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Eawag News

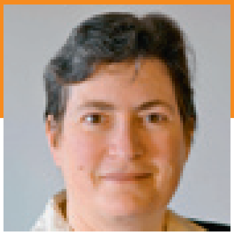
From source to tap – good-quality drinking water for today and tomorrow

Water resources affected by climate change. Page 8

New methods of assessing microbiological safety. Page 20

Where research meets practice. Page 32

Editorial



Janet Hering,
Director Eawag

Provision of Safe Drinking Water: A Critical Task for Society

What was voted the greatest medical advance of the last 166 years by readers of the *British Medical Journal*? Not – as might have been expected – the discovery of antibiotics, anesthesia, or vaccines, but rather the development of sanitation. This was the milestone that came out on top in a survey involving over 11,000 respondents worldwide, published by the BMJ in January 2007. Good sanitation is the key to the protection of drinking water quality and public health.

Access to safe drinking water is often taken for granted in industrialized countries, where the history of epidemics of waterborne diseases such as typhus and cholera has been largely forgotten. But the lack of access to clean water remains a serious threat to public health in developing countries. The Millennium Development Goals adopted by the United Nations recognize the critical need to provide access to safe drinking water and adequate sanitation.

The contamination of drinking water by disease-causing microorganisms (pathogens) remains the most widely recognized and important *acute* threat to human health. Classical methods for detection of microbial contamination are slow, and exposure to pathogens may occur before the threat can be identified. A novel method for rapid detection of microbial contamination in drinking water based on flow cytometry has been developed at Eawag (p. 20). This method is currently being adapted for application in emergency relief situations when the security of drinking water supplies may be compromised.

In addition to microbial contamination, drinking water can also contain chemical contaminants, such as arsenic and fluoride. Chronic exposure to these substances, even at low levels, can cause serious health effects including disfigurement, cancer and premature death. The Eawag cross-cutting project Water Resource Quality (p. 16) includes studies of the occurrence of geogenic contaminants (i.e., elements derived from geologic materials) and methods for their removal from drinking water that can be applied in Africa and South and Southeast Asia, where such geogenic contamination is widespread.

Even in Switzerland and other developed countries, however, the provision of safe drinking water and protection of aquatic ecosystems poses continuing challenges. The ever-increasing use of synthetic organic chemicals (for example in pharmaceuticals and personal care products) has resulted in the ubiquitous occurrence of micropollutants in surface and groundwater. Advanced methods for the detection of such chemicals and for their removal from both wastewater and drinking water must be transferred from the research laboratory to practice (p. 24). This is a principal emphasis of Eawag's cross-cutting project Wave21, which incorporates a strong collaboration with water utilities, private industry and federal agencies. One example is the pilot study conducted in collaboration with the Water Supply Zurich and the engineering firm WABAG (p. 28 and 32).

The need to protect water resources for human consumption must also be balanced against other demands, both competing uses by human society and environmental needs. One example of this is the balance that must be achieved between river revitalization to restore habitat and the protection of the quality of drinking water withdrawn from shallow wells near the river banks (p. 12). Finally, climate change poses potential threats both to aquatic ecosystems and drinking water supplies, which require further research (p. 8).

It is Eawag's mission both to conduct research on water and the water environment and to enable this research to be used for the betterment of human society. Eawag's productive collaborations with partners in engineering practice and with other stakeholders are vital to its success in bridging between theory and practice. The provision of safe drinking water is a fundamental responsibility of society. Eawag's research addresses this need for both developing and developed countries and in the context of a broad view of the water environment that integrates the interconnected needs of both human societies and ecosystems.

Janet G Hering

Cover photo: Eawag researcher Jakob Helbing collecting a sample from the slow sand filtration basin at the Lengg lake water treatment facility. (Photo: Ruedi Keller, Zurich)

Content

Lead Article

Research Reports

Miscellaneous

eawag
aquatic research

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Urs von Gunten, chemist and Titular Professor at the ETH Zurich, is head of the Drinking Water Chemistry group and head of the cross-cutting Eawag project Wave 21 (Drinking water in the 21st century).

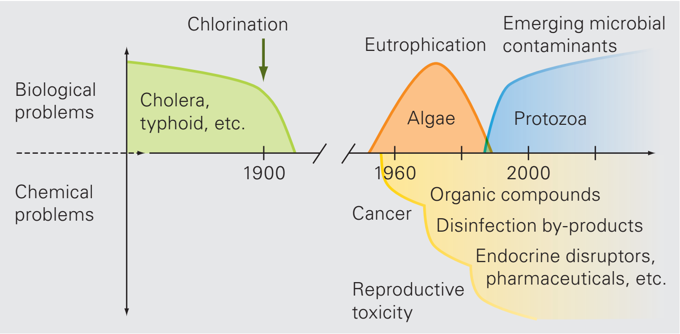
Can the quality of drinking water be taken for granted?

Clean drinking water is generally taken for granted in this country – although Switzerland's water suppliers are also constantly confronted with new challenges. In developing countries, however, the ideal of "safe water for all" is still a long way off. How are Eawag researchers helping to secure drinking water quality in the long term?

Today, tap water is safe to drink throughout the industrialized world, which was not necessarily the case around a century ago (Fig. 1). What factors were crucial in bringing about this improvement? First came the realization that drinking water was responsible for the spread of pathogens that can cause epidemics of diseases such as cholera or typhoid. Then it was discovered that this was due to releases of faeces and untreated wastewater into surface waters. The decisive step, finally, was the consistent separation of water supply and wastewater systems. A number of other developments helped to turn drinking water into a microbiologically safe product: the beginning of the 20th century not only saw the first use of faecal bacteria as water quality indicators and the introduction of appropriate microbial detection methods; in addition, chemical disinfection has been used to treat drinking water ever since.

New Eawag method for assessing microbiological safety. With only a few exceptions, these methods proved to be highly effective. Major water safety problems caused by protozoa did not occur again until the 1990s. Particularly affected were English-speaking countries (Fig. 1), where drinking water is mainly disinfected with chlorine. One of the most severe outbreaks occurred in Milwaukee (US) in 1993, when over 400 000 people contracted cryptosporidiosis. This diarrhoeal disease is caused by the intestinal parasite *Cryptosporidium parvum,* whose infectious stage (oocyst) is extremely resistant to chlorination. To overcome this problem, processes such as ozonation and irradiation with ultraviolet light can be used.

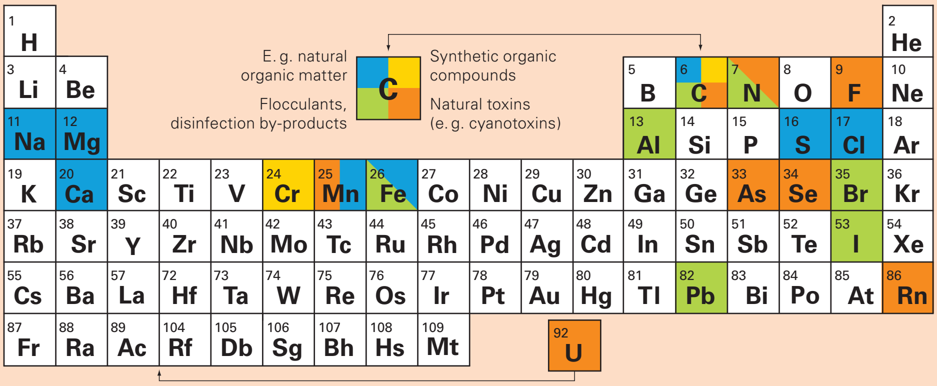
Fig. 1: Development of drinking water problems in industrialized countries since the beginning of the 20th century.



The need to improve conventional methods of assessing the microbiological safety of drinking water was apparent even before the epidemic in Milwaukee – where the contaminated drinking water ironically complied with the legal requirements concerning total cell count and faecal microorganisms. For one thing, the old methods are not able to detect specific pathogens. For another, the tests – based on the growth of visible bacterial colonies – are exceedingly time-consuming: the results are only available after 1–3 days, which in some cases may be too late. At Eawag, therefore, efforts to develop new methods have already been under way for some years. One especially promising technique is based on flow cytometry [1]. This makes it possible not only to enumerate all the microorganisms contained in a water sample within 1–2 hours but also to identify certain pathogens (see the article by Thomas Egli on p. 20).

Protecting resources: a vital measure. Another key prerequisite for high-quality drinking water is careful protection of water resources. In this area, a substantial contribution has been made by wastewater treatment, and in particular the elimination of nutrients (carbon, nitrogen and phosphorus). After the Second World War, the use of phosphate detergents and increased application of agricultural fertilizers had led to the eutrophication of lakes and the consequent proliferation of algae (Fig. 1). As a result, there were increases in turbidity, dissolved organic carbon (DOC) content and concentrations of taste and odour compounds and cyanotoxins (secreted by blue-green algae). Significant improvements in water quality were only achieved after the reduction of phosphate inputs into receiving waters. This correlation can be readily illustrated by the data for Lakes Lucerne, Zurich and Greifensee shown in Table 1. Here, concentrations of the taste and odour compounds studied rise in parallel with the increasing nutrient content (oligo-

Periodic table of chemical contaminants in drinking water



Already present in raw water:

- 🟦 Natural substances causing aesthetic problems, e. g. taste, odour, turbidity and precipitation.
- 🟧 Natural substances of toxicological concern.
- 🟨 Anthropogenic substances of both aesthetic and toxicological concern.

