al.,* 2007), however, the implications of climate change for BF systems are not fully understood. Climate-sensitive factors influencing BF performance are temperature, raw water quality, river discharge and run-off regimes as well as precipitation and groundwater recharge. The impacts of these factors on BF performance can be direct or indirect. Indirectly, they affect BF conditions such as travel time and redox conditions which are both major parameters determining BF performance and the elimination potential of contaminants (see Fig. 1).

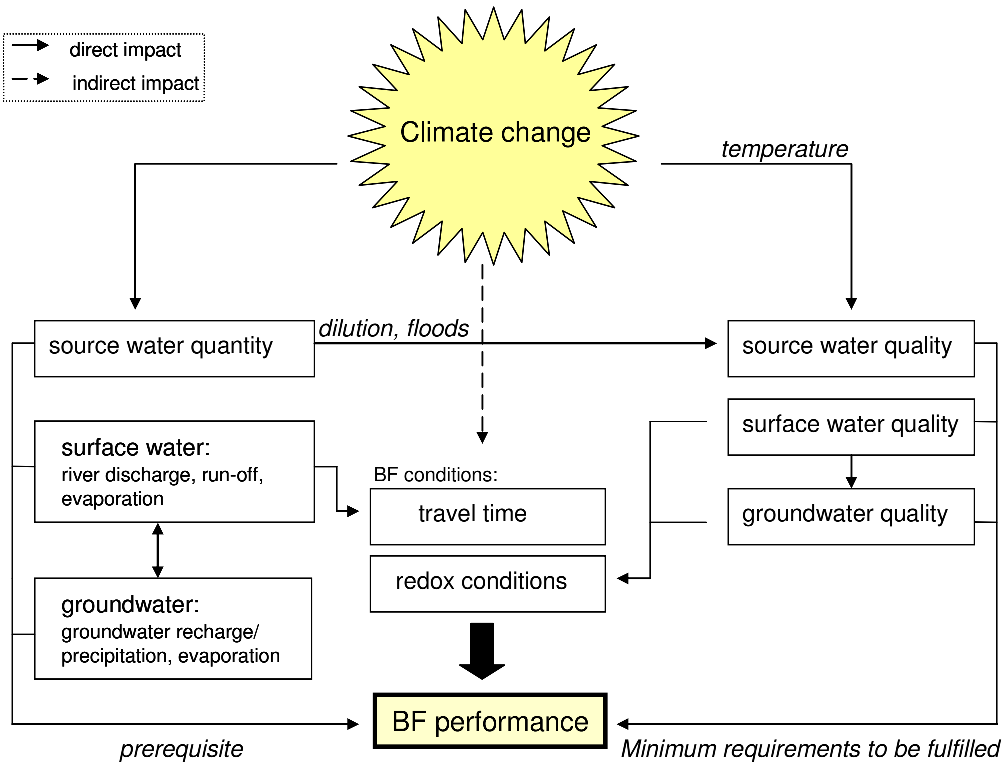

Figure 1: Climate-sensitive factors influencing BF performance

2.2 Temperature

Defined as an area's long-term weather pattern, climate is determined by temperature, precipitation, humidity and wind. Temperature is also the driving force behind the other three climate factors and as such, it has direct and indirect impacts on climate. In the following, trends affecting BF performance which are the result of temperature change are summarised.

2.2.1 Temperature effect on the hydrological cycle and wind pattern

Between 1906 and 2005, the global surface temperature has risen by 0.74 ± 0.18 °C (IPCC, 2007). Temperature has been projected by the IPCC (2007) to rise between 1.1 and 6.4°C by the year 2100. At higher air temperatures, evaporation rates and the air's capacity to hold moisture increase. Temperature as well as the temperature-dependent air moisture and pressure determine the occurrence and intensity of storm events such as hurricanes. More frequent and powerful cyclones have particularly been observed in the North Atlantic in recent years and proposed to be linked to global warming (Elsner, 2008). Coastal storms can inundate water supplying infrastructure and impair water quality (e.g. by salinisation). In the past century, an alteration of abundance and type of precipitation has been noted to result in extreme droughts or floodings (IPCC, 2007). Bank filtration may become deprived for its source water during prolonged droughts while floodings can inundate well fields close to banks and increase contaminant load. Given the rise in temperature and mild winters (as experienced in the EU), precipitation is expected to fall more frequently as rain. When less water is bound as snow, a higher run-off in winter and decreased run-off in spring is expected to impact river discharge (see Ch. 2.3 River discharge and run-off). In some areas, lowered precipitation and discharge patterns will result in reduced groundwater recharge; while elsewhere; mild winters can reduce ground frost allowing for higher infiltration rates (see Ch. 2.4 Groundwater recharge). The sufficient availability of surface and groundwater – influenced by precipitation, river discharge and evaporation rates - is a prerequisite for bank filtration.

2.2.2 *Temperature effect on microbial activity*

The increase in air temperature induces the warming of oceans, stream water, lake water and over the years, groundwater. Higher water temperatures promote algal growth and microbial activity which usually leads to increased oxygen consumption. Moreover, the capacity to dissolve oxygen is lowered in warm water. Redox conditions have a significant impact on the degradation of water contaminants in the aquatic environment and subsurface (see Ch. 2.5 Changes in raw water quality). Concerns have also been expressed that increased water temperatures may lead to microbial regrowth and hygienic problems in the distribution network (Zwolsman, 2008). This might render safety chlorination after BF necessary even where it is at present not applied (e.g. in Berlin). For BF systems, increasing water temperatures can mean enhanced degradation processes in the short term but also cause redox conditions turning faster anoxic/ anaerobic and thereby adversely affecting biodegradation efficiency.

2.2.3 *Temperature effect on freshwater reserves and salinisation*

An overwhelming 97.5% of the world's water reserves are saline with less than 3% being freshwater resources (Hoell, 2002). This unbalance is expected to worsen with climate change and freshwater resources dwindling away. Rising air and water temperatures enhance the melting of ice from polar caps and higher altitudes. A sea level rise of up to 59 cm has been projected by the year 2100 putting coastal areas and many islands at risk for inundation. Permanent or temporary inundations (caused by storm events) can impair water supplying infrastructure and freshwater resources by salinisation. Saline or brackish groundwater environments (salinity expressed as electrical conductivity EC) constitute a problem since already small volumes of saline water ($EC_{sea\ water}$: 45.000-55.000 µS/cm) render freshwater objectionable (Hoelting & Coldewey, 2009). The share of saline water in mixed water could be as low as 0.03% and cause groundwater (~$EC_{groundwater:}$ 1.000 µS/cm) to exceed the German threshold value for salinity ($EC_{drinking\ water}$: 2.500 µS/cm) (TrinkwV, 2001).

In the Netherlands, low river discharge in combination with strong west winds, increase the intrusion of sea water through river mouths. Further, the increase in sea levels causes *upconing* of salt water from deeper (fossil) marine aquifers threatening freshwater resources. Already one quarter out of 200 drinking water production sites in the Netherlands are at risk for salinisation (Zwolsman, 2008). Aquifer recharge is a potential countermeasure to prevent the inflow of saline water into freshwater reserves.

2.3 River discharge and run-off

River discharge is the volume of water transported by a stream in a certain amount of time while run-off is the water originating from rain, snowmelt or irrigation that flows over surfaces and eventually reaches the stream or surface water. Thus, run-off contributes to river discharge. Both are measured as cubic metres per second (m^3/s). The amount and type of precipitation has a direct impact on river discharge, run-off and evaporation. Where precipitation due to mild temperatures is expected to fall rather as rain than snow, an increase in winter run-off and a decrease in spring run-off is probable.

Global warming and its impact on the hydrological cycle will lead to dry summers in Southern Europe and wet winters in Northern Europe (EEA, 2008). There appears to be consensus in literature that there will be a marked increase in winter run-off and decrease in summer run-off in North America (Jyrkama & Sykes, 2007; Marshall & Randhir, 2008) and Europe (Bouraoui *et al.*, 2004; Andersen *et al.*, 2006, Wilby *et al.,* 2006, Eckhardt & Ulbrich, 2003; Arnell & Delaney, 2006) with a slight overall decrease in annual run-off (Jyrkama & Sykes, 2007; Marshall & Randhir, 2008). An increase in run-off is particularly expected for riverine systems transporting snowmelt from higher altitudes such as the Himalaya in Asia or the Alps in Europe. The Alps glaciers have already lost two thirds of their volume since 1850 (EEA, 2008). However, the run-off increase in such glacier-fed rivers is transitory and will dwindle over time. In central Asia, glacier runoff is projected to increase threefold by 2050 and taper to two-thirds of its present value by 2100 (Bates *et al.*, 2008).

An increase of floodings as the result of seasonally higher river discharge is already observed. In Europe, 259 larger floodings were monitored since 1990, of which 165 occurred in the new millennium (EEA, 2008). High river discharge and associated floods put urban, industrial and agricultural areas at risk for inundation whereby pollutants may become mobilised into the water (see Ch. 2.5 Changes in raw water quality) and water supplying infrastructure becomes impaired. Flood events are often accompanied by increased hydraulic gradients inducing a rise in groundwater tables (Eckert *et al.*, 2008). Increased flow velocities during high river discharge may result in shorter travel times and render purification processes in the subsurface less effective (see Ch. 2.6 Changes in BF performance).