Only becoming relevant during treatment/ distribution of drinking water:

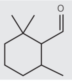
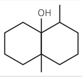
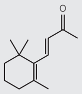
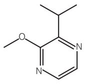
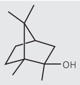
- 🟩 Substances that may be of aesthetic or toxicological concern or reduce the effectiveness of treatment processes.

All organic substances are listed under carbon, comprising both natural and anthropogenic compounds.

trophic Lake Lucerne – mesotrophic Lake Zurich – eutrophic Lake Greifensee).

Groundwater protection zones. The protection of resources, however, includes groundwater bodies as well as surface waters. Under Swiss law, protection zones and contributing areas are to be delineated around groundwater wells [2]. The primary goal of the protection zone known as S2 is to ensure that microorganisms are removed. Experience has shown that, for this purpose, water has to reside in the subsurface for 10 days. The designation of a catchment area, by contrast, is intended to reduce inputs of contaminants; for example, the runoff and leaching of agrochemicals (pesticides or fertilizers) is to be prevented. However, it is not easy to specify the dimensions of groundwater protection zones and catchment areas, especially in karstic regions and in cases where a pumping station is close to a river. The article by Olaf Cirpka on p. 12 describes new methods facilitating the assessment of water exchanges between rivers and aquifers. It focuses in particular on the question of how river restoration projects affect the microbiological and chemical quality of water abstracted from nearby aquifers.

Impact of climate change on water resources. The issue of global warming is being widely discussed at present. What is less well known, but clearly demonstrable, is that water resources – surface and groundwater – are also influenced by changes in climate. The emphasis to date has been placed on quantitative aspects of the water balance, such as precipitation volumes, river discharge regimes, and lake and groundwater levels [3] (see Box on Switzerland's water balance, p. 7). Largely uninvestigated, however, is the impact of climate change on the quality of waterbodies from which drinking water is abstracted. Drawing on discussions with national and international experts who attended the Eawag Workshop on Climate and Water in early 2008, Rolf Kipfer's article (p. 8) summarizes the current state of knowledge and outlines possible implications for drinking water quality. These findings need to be taken into account in our decisions concerning sustainable management of water resources.

Substance	Structure	Oligotrophic Lake Lucerne	Mesotrophic Lake Zurich	Eutrophic Lake Greifensee	Odour threshold concentration and odour
β-Cyclocitral (d)		1,3 ± 0,4 ng/l	1,3 ± 0,4 ng/l	6,6 ± 0,4 ng/l	19 000 ng/l Fruity
Geosmin (d)		1,5 ± 0,6 ng/l	5,7 ± 0,6 ng/l	19,0 ± 0,7 ng/l	4 ng/l Earthy-musty
β-Ionon (p)		0,3 ± 0,1 ng/l	7,1 ± 0,1 ng/l	1,6 ± 0,1 ng/l	7 ng/l Violets
2-Isopropyl-3-methoxypyrazine (IPMP) (p)		10,0 ± 0,3 ng/l	14,7 ± 0,5 ng/l	16,1 ± 0,5 ng/l	0,2 ng/l Vegetables
2-Methylisoborneol (p)		1,3 ± 0,1 ng/l	2,6 ± 0,1 ng/l	2,7 ± 0,1 ng/l	15 ng/l Earthy-musty

Tab. 1: Taste and odour compounds in three Swiss lakes. With the exception of β-Ionone, concentrations depend on the nutrient content of the water.
d = dissolved, p = particulate.

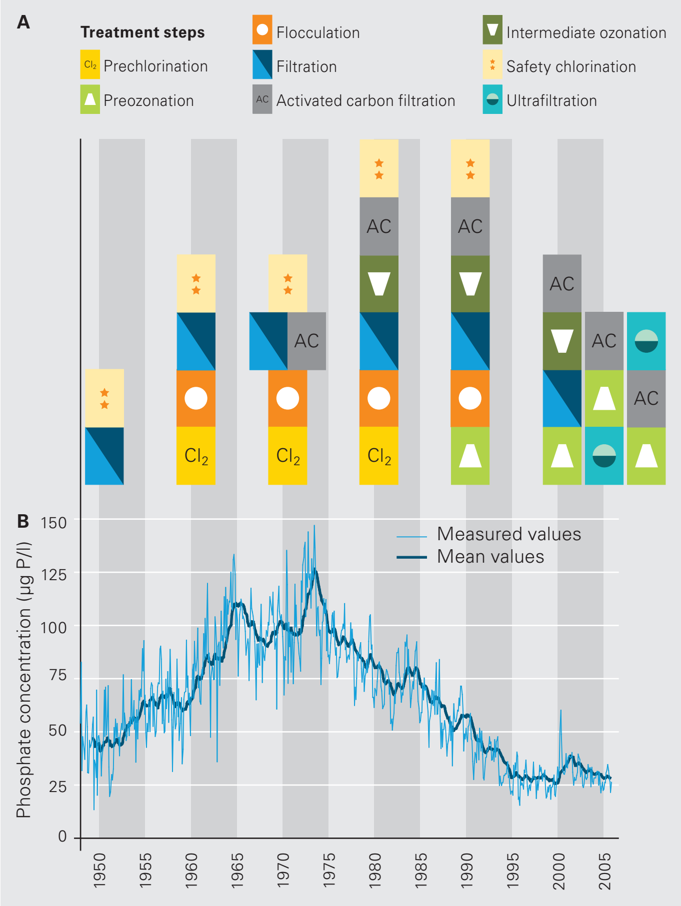


Fig. 2: (A) Development of lake water treatment in Switzerland (based on information from A. Gmünder, Wabag, 2006).
(B) Development of mean phosphate concentrations in Lake Zurich (based on information from H.-P. Kaiser, Water Supply Zurich /WVZ, 2008). Higher phosphate concentrations are associated with lower raw water quality, necessitating more elaborate treatment processes.

Development of leaner but equally effective process chains. Alongside the protection of resources, the treatment of drinking water offers another way of improving water quality. Since it was first introduced, water treatment has evolved from simple sand filtration, through chemical disinfection (chlorination and ozonation), to today's multibarrier systems, frequently comprising several filtration and oxidation steps (Fig. 2). In some cases, the quality of water after treatment is so good that it can be distributed without any further safety measures (e.g. addition of chlorine), provided of course that this is permitted by the condition of the distribution system.

Thanks to the improved quality of lake water and the use of membrane filtration, it should even be possible to reduce the number of treatment steps for the next generation of lake water facilities. As part of the cross-cutting Eawag project Wave 21 (Drinking water in the 21st century), the process chain ozonation – biological activated carbon filtration – ultrafiltration was studied in detail (see the article by Wouter Pronk on p. 28). For this purpose, a pilot plant with a flow rate of about 10 m^3 per hour was operated at the Lengg lake water facility in collaboration with Water Supply Zurich (WVZ) and the systems engineering company Wabag. We demonstrated that the plant not only completely removes microorganisms but also eliminates micropollutants.

Micropollutants – a new challenge. The post-war period saw a dramatic rise in the use of synthetic industrial chemicals (Fig. 1). The fact that these compounds also entered water resources and were therefore present in drinking water was only discovered as a result of new developments in analytical chemistry. Here, the initial focus was on the carcinogenic effects of such substances. The situation was alleviated to a certain extent by regulations of dangerous chemicals and by improvements in water protection. At about the same time, it was found that the reaction of chlorine with natural organic matter (NOM) during the disinfection process leads to the formation of disinfection by-products, some of which are hazardous to health. To date, more than 600 chlorine by-products have been identified, and undesirable substances are also formed when ozone and chlorine dioxide are used as disinfectants, the most important being bromate and chlorite respectively. Accordingly, chemical disinfectants are now applied much more selectively and sparingly, and processes are optimized so as to keep concentrations of disinfection by-products to a minimum.

In the 1990s, the coupling of liquid chromatography with mass spectrometry represented another major advance in analytical chemistry, leading to the detection of growing numbers of synthetic micropollutants in water. These substances derive, for example, from medicine, agriculture or transport. Also significant as a source of contamination are natural substances such as the taste and odour compounds mentioned above. In the article on p. 24, Andreas Peter summarizes a study which was designed to assess the effectiveness of activated carbon filtration and chemical oxidation in removing trace organic contaminants [4]. Here, it needs to be borne in mind that treatment processes and the elimination of contaminants are adversely affected by the presence of natural organic matter (Tab. 2).

Inorganic contaminants in drinking water. The quality of drinking water can be significantly impaired not only by organic contaminants but also by a variety of inorganic substances. Often, these elements are released into groundwater as a result of natural processes, especially under anoxic conditions. In par-

Tab. 2: Effects of natural organic matter (NOM) in various drinking water treatment processes.