While high river discharge and run-off events constitute a problem to water quality (see Ch. 2.5 Changes in raw water quality); low discharge and run-off are not only a problem to quality (lowered dilution of contaminants, salinisation) but quantity. Surface water as major raw water source to bank filtration systems should carry high enough amounts to ensure sustainable drinking water production. In Berlin, a weir system prevents that surface water levels drop, thus, in periods of temporary low river discharge, the hydraulic head necessary for the production yield remains stable. Also at a BF site near the river Rhine, the maximum abstraction from BF wells could be realised in the drought summer 2003 despite low river levels thanks to deep enough wells (Eckert *et al.*, 2008). Although, it remains uncertain how BF sites in moderate climate zones will be affected by prolonged droughts, bank filtration is considered much less vulnerable to climate change than drinking water production relying on the direct abstraction of surface water due to its buffer capacity.

2.4 Groundwater recharge

Groundwater recharge is influenced by temperature (see Ch. 2.2 temperature), the amount and type of precipitation, land cover and human activities. In Northern Europe, a precipitation increase between 10 and 40% has been observed in the past century while in Southern Europe, a decrease by 20% was monitored (EEA, 2008). It is projected that aside from altered precipitation rates, the nature of precipitation will shift from snow to more rain (Eckhardt & Ulbrich, 2003). Increased rainfall and run-off in combination with less ground frost as projected for Northern Europe, is expected to enhance infiltration and thus, groundwater recharge.

Only a portion of the precipitation infiltrates into soil and replenishes groundwater. Water is also retained on the vegetation canopy through interception (e.g. by leaves) and will eventually become subject to evaporation. The majority of water that is taken up by the vegetation and plant roots is later discharged into the atmosphere via transpiration. While losses due to evapotranspiration (evaporation + transpiration) may be insignificant when compared to rainfall and run-off in the short term (hours to a few days), in the long-term, losses can become substantial for a watershed. Urbanisation has lead to deforestation, destruction of wetlands and soil sealing, thereby reducing potential infiltration areas. Groundwater recharge can be impaired by human activities such as soil sealing or enhanced by artificial irrigation or recharge schemes (Lerner, 2002).

Groundwater systems respond more slowly to climatic changes than surface water systems. Yusoff *et al.* (2002) suggested that for West Norfolk (UK) a lowered summer precipitation and increased potential for evapotranspiration would decrease autumn river discharge by 14% while summer groundwater levels would only decrease by 1-2%. The deeper the aquifer, the better the storage and buffer capacity. Shallow aquifers supplying streams, lakes and wetlands – i.e. those adjacent to BF sites – are probably the most vulnerable to climate change (Alley, 2001). The majority of the reviewed literature expects a decrease in groundwater recharge (see table 1), however, modelling scenarios contain a considerable degree of uncertainty. Site-specifics such as land use, population growth and unsustainable abstraction practices are more likely to threaten groundwater resources than climate change. If the projections for Northern Europe come true, the implementation of subsurface storage schemes (BF or other artificial recharge schemes) could be a good option to store winter run-off for the dry summers.

Table 1: Projected effects of climate change on groundwater recharge in moderate climate zones

location	changes in groundwater recharge	reference
River Rhine,Germany	decrease by 50% in summer, increase during 2 months in winter	Eckhard & Ulbrich, 2003
West Norfolk, UK	decrease by 17 to 35% in autumn	Yusoff *et al.,* 2002
Grand River watershed, Canada	increase by 53% of annual recharge	Jyrkama & Sykes, 2007
Ogallaga Aquifer, U.S.	decrease by 17 to 25% at 1 °C temperature increase	Rosenberg *et al.,* 1999
Abbotsford–Sumas Aquifer, Canada	minor changes, dominating river-aquifer interactions	Scibek & Allen, 2006
Geer basin, Belgium	decrease in groundwater levels and reserves	Brouyère *et al.*, 2004
3 sites in UK	decrease of potential recharge groundwater by 7%, 20% and 40% by 2100	Herrera-Pantoja & Hiscock, 2008

2.5 Changes in raw water quality

During bank filtration, surface water is induced to infiltrate into groundwater systems by the operation of abstraction wells adjacent to banks. The ratio at which infiltrated surface water and groundwater are mixed in abstraction wells can be managed to overall improve water quality for drinking purpose, e.g. by diluting high nitrate levels (NO_3^-) from groundwater. Factors influencing **surface water** and **ambient groundwater** quality are identified and evaluated in the following.

2.5.1 *Surface water quality*

Surface water quality is largely determined by human activities (e.g. municipal effluent) and in future, more and more subject to climate-related changes (e.g. altered river discharge). Man-made pollution is commonly easier to address (e.g. by sewage treatment) than complex environmental changes. The climate change effects projected vary among regions and modelling scenarios. Therefore, (1) dry and (2) wet climate conditions are taken as two basic scenarios to assess their effect on surface water quality.

(1) In case of **dry conditions** of (temporarily) decreased precipitation, run-off and river discharge (as projected for European summers), streams influenced by point sources are likely to exhibit higher contamination levels (e.g. pathogens, organic micropollutants) as a result of the lowered dilution potential. In addition, low flow velocities in eutrophic water bodies are favourable for the development of non-harmful and harmful algal blooms (HABs). The eutrophication in polluted streams is accompanied by oxygen depletion, thereby reducing in-stream nitrification and other in-stream degradation of contaminants. This effect is enhanced by higher water temperatures at which less oxygen is dissolved and microbial activity is enhanced. Due to the large surface area exposed, surface water is more susceptible to evaporation and warming than groundwater.

Table 2: Water contaminants and their redox-dependent removal during BF[1]

	better removal or degradation under (sub-) oxic conditions	**better removal or degradation under anoxic / deep anoxic conditions**
relevant water contaminants	bulk organic carbon (DOC), some heavy metals (Fe, Mn), NH_4^+ (oxidised to nitrate), algal toxins, BTEX, PAHs, lower substituted chlorinated hydro-carbons, endocrine disruptors, many pharmaceuticals (e.g. DMAA, phenazone)	NO_3^- (reduced to N_2), SO_4^{2-}, higher substituted chlorinated hydrocarbons (e.g. TCE, PCE, DCE), disinfection-by-products (THM's), some pharmaceuticals (e.g. sulfamethoxazole, amido-trizoic acid)

[1] Huelshoff *et al.*, 2009

The European summer 2003 was extraordinarily dry and commonly serves as an example for climate change in the moderate climate zone. The water levels of the river Rhine fell 2 m below the annual mean (~ 30 m.a.s.l) while surface water temperature reached up to 25°C. The oxygen concentration fell from super-saturation levels (~13 mg/l) to 7 mg/l (Eckert *et al.*, 2008). Redox conditions are considered crucial for the degradation of water contaminants which are overall less efficient in the absence of oxygen (table 2). Due to the lowered dilution potential in the river Rhine, higher chloride concentrations were observed originating from salt mines upstream (Eckert *et al.*, 2008). Also a Rhine tributary used for BF in the Netherlands showed increasing salinisation (Zwolsman, 2008). A study on the impact of dry conditions (1976-2003) on water quality in the Netherlands confirmed that point-source pollution (e.g. fluoride, aluminium) was more pronounced and algal growth was shown to be higher as the result of elevated water temperature (Zwolsman, 2008). Diffuse-source pollutions (nitrates, pesticides) do not have the same importance as during wet conditions because of less run-off events experienced. At the same time, however, this positive effect might be outweighed by the general lowered dilution of contaminants in streams.

➔ Substances likely to show increasing concentrations under **dry conditions**:
- pathogens,
- algal toxins,
- DOC,
- Ammonium,
- anions & cations,
- heavy metals,
- trace organics (except for pesticides, due to decreased run-off).

(2) In case of **wet conditions** of (temporarily) increased precipitation, run-off and river discharge (as projected for European winters), surface water quality is more at risk for contamination by nitrates, and pesticides washed off from agricultural surfaces. An increase of nitrate levels related to increased winter run-off has been projected by several modelling studies from Scandinavia (Bouraoui *et al.* 2004, Andersen *et al.*, 2006), the UK (Wilby *et al.,* 2006) and France (Ducharne *et al.*, 2007). Also, a rise in ammonia levels has been predicted (Ducharne *et al.*, 2007). In most urban areas, heavy rainfall induces combined sewer overflow, whereby ammonia (NH_4^+) and organic-rich waste water is discharged into streams. The discharge of untreated effluent into rivers is known to promote eutrophication and oxygen depletion, impairing biodiversity, in-stream degradation and BF performance (see Ch. 2.6

Changes in BF performance). In this context, ammonia is a problematic surface water quality parameter. The TECHNEAU investigations carried out at a BF field site in India have demonstrated that ammonia from stream water was not removed during BF passage (Pekdeger *et al.*, 2008). However, a high river discharge has the advantage of contaminant dilution and accompanied water turbulences. The latter can introduce oxygen and prevent algal growth.

Nutrients and agricultural contaminants (NO_3^-, NH_4^+, DOC, pesticides) are not the only substances being mobilised into the water phase during high run-off events. In the United States, 77 out of 127 tested priority pollutants were detected in urban runoff in a nationwide study (EPA, 2001). The inundation of industrial or urban areas, the remobilisation of sediments by erosion (Carpenter *et al.,* 1992; Marshall & Randhir, 2008; Schubert, 2006) and the discharge from combined sewer overflow (Patz *et al.,* 2008; Semadeni-Davies *et al.*, 2008) will potentially increase the concentration of micropollutants (e.g. aromatic hydrocarbons, pharmaceuticals), pathogens and suspended solids in surface water. Increased loads in suspended solids enhance the clogging risk of the infiltration zone and can impair production yield. This is particularly true where river flow is influenced by hydropower stations (e.g. in Switzerland) and for gravel river beds (Hubbs 2006). However, the high flow velocities seen during increased run-off events counteract clogging by shear forces at the water-sediment boundary.