Process	Effects of NOM
Chemical oxidation/ disinfection	Consumption of oxidant, formation of by-products
Activated carbon filtration	Competition with contaminants for adsorption sites
UV disinfection	Attenuation of UV intensity
Ultrafiltration	Membrane fouling (reduction in permeability

Switzerland's water balance

In Switzerland, the annual volume of precipitation – with a high portion in the form of snow falling in the Alps – is approx. 60 km^3. However, only 20 km^3 is actually available, as the remaining two-thirds is lost through rapid runoff and evapotranspiration. Of this 20 km^3, in turn, about 1 km^3 per year is used for water supplies – i. e. only 5 % of the total available precipitation. In addition, Switzerland has substantial freshwater reserves: 50 km^3 groundwater, 67 km^3 glaciers, 235 km^3 natural lakes (including border lakes), 4 km^3 artificial lakes/reservoirs. These resources are an important element in the hydrological cycle and help to compensate for variations in annual precipitation volumes. Shortages in drinking water supplies due to changes in precipitation patterns are not to be expected. Any difficulties would be more likely to occur at the local level, especially in cases where irrigation is required for agriculture as a result of climate change.

ticular, iron and manganese are among the most frequent causes of drinking water problems worldwide. Both of these elements, which are readily water-soluble in their divalent form, give rise primarily to aesthetic problems – through precipitation and discoloration – when they are oxidized to their poorly soluble tri- or tetravalent form. In addition, manganese is of toxicological concern. During drinking water treatment, both manganese and iron can be precipitated by chemical and/or biological oxidation and subsequently removed.

For more than 100 million people, mainly in developing countries, the consumption of untreated groundwater contaminated with arsenic or fluoride represents a serious health threat. Through its cross-cutting Water Resource Quality (WRQ) project, Eawag is seeking to combat these problems (see the article by Annette Johnson on p. 16). Researchers have prepared global and regional maps indicating the risk of the occurrence of elevated concentrations of arsenic or fluoride [5]. In addition, appropriate methods of eliminating arsenic and fluoride from groundwater are being developed.

Future developments. There is no doubt that drinking water quality will continue to be a top priority, and accordingly a variety of new tasks will need to be addressed in the years ahead:

- Using flow cytometry, Eawag scientists have demonstrated that drinking water contains far more bacteria than are determined by conventional methods. The implications of these findings for water quality should now be investigated in detail.
- The new Eawag method is currently being further developed so as to permit the detection – in the near future – of viruses, whose significance in drinking water remains largely unknown.
- It is often difficult to assess precisely how toxic contaminants are and how they behave in drinking water treatment processes. There is thus a need for improved models.
- To allow continuous monitoring of water quality, methods of chemical and microbiological analysis need to develop in the direction of online measurement.
- The distribution of drinking water requires an intact network, which has to be kept in good condition. But at present, not enough is known about the state of this infrastructure and whether adequate resources are available for its renovation.
- Not least, the water supply system needs to be seen in the context of urban water management as a whole. Do centralized systems of water supply and discharge still make sense, or could decentralized facilities be operated more sustainably? This question is also influenced by factors such as demographic trends, climate change and water quality requirements.

In the past, Eawag has already shown – for example, with Zurich Waterworks – how effective the combination of research and practice can be in pursuing innovative approaches (see the article by Erich Mück on p. 32). In the interests of secure water supplies, partnerships of this kind should be further developed, both nationally and internationally. ○ ○ ○

[1] Hammes F., Berney M., Wang Y., Vital M., Köster O., Egli T. (2008): Flow-cytometric total bacterial cell counts as a descriptive microbiological parameter for drinking water treatment processes. Water Research *42,* 269–277.

[2] http://www.admin.ch/ch/d/sr/814_201/app6.html

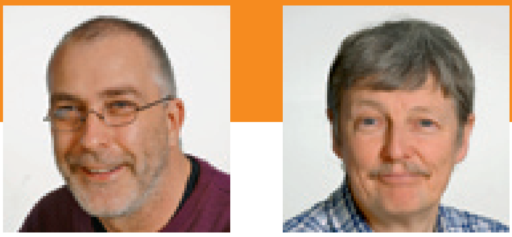
[3] BUWAL, BWG, MeteoSchweiz (2004): Auswirkungen des Hitzesommers 2003 auf die Gewässer. BUWAL, Bern, Schriftenreihe 369, 174 S.

[4] Peter A., von Gunten U. (2007): Oxidation kinetics of selected taste and odor compounds during ozonation of drinking water. Environmental Science & Technology *41,* 626–631.

[5] Winkel L., Berg M., Amini M., Hug S J., Johnson A.C. (2008): Predicting groundwater arsenic contamination in Southeast Asia from surface parameters. Nature Geoscience *1,* 536–542.

Research Reports

Water resources and climate change



Rolf Kipfer (left), geophysicist and Titular Professor at the ETH Zurich, head of the Water Resources and Drinking Water department (W+T), and David M. Livingstone, physicist and data analyst, also in W+T.

Good-quality drinking water should have the right temperature and be colourless, taste-free, odour-free, microbiologically safe and toxicologically acceptable. But how are water resources – and hence drinking water quality – affected by climate change? This article is an attempt to take stock.

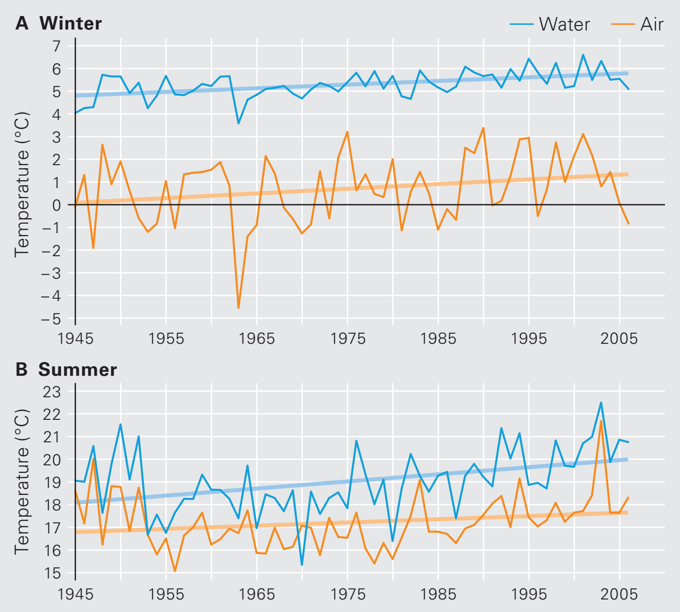
Surface waters, groundwater, and snow and ice, as the only freshwater resources available to mankind, are essential to our survival as a species. At the same time they are integral parts of the hydrological cycle and thus respond directly to changes in the climate. While attention is increasingly being paid to the impacts of climate change on the quantitative aspects of the hydrological cycle – precipitation amounts, discharge regimes of rivers and streams, lake and groundwater levels and the like – the influence of climate change on water quality in lakes, rivers and groundwater, and hence on the drinking water obtained from these sources, is largely unknown. On the basis of the discussions with national and international experts that took place at the Eawag Workshop on Climate and Water held at the beginning of 2008, we venture here to give a tentative summary of the current, incomplete state of knowledge on the effect of climate change on water resources and to outline possible consequences for drinking water quality. In doing so, we take the existence of climate change to be an empirical fact, and consider not only the effects of long-term climatic change, but also the effects of extreme events such as the summer heatwave of 2003.

Long-term time-series show that lake water temperatures are undergoing a continual increase. Various models predict that rising atmospheric concentrations of greenhouse gases will lead not only to increases in air temperature, but also to the warming of lakes and rivers. In the case of lakes, this prediction has been confirmed by analysing long-term time-series of water temperature. For example, Lakes Zurich (Fig. 1) [1], Constance, Garda, Maggiore and Lugano have undergone constant warming at various depths over the past few decades. Similar behaviour has been noted in lakes in America, Africa, Asia and the Antarctic [2].

Since 1945, water at a depth of 5 m in Lake Zurich has warmed by an average of 0.016 °C per year from winter to winter (Fig. 1A) and 0.031 °C per year from summer to summer (Fig. 1B). For both summer and winter, the short-term variations in water and air temperatures correlate well with each other (jagged curves). The curves showing the long-term increases in winter water and air temperatures are also fairly similar (Fig. 1A, straight lines); from summer to summer, however, the water has warmed at a faster rate than the overlying air (Fig. 1B). In deep waters, the situation is more complicated (Fig. 2). Of interest here are two periods (1985–1991, 1999–2003) marked by a sawtooth pattern, with a rise in temperature extending over several years being terminated by abrupt cooling. Such patterns arise when a lake undergoes incomplete mixing as a result of a series of mild winters [3]. The comparatively slight increase in deep-water temperatures obtained by averaging over a longer period (0.004 °C per year), which is associated with climate change, can be viewed as a result of the increasing frequency and duration of these sawtooth events.