Surface water quality is influenced by climate change, but also subject to stresses not related to global warming. It has been hypothesized, for instance, that the dramatic increase of dissolved organic carbon (DOC) seen in surface waters across Europe and North America since the 1980’s might be linked to climate change. However, more conclusive evidence has been provided explaining the DOC rise by declines in sulphur deposition chemistry and catchment acid sensitivity (Monteith *et al.*, 2007; Erlandson *et al.*, 2008). Similarly, the human response to climate change may have a larger influence than climate change itself. Land use driven by climate change was suggested to have more impact on pesticide fluxes than direct impacts of climate change (Bloomfield *et al.*, 2006). Ducharne *et al.* (2007) proposed that good agricultural practice can outweigh the increase of expected nitrate leaching.

➔ Substances likely to show increasing concentrations under **wet conditions**:

- pathogens,
- suspended solids,
- DOC,
- nitrate, ammonium,
- heavy metals,
- trace organics from diffuse sources (pesticides, chlorinated hydrocarbons, aromatic hydrocarbons).

2.5.2 *Groundwater quality*

Groundwater is affected by climate change through the process of recharge, and the interaction with hydraulically-linked surface water bodies (Jyrkama & Sykes, 2007). Being located in the subsurface, groundwater is better protected from contamination than surface water and less prone to evaporation or warming. Nonetheless, groundwater contaminants may derive from numerous sources such as agriculture (e.g. nitrate, pesticides), landfills, industrial legacies and septic tanks (e.g. ammonia, pathogens, micropollutants). They can also be of geogenic (e.g. arsenic, fluoride) or marine origin (e.g. salinity). In the following, the effect of climate change on groundwater quality is evaluated in scenarios of water depletion (dry scenario) (1) and water abundance (wet scenario) (2).

(1) A decrease of precipitation (**dry scenario**) in combination with higher temperatures and evapotranspiration rates will lead to reduced natural replenishment of groundwater resources. A continued unbalance between groundwater abstraction and natural replenishment will lower the water table. As a result, dependent ecosystems (e.g. wetlands) can dessicate and wells run dry. This may lead to the oxidation of anoxic environments and subsequent release of sulphate as well as acidification. Under dry conditions, very shallow groundwater is susceptible to evaporation and salinisation. Soil salinisation may become enhanced by irrigation and subsequent evaporation.

(2) An increase of precipitation (**wet scenario**) and subsequent higher agricultural surface run-off and infiltration will promote the transport of nitrate and pesticides to groundwater systems. Bank filtration can serve to improve groundwater quality by the mixing with surface water (e.g. dilution of nitrate). Sea-side floodings caused by storm events (e.g. in the Netherlands) can contaminate freshwater surface and groundwater resources and supply infrastructure (e.g. well fields). In this scenario of groundwater abundance, quality deterioration can be avoided by good land management practices and pollutants be diluted.

In general groundwater quality will change at a much slower rate than this is expected for surface water quality. This gives the opportunity to prevent deterioration by duly countermeasures. On the other hand, it is more difficult to control, once deterioration has taken place.

2.6 Changes in BF performance

In the previous chapters, the climate-sensitive factors *temperature* (Ch. 2.2), *river discharge* & *run-off* (Ch. 2.3), *groundwater recharge* (Ch. 2.4) and *raw water quality* (Ch. 2.5) were identified to have a direct impact on BF performance in terms of available water quantity and quality. They all indirectly affect the elimination potential by altered BF conditions such as the *travel time* from (river) bank to abstraction wells and *redox conditions*. Both are crucial to the natural cleaning capacity of BF systems.

2.6.1 *Travel times*

In the subsurface, the processes contributing to the attenuation of contaminants require minimum (contact) times. Long travel times provide more opportunities and time for sorption and biodegradation processes which is particularly important for the removal of potential pathogens. In Germany, a travel time of 50 days defines the borders of the groundwater protection zone II and proved a suitable distance to provide microbially safe drinking water.

Travel times are influenced by (i) the distance from the bank to the abstraction well, (ii) the physical aquifer properties (e.g. hydraulic conductivity, soil texture) and (iii) the hydraulic gradient affected by recharge rates and hydraulic properties (Pijanowski *et al.*, 2007). Assuming travel distances are similar, travel times are shorter in aquifers exhibiting high hydraulic conductivity and recharge when compared to aquifers with low conductivity and recharge. In contrast to travel distance and physical aquifer properties, recharge rates and hydraulic gradients are affected by climate change.

During flood events at the river Rhine, infiltration rates of 2.400 l/s*km were observed which was 3-5 times higher than usual (Schubert, 2006). Because of the higher gradients seen along with flood events, a high river discharge may result in shorter travel times and less efficient purification processes in the subsurface (Schubert, 2002). Rohns *et al.* (2006) reported that during flood events the hydraulic residence time was reduced from 35 days down to 5-7 days at a BF site near the Rhine. Positive findings of indicator bacteria were observed in production wells where usually none were detected (Eckert *et al.*, 2008). Despite the rather low numbers of indicator organisms monitored (<10 MPN/100ml), it is a warning for potential system failure and breakthrough of pathogens under high discharge conditions.

2.6.2 Redox conditions

Under anoxic and deep anoxic conditions, the microbial degradation of contaminants is regarded less efficient than under (sub-) oxic conditions. The absence of oxygen may not only slow down biodegradation but remobilise iron and manganese into the water phase. Since most degradation processes in the subsurface occur under oxygen consumption, oxygen levels in the groundwater systems are usually lower than what is observed in surface waters. At a BF site near the river Rhine, for instance, the subsurface passage fell anoxic for a 3-months period after oxygen levels in the river fell from saturation levels (~13 mg/l) to 7 mg/l in the drought summer 2003 (Rohns *et al.,* 2006).

It seems likely that anoxic aquifer conditions are prevalent in developing and newly-industrialised countries when the hydraulically-connected stream water is characterised by high organic pollution and high water temperatures (Huelshoff *et al.*, 2009). Such conditions, as reported for the Yamuna River in Delhi (India), can impair BF performance leading to incomplete degradation or turnover (e.g. DOC, NH_4^+) and the mobilisation of trace elements (e.g. iron, manganese, arsenic). Assuming that groundwater temperatures reflect air and surface water temperatures over time, groundwater temperatures between 20 and 30 °C are expected for warm climate zones. Although the German average air and groundwater temperature is much lower (10°C), the respective maximum temperatures of 20°C and 25°C in ground- and surface water observed, were sufficient to cause anoxic conditions in summer 2003 (Rohns *et al.,* 2006).

2.7 Two scenarios influencing source water quality and BF performance

Two opposite climate change scenarios have been selected in this report to illustrate the potential impacts of changing environmental conditions on BF performance in moderate climate zones. The admittedly exaggerated scenarios assume **'dry'** (high evaporation, low precipitation, low groundwater recharge, low run-off and discharge regime) and **'wet'** conditions (low evaporation, high precipitation, high groundwater recharge, high run-off and discharge regime).

Dry conditions: As conditions of drought were seen to promote anoxic conditions in BF systems, compounds that are better degraded under aerobic conditions like DOC, ammonium etc. (see table 2) may be more persistent in the 'dry' scenario. On the other hand, travel times may increase (advantageous for removal) and deep anoxic conditions might promote the removal of several organic micropollutants (e.g. many heavy metals or x-ray contrast media).

Wet conditions: Redox conditions are not expected to change in the wet scenario, but increased flow velocities can reduce travel times and impair degradation processes in the subsurface. Many organic micropollutants are rather persistent hydrocarbons and often require long retention times. Thus, it is not expected that removal efficiency will improve in the 'wet' scenario with its shorter travel times.

Table 3, provides an overview on common water pollutants for which the removal efficiency of BF systems has been evaluated in the TECHNEAU report 5.2.9 (Hülshoff *et al.*, 2009). Based on the latter, the removal efficiency of today's operating BF systems is herein categorised into 'good', 'moderate' and 'poor'. The term 'inconsistent' denotes where large differences within a parameter group and substance-specifics do not allow for generalisation. The projected removal efficiency affected by climate change (wet + dry) is compared to the removal efficiency under today's operating conditions. The projected change in transport load from surface source water is also provided for both scenarios.

Table 3: Projected climate change effect on contaminant load in source water and BF removal efficiency under two major climate change scenarios

substances	**removal efficiency of BF systems**[1]	**a) transport load in surface source water**[2]		**b) assumed trend of BF removal efficiency**[2]	
scenario		**wet**	**dry**	**wet**	**dry**
pathogens	good	+	+	–	+
susp. solids	good	+	–	o	
algal toxins	good	–	+	–	–
DOC	good to moderate	+	+	–	–
NO_3^-	good to moderate	+	–	–	+
NH_4^+	good to moderate	+	+	o	–
anions & cations	poor	–	+	o	o
heavy metals	inconsistent	+	+	–	+
pesticides	inconsistent	+	–	–	–
chlorinated hydrocarbons	moderate to poor	+	+	–	+
aromatic hydrocarbons	moderate	+	+	–	
endocrine disrupting	good to moderate	+	+	o	o

substances	removal efficiency of BF systems[1]	a) transport load in surface source water[2]		b) assumed trend of BF removal efficiency[2]	
scenario		**wet**	**dry**	**wet**	**dry**
chemicals					
pharmaceuticals	inconsistent	+	+	o	–
disinfection by-products	good	–	+	–	+