Warmer lake water promotes the proliferation of cyanobacteria. Increased water temperatures are one of the main factors promoting the occurrence of cyanobacteria. Under suitable condi-

Fig. 1: Development of water temperature measured at a depth of 5 m (representative of the epilimnion) in Lake Zurich from 1945 to 2008, compared with air temperatures recorded in Zurich over the same period. (A) Winter (mean values for December–February), (B) Summer (mean values for June–August).



Michael Heid, Oberwenigen

Sämtisersee (Canton of Appenzell Inner Rhodes) in the summer of 2003, almost completely dried up.

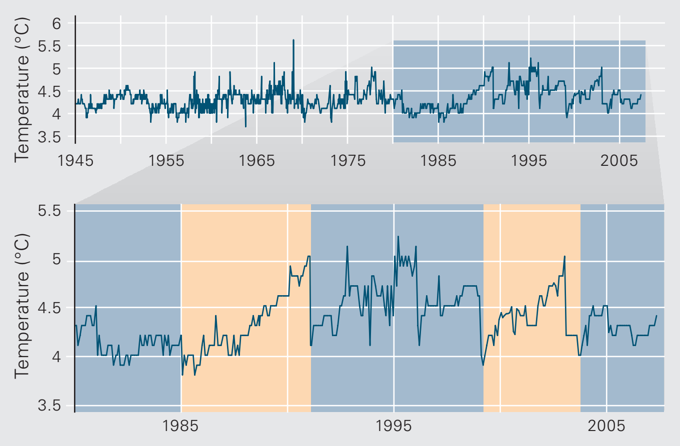
tions, these organisms – also known as blue-green algae – tend to form blooms which may be visible as dense microbial mats on the surface. As well as taste and odour compounds, cyanobacteria produce more or less potent cyanotoxins that can be dangerous to human health. One prominent species found in many Swiss lakes is *Planktothrix rubescens,* the "Burgundy blood" alga, whose toxins can adversely affect water quality. In the event of further lake warming, however, more toxic cyanobacteria such as *Microcystis* could also become prevalent, leading to a major deterioration in water quality.

Mixing is likely to become less frequent and less intense as lakes warm. Apart from the heat balance, climate change is also expected to influence vertical temperature profiles in lakes, and hence stratification and mixing behaviour. This view is supported by a number of modelling calculations [4]. Many lakes in Switzerland are typically thoroughly mixed during the cold months. For this to occur, the temperature of the water column must be uniform (homothermy). In contrast, in the summer months vertical water exchange is prevented by thermal stratification (warmer surface and colder deep waters = summer stagnation).

As a result of climate change, however, the upper water layers of lakes (the epilimnion and metalimnion) are likely to undergo significant warming in coming years, leading to a more stable temperature stratification in all large Swiss lakes, at least during a transitional period. This in turn will prolong the summer stagnation period and shorten the period of homothermy, thereby ultimately reducing the frequency and intensity of mixing events [4]. This reduced mixing can lead to extremely low oxygen concentrations in the deep water [5]; however, this is unlikely to cause serious problems regarding the use of lake water as a source of drinking water since the water extraction depth can easily be altered if necessary.

For lakes that are normally frozen in winter, the opposite is true: freezing will occur later and thawing earlier, reducing the duration of the period of ice cover and intensifying mixing [6]. This will tend to have a favourable effect on deep-water oxygenation.

Fig. 2: Development of water temperature measured at a depth of 120 m (representative of the hypolimnion) in Lake Zurich from 1945 to 2008.



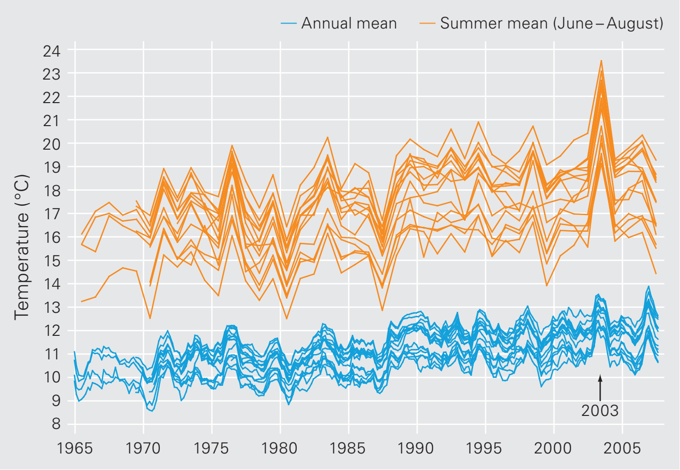


Fig. 3: Water temperatures in selected Swiss rivers between 1965 and 2008 [7, 8].

Rivers are also expected to become warmer. Modelling studies predict long-term increases in temperature not only for lakes but also for rivers – a trend that is already noticeable in long-term data series (Fig. 3) [7, 8]. In the extremely hot summer of 2003, as in other dry years, river discharge rates were considerably lower than usual. In combination with the high water temperatures, this resulted in an increased incidence of fish kills [7].

Large rivers perform a crucial function in the cooling of industrial complexes and nuclear power plants. In future, any further warming of rivers, possibly combined with low water levels, is likely to give rise to problems in cooling such facilities, possibly even necessitating the complete shutdown of nuclear power plants.

Little is known about the effects of climate change on rivers, especially as far as the geochemical aspects are concerned. However, information is available in the records of the Swiss National River Monitoring and Survey Programme (NADUF), initiated in 1972 [9]. These data urgently need to be analysed with a view to detecting the possible effects of climate change on rivers.

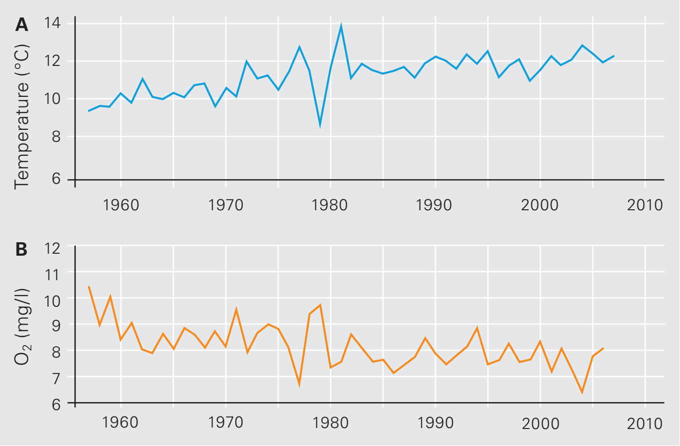
Scant evidence exists for the effects of climate change on groundwater quality. The impacts of climate change on groundwater have yet to be elucidated. While old groundwaters with residence times of 10,000 to 1 million years have proved to be important archives for reconstructing continental climate history during the transition from the last glacial period to the Holocene interglacial, they give no indication of how climate change has affected or will affect water quality.

However, there is at least some evidence – albeit of a somewhat anecdotal nature – concerning the effects of climate change on the quality of young groundwaters (residence times: 1 to 1000 years). For example, the higher concentrations of dissolved organic carbon (DOC) found in drinking water in Scandinavia [10] were taken to indicate that an increase in atmospheric temperature accelerates soil carbon turnover, with infiltration then leading to increased DOC concentrations in groundwater used as drinking water. This can affect the colour of drinking water – for example, humic substances give water a brownish colour. In addition, elevated DOC concentrations adversely affect all stages of the drinking water treatment process. To ensure effective treatment, DOC would have to be eliminated in advance.

Climate change and groundwater recharge. It is not known whether groundwater in Switzerland is undergoing similar changes. Prompted by its internal Workshop on Climate and Water, which identified the recording and analysis of long-term data (decadal monitoring) as an essential requirement for documenting the effects of climate and environmental change on water resources, Eawag recently began a systematic search for appropriate groundwater time-series in Switzerland. Initial analysis results are encouraging, demonstrating a clear and surprisingly marked response to climate change in individual groundwater bodies. For example, groundwater temperatures at a pumping station close to the River Rhine at Rheinau have risen steadily over the past 60 years (Fig. 4A), while oxygen concentrations have steadily declined (Fig. 4B). It is striking that the temperature effect is much more pronounced in winter than in summer, and therefore cannot be attributed solely to higher air temperatures. Rather, it could indicate either that the seasonal window for groundwater recharge has shifted towards the summer and/or that the hydrological situation (hydraulics, mixing ratios, etc.) has changed fundamentally. In the Paris Basin, groundwater temperatures have also risen steadily over the past 500 years. As recently as the 19th century, groundwater infiltrated at a lower annual mean temperature than it does today.

Extreme events as harbingers of the future – the 2003 summer heatwave. While long-term changes barely impinge on public awareness, extreme short-term climatic events – floods, heatwaves or droughts – are often etched into the collective memory. In 2003, central Europe experienced the hottest sum-

Fig. 4: Long-term changes in temperature (A) and oxygen concentration (B) in groundwater (Seewerben pump station, Rheinau, Canton of Zurich). Data (monthly means for February) from a term paper by Julien Gendre.



mer since regular meteorological measurements began in the middle of the 19th century [11]. The air temperatures recorded in northern Switzerland exceeded the long-term mean by more than 5 standard deviations, or 5.4 °C. Although such temperatures may appear extreme to us today, they correspond to the summer temperatures calculated by climate models for the period 2071–2100 [11]. For this reason, the effects of the 2003 summer heatwave can be used to obtain a rough estimate of the possible consequences of future "normal" summers.