[1] Hülshoff *et al.*, 2009

[2] symbols: '–' decreased, '+' increased, 'o' no change expected, 'blank' uncertain

It appears from table 3 that 'wet' conditions are more problematic for BF performance due to an increased transport load and less efficient removal. This is especially true for pathogens as the most critical parameter to drinking water quality. Overall, both climate change scenarios can potentially impair BF performance. Droughts promote less effective anoxic conditions; floods can drastically shorten travel times allowing pathogens and other contaminants to breakthrough.

Bank filtration systems have potential to balance temperature fluctuations and mitigate shock load events. They can cope with moderately increased contamination levels and remove turbidity with great reliability. Oxic redox conditions and long travel times are crucial for an optimal removal of contaminants by sorption and biodegradation. Climate change effects that affect these BF conditions directly or indirectly (e.g. by high river discharge) can overall impair BF performance.

3 Case study: Berlin, Germany

Effects of climate change are usually not projected without highlighting the considerable degree of incertitude and dependence on the modelling scenarios involved. Apart from climate change, water supply management needs to take a variety of factors into account such as a region's socioeconomic and industrial development. This chapter aims at illustrating how water suppliers using bank filtration assess the potential hazards from climate change for their watershed and supply area.

For more than 100 years, the city of Berlin has been producing drinking water by bank filtration. The water abstracted from wells derives from bank filtrate (60%), naturally (30%) and artificially recharged groundwater (10%). In cooperation with the Berlin Senate, the Berlin Water Works (BWB) have published a water supply concept for the supply area until the year 2040 (Moeller & Burgschweiger, 2008). The aim was to evaluate the impacts of demographic development, changes in demand, issues of stream water quality and climate change in different future scenarios.

Like elsewhere in Germany, the capital's population (2006: 3.4 mio) is likely to decrease over the next decades due to an ageing population and low birth rates despite a positive migration balance. This was largely confirmed by demographic modelling based on different scenarios of the region's economic development. Even under the assumption of a significant and permanent economic rise, Berlin's population would only increase by approx. 5.3% in the next four decades. Since 1991, the water demand has declined by almost 30% as a result of water saving efforts by private households and the industry. With regard to the consumption pattern observed in the drought summer 2003, the BWB suggested future decreases might become partiallly compensated by increasing demand related to rising temperatures. Assuming a moderate global temperature rise of 1.4 °C by 2055, the average rise in Berlin will be as high as 2 °C. For summer time, it was further projected as worst case scenario that by the year 2040, the annual river discharge and the natural replenishment may both decrease by 40% and precipitation in the area may decline from 585 mm/a to below 450 mm/a.

The summer 2003 was extraordinarily dry in Central Europe and often serves as an example of climate change for the area. In this year of drought, river discharge could still be managed such that drinking water supply in Berlin was ensured (abstraction for bank filtration and groundwater recharge) and flow in tributaries was maintained despite the higher water demand and evaporation losses experienced. In this context, sewage effluent can be a beneficial addition to the discharge regime.

During dry periods, sewage effluent also gains a larger influence on river water quality. Throughout the year, surface water quality is subject to municipal pollutants such as TOC, phosphate, ammonia and pharmaceuticals (particularly during combined sewer overflow under wet conditions). A major source of pollution to the river Spree, one of Berlin's larger supplying rivers, is the mining industry. Elevated sulphate levels are discharged into the river from brown coal open cast mining upstream in the catchment (Lausitz). While the mining activity deteriorates water quality by higher SO_4^- levels and acidification, the dewatering of the mining area (by pumping water into the Spree) has supplied the city of Berlin for years with a higher discharge than what would be naturally observed. The close-down of mines and water management practices to recharge the open pits (groundwater storage in artificial lakes) render future river discharge levels uncertain. In combination with climate change (e.g. evaporation losses), the mining activity upstream can result in insufficient river discharge and sulphate accumulation. As a rather conservative contaminant, sulphate is persistent during bank filtration and becomes only reduced under strictly anaerobic BF conditions.

Ambient groundwater reserves are also subject to anthropogenic pollution. More than 8.000 potentially contaminated sites (e.g. industrial legacies) have been identified in the area (Berlin Senate, 2009), several of which may impair groundwater quality. Due to the declines in demand, the city has nowadays more water work facilities at its disposal than are necessary to supply the population. This enables the BWB to carry out groundwater sanitation at closed sites and to reactivate inoperative water works to back up supply.

For Berlin, the strategy outlined to deal with a potentially low river discharge and precipitation regime as well as increasing sulphate levels includes the improved point-source pollution management and sulphate elimination upstream, the enhanced operation of less affected water works and enhanced groundwater recharge as well as the reactivation of inoperative water works.