In 2003, both deep, nutrient-poor Lake Zurich and shallower, nutrient-rich Greifensee exhibited extremely high thermal stability owing to the surface water layer being considerably warmer than usual. As a result, oxygen concentrations in the deep waters of Lake Zurich decreased significantly; in Greifensee, by contrast, no decrease occurred because the hypolimnion is often anoxic in summer anyway [12].

Groundwater bodies also reacted sensitively to the drought and heat of the summer of 2003. Across Switzerland, the water table fell, in some cases to historically low levels – a deficit that could not be made good in the following normal year. These quantitative impacts were also accompanied by adverse effects on water quality: for example, due to changes in the redox status of shallow groundwater in the Canton of Thurgovia, the oxygen content was completely consumed (anoxia). Later, the nitrates that had accumulated in the soil during the drought were abruptly washed out by the first rainfall. The resultant nitrate pulse caused additional contamination of the groundwater, hence influencing the quality of the drinking water [8].

The groundwater pump stations along the River Limmat were also affected by lower oxygen concentrations in the water. Here, markedly warmer Limmat water infiltrated into the aquifer. This stimulated microbial metabolism in the riverbed, resulting in consumption of much of the available oxygen and hence in a reduction in the quality of the raw water. Problems arise because most of the existing groundwater facilities are not designed to treat raw water that is oxygen-poor, let alone anoxic. As soon as the water is pumped to the surface it takes up oxygen again, causing dissolved iron to be precipitated out as reddish-brown particles of iron oxide. These have to be removed before the water can be used as drinking water.

Implications for Eawag research: an increased focus on the impact of climate change on water quality. The dynamics of water bodies respond both to long-term climate change and to extreme events, which can be read as normal states of a future climate. While the consequences of climate change for lakes are reasonably well documented and comprehensible in mechanistic terms, research on groundwater – the most important global drinking water resource – is in its infancy and requires increasing attention.

Despite the many unresolved questions, we can conclude that climatic and environmental changes are occurring, and that their impacts on water bodies and water resources are already detectable today. These facts need to be incorporated into our decisions now, in order to ensure that our water resources are managed sustainably for the benefit not only of our own generation, but also of future generations. In addition to assessing the impact of climate change on water quantity, it is becoming increasingly evident that consideration needs to be given to assessing its impact on water quality. Eawag, in its function as the aquatic research institute of the ETH domain, intends to play an active role in future research in this area. ○○○

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Co-author: Eduard Hoehn

River restoration and groundwater protection

Mainly for quantitative reasons, groundwater wells used for drinking water are often located near rivers. In many cases, natural purification processes in the subsurface are strong enough to allow distribution of the extracted groundwater without further treatment. But is this still possible when channelized rivers are widened and the distance to pumping stations is reduced?

In Switzerland, 40 % of the drinking water is actively pumped from aquifers, particularly from the productive gravel layers found in the river valleys of the Central Plateau. Many pumping stations are situated close to watercourses, where a significant proportion of the extracted groundwater originated from infiltration of river water. As it passes through the subsurface, the water is purified: bacteria are retained by filtration, and biofilms on particle surfaces degrade natural and anthropogenic organic compounds contained in the water. Adequate purification requires a sufficient residence time in the subsurface. In the Water Protection Ordinance, the area of the inner groundwater protection zone S2 is defined by a minimum residence time of 10 days. In the course of river restoration projects, formerly channelized water courses are made more natural, including widening of the river. This may bring rivers closer to the wells and reduce the travel time of water in the aquifer. As precautionary measure, river restoration was prohibited in the inner protection zone of drinking water wells from 2004 [1]. Thus, a seemingly paradoxical conflict has arisen between two approaches to water protection. The River Thur has already been restored in several reaches. Here, Eawag is coordinating the RECORD (Restored Corridor Dynamics) project [2], in which research partners from the ETH Domain develop the scientific basis allowing an objective assessment of this conflict.

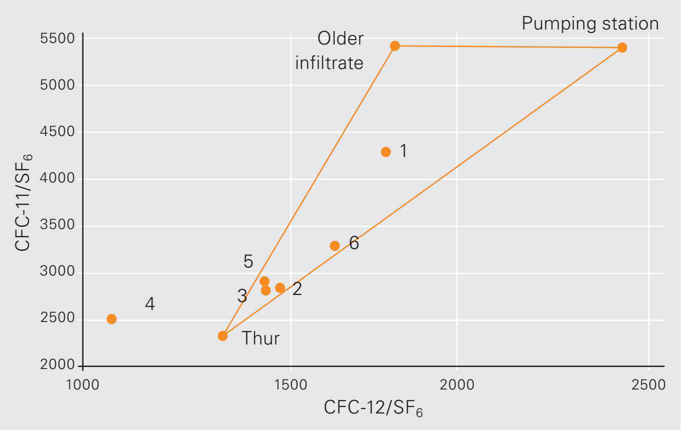
RECORD: the first detailed study of a widened river section. Eawag has a long standing record in analyzing the interaction between rivers and groundwater, having developed numerous methods to quantify water-exchange processes. A detailed studies at River Thur was performed in the vicinity of pumping station Widen III in Felben-Wellhausen (Canton Thurgau), which lies beside an engineered section of the river. The results of these studies are summarized in this article.

As part of the RECORD project, two sites at River Thur have been instrumented for further analysis: The existing site at Widen, where the river is still channelized, and a site at Niederneunforn (Canton Thurgau)/Altikon (Canton Zurich), which has undergone

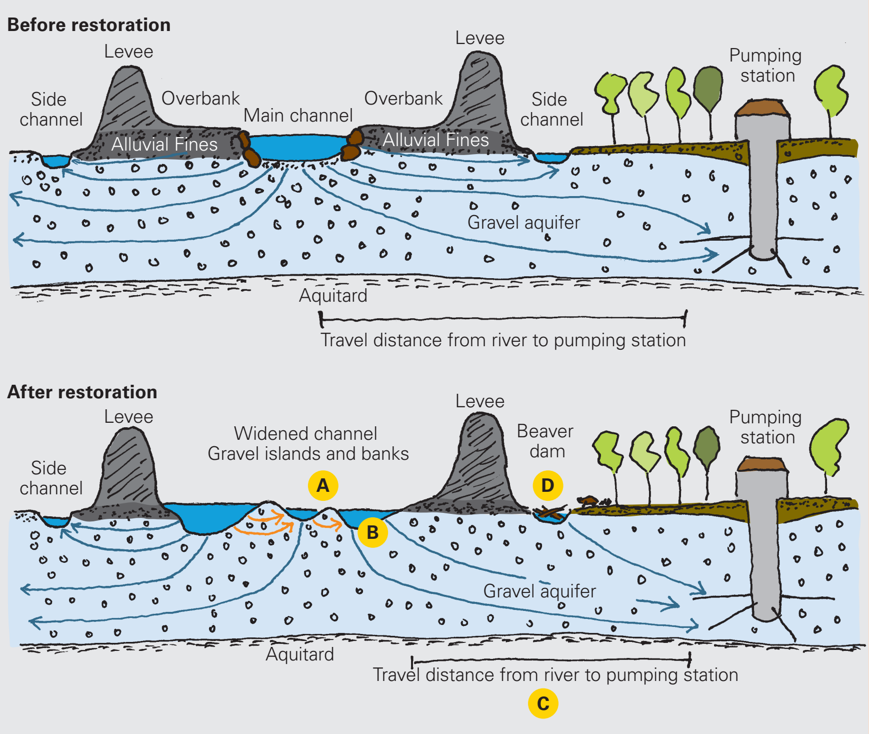
Groundwater studies at River Thur.

Photos: Olaf Cirpka, Eawag

Fig. 1: Three-component plot of CFC-11, CFC-12 and SF6. Concentrations of these substances were determined in the River Thur, at the pumping station and at various groundwater monitoring sites in between. Data supplied by Markus Hofer, Eawag.



How does river restoration affect groundwater?



Restoration measures provide a river with more room to establish a natural, dynamic discharge and sediment regime, creating habitats of high ecological quality. One of the largest restoration projects, which has been under way for several years now, involves the middle reaches of the River Thur in Canton Thurgau.

On the sections of the Thur where restoration has not yet been carried out, the banks of the channelized main watercourse are armoured with rock-fill, accompanied by overbanks and levees on either side. On the landward side of the levees, side channels drain the surrounding areas and carry off water from tributaries. Under average discharge conditions, river water only infiltrates into the aquifer from the main channel. Even when the overbanks are flooded during high flow events, infiltration at the overbanks is negligible because of the low permeability of the alluvial fines. In addition, hardly any water enters groundwater from the side channels. In this area, the groundwater table is higher than the water level in the side channels, so that groundwater tends to exfiltrate into the channels.

How is water exchange between the river and groundwater affected when the main channel is widened by removal of the overbanks?

(A) Gravel islands and banks develop, move and disappear again. This increases the water exchange between the river and the riverbed (hyporheic exchange). The horizontal passage of river water through the riverbed and gravel islands leads to improved filtration of pathogens and increased degradation of dissolved contaminants – the self-cleaning capacity of the river is enhanced.

(B) The permeability of the riverbed may be altered, but it is not clear in which way. On the one hand, the flow velocity in the widened riverbed is decreased, so that fine-grained sediments are deposited, decreasing the bed's permeability. On the other hand, the clogging layers may more readily be broken up again by the increased sediment dynamics during floods, making the riverbed more permeable.

(C) The travel distances – and thus also travel times – between the river and the pumping station are shortened, which reduces the purifying effects of the aquifer.

(D) The restored river reaches become attractive for beavers again. Beaver dams in the side channels locally impound the water level in side channels, which may cause a reversal of the flow direction (infiltration of side-channel water rather than exfiltration of groundwater).

intensive restoration. In particular, we try to address three questions:

- ► What fraction of the pumped water originates from the river?
- ► How long does water reside in the aquifer before it is pumped?
- ► How does the water change during its passage through the subsurface?

Mixing calculations to quantify the fraction of river infiltrate in the extracted water. If the chemical composition of river water and terrestrial groundwater (originating from infiltration of precipitation into the soil) differ, we can determine the fraction of river infiltrate in the water extracted in the pumping station. This involves measuring the concentrations of major anions and cations, dissolved trace gases and stable isotopes. Concentration ratios are computed for various chemically inert substances, which are not transformed during groundwater passage, and plotted. At the pumping station Widen III, we measured the concentrations of chlorofluorocarbon-11 and -12 (CFC-11 and CFC-12) and sulphur hexafluoride (SF6). The ratios of CFC-11 to SF6 and of CFC-12 to SF6 are plotted in Fig. 1.

In the simplest case, drinking water originates from only two sources – infiltrating river water and terrestrial groundwater. In this case the measurements from all sampling points would lie on a straight line, with the composition of the two source waters marking either end. The position of the measurement data on this straight line would then indicate the proportion of river water. Often, however, the situation is more complex, and the pumped water is composed of water of more than two different origins. For example, unconsolidated aquifers are frequently stratified, with an additional water layer consisting of older infiltrate flowing between the younger infiltrating river water and the terrestrial groundwater. This is also the case at the Widen site, as can be seen from the measurement points in Fig. 1 lying within a triangle formed by the three end members [3].

Estimating travel times from chemical and physical properties of water. The chemical composition may also indicate how long the infiltrating river water in the subsurface takes to reach a drinking water well. For travel times of less than 15 days, for example, concentrations of the dissolved radon isotope Rn-222 can be used [4]. In contrast, water samples with an age between 2 and 40 years can be dated using the ratio of tritium to helium.

In addition, readily measurable, time fluctuating physical water properties have been shown to be particularly reliable. Continuous measurements of water level and temperature represent a valuable approach [5]. To record such time series, probes are installed in the river, at the pumping station and in monitoring wells in between. After several months, the data collected can be used not only to calculate how long it takes for water to travel from the river to the various monitoring points but also whether infiltration or exfiltration occurs at a given site and what fraction of the groundwater originates from the river.

For example, diurnal and seasonal temperature variations are "conserved" by infiltrating river water. The signals observed in monitoring points are increasingly more delayed and dampened the more distant these points are from the river. Consequently, subsurface residence times of several hours can be estimated on the basis of diurnal variations, and travel times of several months on the basis of seasonal temperature variations [5]. A simple example would be a case in which no daily pattern is detected at a groundwater measurement point close to a river and the maximum temperature is recorded in December. These findings would clearly demonstrate that no significant infiltration of river water occurs.

Conductivity: an elegant indicator of travel time. Another fluctuating quantity is specific electrical conductivity. This parameter measures the degree to which water can conduct an electric current, with higher values reflecting an increased concentration

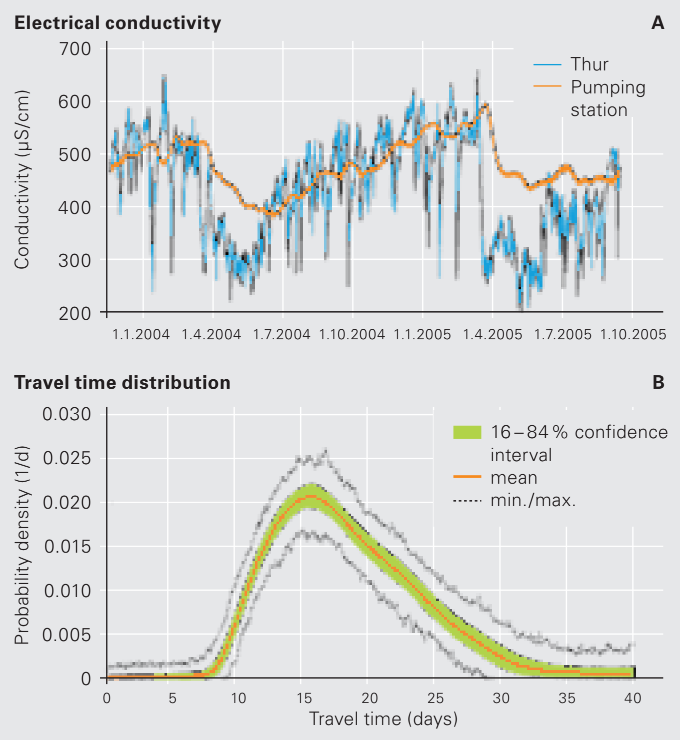
Direct-push installation of a new observation well on the overbank of River Thur at Niederneunforn.

of ions. Rainfall in the upper catchment leads to a temporary decrease in the conductivity of river water. These variations are also transferred to groundwater. Figure 2A shows measurements of electrical conductivity in the Thur and in groundwater extracted at the pumping station Widen III. The changes in conductivity appear with a time shift in the groundwater, and the signal is smoothed compared to that observed in the Thur. Using a mathematical method developed at Eawag, it is possible to infer the travel time distribution for infiltrating river water from the river to the pumping station. According to these calculations, a small proportion of the infiltrate probably already arrives at the pumping station after just over 7 days. However, the great majority takes over 15 days, and the mean travel time is approximately 18 days (Fig. 2B) [6].

Degradation of contaminants and increase of mineralization during passage through the subsurface. Concentrations of minerals (e. g. calcium, magnesium, dissolved inorganic carbon) typically increase with increasing distance from the river, while the oxygen content decreases. Dissolved organic carbon, consisting mainly of natural organic matter, but also anthropogenic micropollutants such as pharmaceuticals and pesticides show decreasing concentrations with travel distance and changes in composition, since only poorly degradable components persist in the water. As part of the RECORD research project, the connection between water quality and travel time will be investigated in more detail. The goal is to reduce the number of expensive chemical analyses and estimate water quality using travel-time data which can be determined in a less costly manner.

Recommendations for practice. Even though further research is needed to understand the processes during river-water infiltration in detail, the recommendations for practical purposes are already fairly clear: at sites where no significant infiltration of river water occurs, river widening raises no concerns, as long as the operation does not involve the incision of more permeable sediment layers. Similar recommendations apply in the case of sites where the travel time for infiltrating river water is found to be more than 20 days. At sites where travel times are close to 10 days, the precautionary principle prohibits widening on the riverward side of the pumping station. ○ ○ ○

Fig. 2: (A) Specific electrical conductivity measured in the Thur and at the pumping station Widen III in Felben-Wellhausen (Canton Thurgau).
(B) Distribution of travel times between the Thur and the pumping station (including uncertainty) calculated on the basis of these measurements.



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Geogenic contaminants

Arsenic and fluoride are the most widespread geogenic contaminants in groundwater worldwide. In many developing countries, drinking water from contaminated sources is consumed untreated. The cross-cutting Eawag project “Water Resource Quality” involves the production of risk maps enabling potentially vulnerable regions to be identified and the development of elimination methods suitable for implementation in practice.