4 Conclusions

There appears to be consensus in the literature reviewed that in Central Europe and North America, global warming will enhance snow melting and cause a shift in precipitation from snow to rain, increase winter- and reduce spring run-off. At the same time, groundwater recharge is predicted to decrease and evaporation losses to increase (especially in summer months). In future, a stronger variation in available freshwater amounts is projected and may trigger an increased use of water storage schemes such as BF or AR. During the last decades, Europe experienced an increase in floods and droughts, therefore, the approach chosen in this report was to evaluate BF performance under 'dry' and 'wet' conditions.

Under dry conditions, it is supposed that evaporation rates are higher while rainfall and groundwater recharge as well as surface run-off and river discharge are decreased. It is obvious from the principle of bank filtration, that a minimum river discharge has to be maintained for BF operation. However, in contrast to mere surface water abstraction, BF holds storage capacity and may temporarily switch to abstraction wells with higher groundwater share. Dwindling groundwater resources can potentially be addressed by artificial replenishment with surface water from adjacent rivers. The storage capacity and availability of two freshwater resources renders BF for drinking water supply less vulnerable in the dry scenario than surface water or groundwater abstraction alone. In terms of quality, the impact of point-source pollutions on receiving waters is more relevant than in the wet scenario. Typical diffuse-pollution source contaminants such as nitrates and pesticides are expected to occur at lower concentrations as a result of decreased surface run-off. However, all contaminants irrespective whether they originate from agriculture, industrial (e.g. chloride, aluminium) or municipal sewage (e.g. ammonia, pharmaceuticals, organics) are likely to accumulate in rivers because of a decreased discharge and lowered dilution potential. From anaerobic BF sites in India, it is known that ammonia from surface water is not degraded during subsurface passage. The problem of groundwater salinisation may become more pronounced and already prevents the implementation of bank filtration in numerous locations in the southern hemisphere (e.g. in India, Australia). A lower river discharge is usually accompanied by low flow velocities, eutrophication and warming of water bodies promoting algal growth and oxygen depletion. Conditions of drought were seen to reduce oxygen levels in rivers and promote anoxic conditions in BF systems. In India, for instance, where high annual average temperatures prevail, BF conditions tend to be anoxic. Although the surface water quality in Germany has markedly improved in the past decades, temperatures of 25°C in the river Rhine (summer 2003) were seen to temporarily cause anoxic BF conditions. A shift in redox conditions may impair removal efficiency in the 'dry' scenario since oxic conditions are regarded favourable to remove the bulk of water contaminants (see table 2).

Under wet conditions, it is supposed that evaporation rates are lower while rainfall and groundwater recharge as well as surface run-off and river discharge are increased. Large water quantities in combination with wind increase the risk for inundation of urban areas and water supplying infrastructure. Intruding sea water may then cause the salinisation of freshwater resources. In terms of quality, the impact of diffuse source pollution on contaminant load transported in water is more relevant than in the 'dry scenario'. Surface run-off from industrial and agricultural areas will transport higher levels of micropollutants (e.g. aromatic hydrocarbons) and fertiliser (e.g. nitrate, pesticides) to surface- and groundwater systems. In addition, occasional events of combined sewer overflow discharge organics, ammonia and pharmaceuticals into surface water. The higher river discharge has due to an increased dilution potential also a beneficial impact on contaminant load. Further, water turbulences may introduce oxygen and counteract algal development. The increased run-off will mobilise sediments, suspended solids and associated pathogens into streams. Although redox conditions are not expected to change in the 'wet' scenario, increased flow velocities can constitute a problem to BF performance by reducing travel times and thus, impair biodegradation processes. Shorter travel times were reported to adversely affect degradation of organic matter (e.g. DOC) and have caused breakthrough of microbial indicators.

General projections for water suppliers using BF schemes are difficult as climate change is highly site-specific and predictions are prone to uncertainties of climate scenarios and hydrological modelling. As a result, literature on the effect of climate change on BF systems is scarce. Two scenarios ('dry' and 'wet') were selected in this report to allow for conclusions on how BF systems may become affected irrespective of other concomitant changes (e.g. land adaptation). In fact, it has been suggested that anthropogenic influences and responses to climate change will have a larger impact on water supply than climate change itself. A case study from Berlin helped to illustrate the various considerations and challenges (here: excess sulphate levels) to be taken into account for a BF site. Overall, BF is vulnerable to climate change although anthropogenic impacts are at least as important. While dry conditions constitute a problem to water quantity and quality (e.g. salinisation), wet conditions are critical only for water quality. However, compared to the conventional methods of surface or ground water abstraction and subsequent treatment, the concept of bank filtration is the more sustainable and less vulnerable alternative.

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