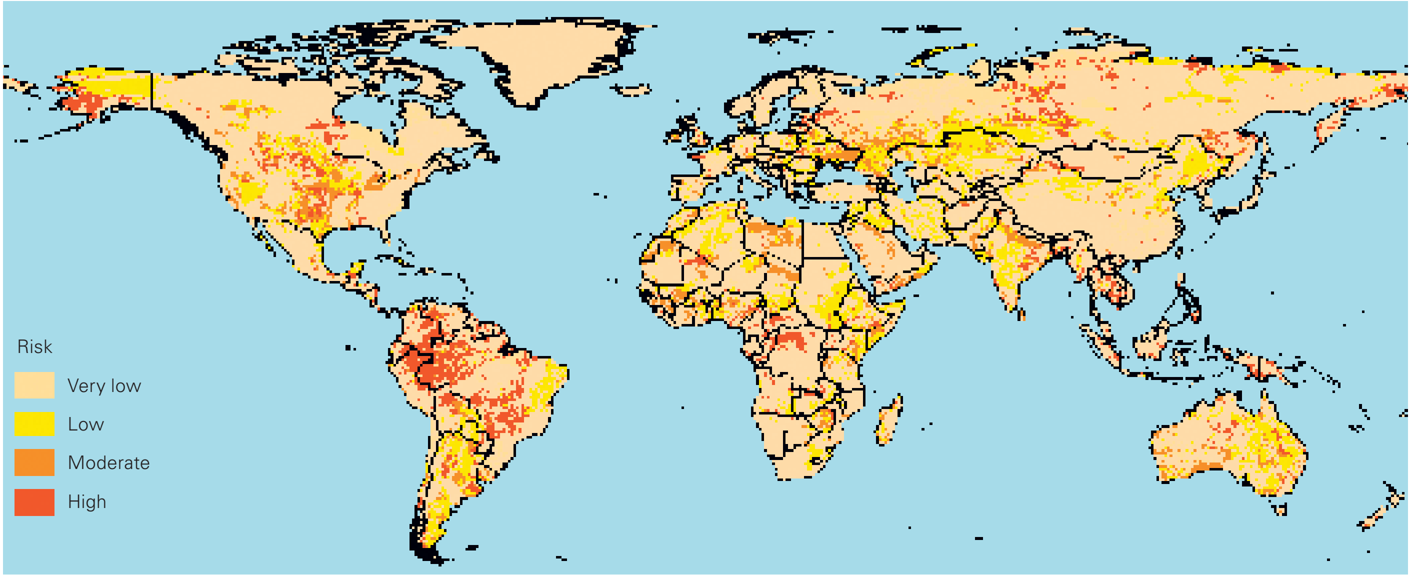
The intake of excessive amounts of arsenic or fluoride poses a health risk for some hundreds of millions of people worldwide. These geogenic substances (see Box) are mobilized from aquifer materials under certain conditions. In many developing countries, contaminated groundwater is used as a source of drinking water, for irrigation and in the preparation of food. In addition, groundwater is increasingly being tapped for drinking water supplies, partly because of the growing scarcity of water resources and also because groundwater is preferred as a source of “clean” drinking water.

The adverse health effects of an excessive intake of arsenic or fluoride only become apparent after some years. Exposure to arsenic can cause a variety of disorders, ranging from changes in skin pigmentation, hyperkeratosis (skin thickening) and cardiovascular problems to cancer. While small amounts of fluoride provide protection against caries and strengthen bones, elevated concentrations in water can lead to irreversible fluorosis. The main characteristics of this condition are staining and pitting of the teeth (dental fluorosis) and bone deformities and brittleness (skeletal fluorosis).

Although a number of regions affected by elevated arsenic and fluoride concentrations have already been identified, it remains largely unclear in which other parts of the world contaminated groundwater can be expected to be found. For many reasons, it is not possible to resolve this question solely by analysis of water samples. As part of the cross-cutting Eawag project “Water Resource Quality” (WRQ), we have therefore produced global and regional risk maps indicating the probability of occurrence of groundwater contaminated with arsenic or fluoride. In addition, we are currently developing and testing simple, low-cost treatment methods particularly suitable for use in developing countries.

Predicting high-risk areas – even in the absence of groundwater measurement data. Risk maps delineating areas with elevated arsenic or fluoride concentrations in groundwater can be very useful for countries that lack groundwater quality moni-

Fig. 1: Global arsenic risk map – modelled probability of arsenic contamination in groundwater.



toring programmes. The predictive maps are based on a model incorporating measured groundwater data and known geological and geographical parameters; the significance of these variables for the occurrence of increased arsenic or fluoride concentrations is calculated in order to develop a simulation model. For the modelling process, we developed a new method, which combines statistical procedures with expert knowledge, taking account of the natural causes of increased concentrations in groundwater. This means that the probability of groundwater contamination can be estimated even for areas where no groundwater quality data are available.

As a first step, we compiled a database (geographical information system/GIS) using digital maps of physical properties such as soil type, geology, climate and topography. At the same time, we collected data on the chemical composition of groundwater from publications and from responses provided by authorities and institutions. Altogether, around 20 000 data points were recorded for arsenic and 60 000 for fluoride.

Arsenic-rich groundwaters found in many regions worldwide. By defining and separately simulating two different geochemical environments – "reducing" and "oxidizing/high pH" – it was possible to develop an optimal model for arsenic [1]. Chemically reducing conditions – as occur, for example, in young river deposits with organic-rich sediments – cause arsenic to be released in the form of reduced As(III), whereas in arid regions with high pH values, arsenic is released in oxidized form as As(V).

Our risk map (Fig. 1) indicates that arsenic-rich groundwaters evidently occur worldwide. The probability is particularly high in North (Alaska and Central US) and South America (e.g. Brazil), in Africa (Congo), and in Southeast Asia (Bangladesh, India, Nepal, Cambodia, Vietnam and China).

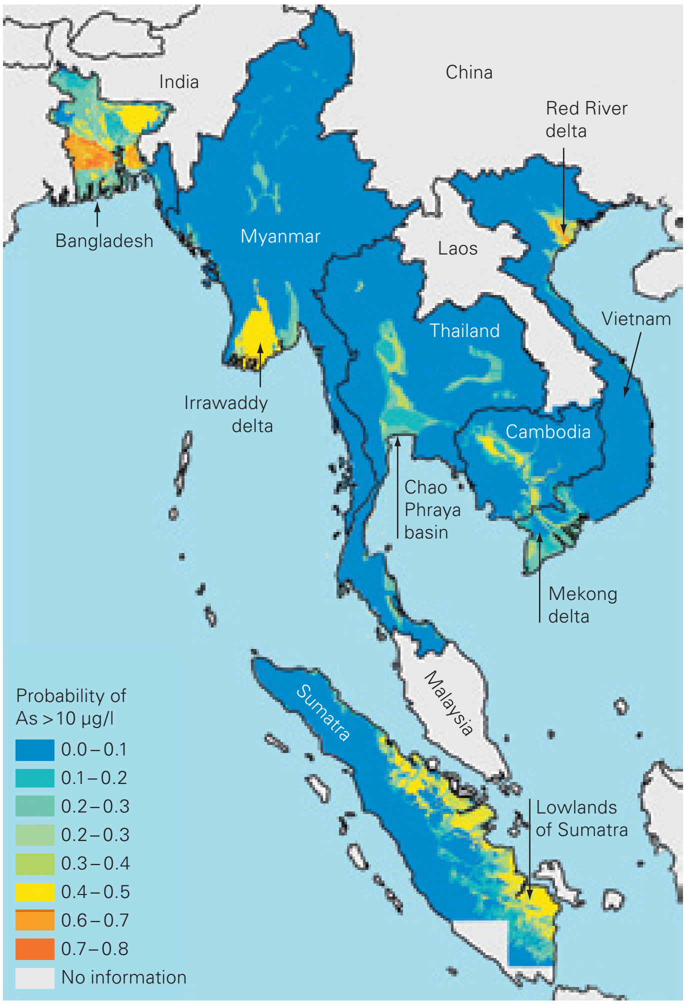
Geogenic contaminants

Groundwater is not always a source of particularly pure drinking water: in areas where problematic substances are mobilized in the subsurface under certain geochemical and geological conditions, the use of groundwater as drinking water can be a health hazard. For example, manganese and reduced arsenic (arsenite) are soluble under anoxic, chemically reducing conditions. Under basic conditions, anions such as fluoride, arsenate, vanadate, selenate, borate and uranyl-carbonate complexes are desorbed from negatively charged mineral surfaces. Elevated concentrations of anions (e.g. fluoride, arsenate, vanadate) may also occur in groundwaters with low dissolved calcium levels. The most significant geogenic contaminants worldwide are arsenic and fluoride. The guideline values issued by the World Health Organization are 10 µg/l for arsenic and 1.5 mg/l for fluoride.

As contamination was already known to be a major problem in Southeast Asia, we decided to carry out a detailed study of this region at the subcontinental level, additionally incorporating the geology of young sedimentary deposits in our model [2]. Digital maps of Bangladesh, Cambodia, Thailand, Vietnam, Myanmar and Sumatra and more than 4600 data points were included in these calculations (logistic regression). We found that geologically young (Holocene) deltaic sediments and organic-rich surface sediments are key indicators of groundwater arsenic contamination. Our model also identifies extensive high-risk areas on Sumatra and in Myanmar where arsenic measurements have not been performed to date (Fig. 2).

Risk of fluoride-rich groundwater in parts of India and China, in North Africa and in the Middle East. Geology is also a key factor in fluoride contamination of groundwater [3]. In particular, high concentrations of fluoride often occur in magmatic rocks. In addition, the release of calcium from rocks plays an important role

Fig. 2: Detailed study of arsenic risk in Southeast Asia, in which the geology of young sedimentary deposits was also considered – modelled probability of arsenic contamination in groundwater under reducing aquifer conditions.



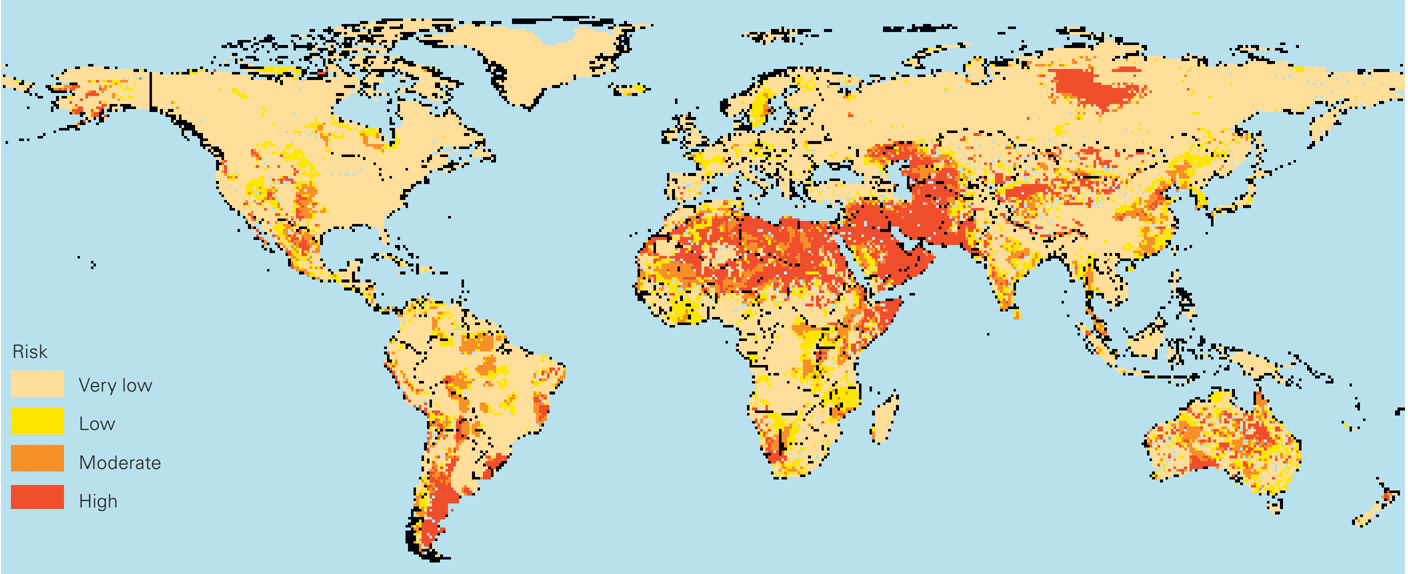


Fig. 3: Global fluoride risk map – modelled probability of fluoride contamination in groundwater.

since fluoride can be precipitated in the form of calcium fluoride. Climatic conditions also need to be taken into account, as salts (including fluoride) are readily enriched in shallow aquifers in an arid climate. Soil pH is likewise important because, as an anion, fluoride is released under alkaline conditions.

For the simulation, eight geochemical situations involving different combinations of the above-mentioned factors were defined and separately modelled. The overall results are shown in Figure 3. A particularly striking finding is the broad belt extending from northern Africa across the Middle East to Pakistan, Uzbekistan and Kazakhstan, where the risk of encountering fluoride-contaminated groundwater is high.

Risk maps need to be interpreted correctly! It is important to emphasize that the risk maps only indicate how high the probability is that arsenic or fluoride contamination will occur in individual regions, and not whether the groundwater there actually contains high levels of arsenic or fluoride. It therefore cannot be ruled out either that arsenic- or fluoride-rich groundwaters may in fact be found in areas with a low arsenic or fluoride risk, or that uncontaminated aquifers may also be present in high-risk areas.

The accuracy of such models is limited by two factors – spatial resolution and data availability. Ideally, data would be recorded as a function of depth since the quality of groundwater changes with depth and thus with geological and geochemical conditions. Unfortunately, however, information of this kind is not yet available at a suitable spatial resolution. Accordingly, modelling is no substitute for analysis of groundwater quality at the local level.

Water treatment requirements – simplicity, effectiveness and affordability. The requirements for sustainable drinking water treatment in developing countries, and especially in rural areas, are highly demanding. Appropriate treatment methods can be used both in households and in community facilities. Ideally, such systems should be highly efficient and have a long service life, should be easy to operate and maintain, and should produce sufficient treated drinking water to meet daily needs. To ensure that such water treatment methods can be sustainably implemented, it is necessary to consider not only technical but also socioeconomic and sociocultural aspects – for example, the question of costs, or acceptance among the target population – before suitable, locally adapted dissemination strategies can be developed.

Tailor-made arsenic removal techniques. In regions with elevated arsenic concentrations, we are evaluating various measures, depending on the specific circumstances [4]. In the Hanoi area, for example, arsenic can often be satisfactorily removed by a simple process of groundwater aeration followed by sand filtration. This is because water in the Red River Delta typically contains 10–30 mg/l dissolved Fe(II), which when oxidized with atmospheric oxygen forms red Fe(III) hydroxide. Arsenic, in turn, is adsorbed to these particles, which are then retained in the sand filters.

In Bangladesh, however, the natural iron content is usually too low, and arsenic removal is further impaired by high natural phosphate concentrations. As a simple way of increasing the iron content of water, various sand filters containing metallic iron (e.g. iron filings or nails) were developed, which remove arsenic more or less effectively depending on the composition of the water. To improve our understanding of the effects of these filters and to optimize their performance, we are currently conducting laboratory and field experiments with local partners in Bangladesh, El Salvador, Greece and Rumania.

In addition, we are working with local partners in Bangladesh to assess whether deeper tube wells (160–230 m) supply arsenic-free water. Unfortunately, at many sites, groundwater from a certain depth contains high levels of manganese and salts, so that the right depth has to be identified for each region if the limits for both arsenic and manganese are to be complied with.

Bone char filters for fluoride removal. The use of filters to remove excess fluoride from drinking water dates back as far as the early 1940s. The filter materials developed consist of aluminium oxides or calcium phosphates. However, these applications have been and continue to be confined largely to industrialized countries; only a small number of defluoridation projects have also been successfully implemented in developing countries. The failure of such drinking water projects is attributable mainly to a lack of efficiency and inadequate adaptation to local conditions.

In cooperation with the Catholic Diocese of Nakuru (CDN, a Kenyan organization), we are studying treatment materials and methods based on the use of calcium phosphates, which can be applied in rural areas of developing countries. CDN has already been working for ten years on the use of bone char for fluoride removal. Although this method of drinking water treatment is very simple and effective, the production of high-quality bone char requires a great deal of experience: the quality of the end product is significantly influenced by the temperature, oxygen levels and duration of the animal bone charring process. In addition, as bone char can only be used for a few months, it has to be replaced periodically. To increase the lifetime of the filter material, we are currently working on an enhanced bone char filtration method, in which calcium and phosphate are added to the filter to precipitate fluoride. To avoid the need for daily addition of chemicals, CDN has developed pellets which dissolve in water, slowly releasing the required substances. The results of initial laboratory and field tests are promising: the filter lifetime can probably be extended by a factor of 5–7 [5].

In search of arsenic-free groundwater: a drilling team in Sreenagar (Bangladesh) installs a 220-metre-deep tube well in the soft sediments of the Bengal delta.


Stephan Hug, Eawag

Outlook: delivering practical treatment methods to affected areas. While fluoride removal technologies are still at the development stage, efforts to disseminate treatment methods for water contaminated with arsenic have been under way in Asia for some years. Nonetheless, arsenic-related health problems have become more serious, especially in Bangladesh. There are many reasons for this: the population is not sufficiently aware of the issue, treatment methods are too complicated, culturally unacceptable or contrary to established habits, and water quality problems are often overshadowed by the daily struggle for survival. In addition, outsiders frequently lack a sufficient understanding of institutional structures to allow water treatment to be established in communities. However, it is essential for solutions to be adapted to local conditions and to take account of institutional, technical and social aspects. Accordingly, in the cross-cutting WRQ project, Eawag will be seeking the development of a systematic methodology permitting the implementation of sustainable solutions in developing countries over the next few years. ○ ○ ○

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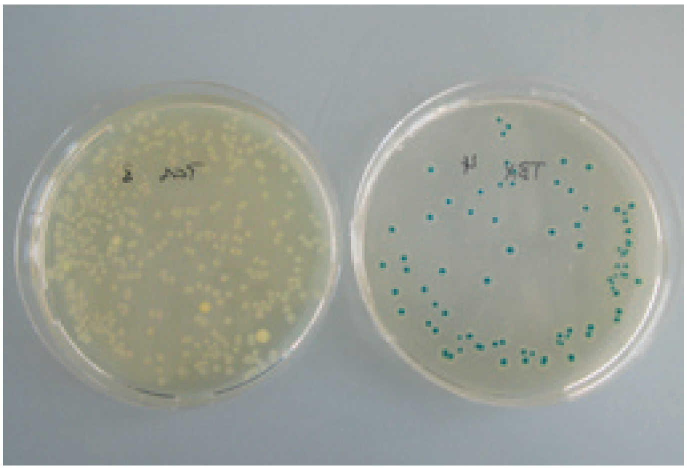
New methods for assessing the safety of drinking water

Thomas Egli, microbiologist, head of the Environmental Microbiology department and of the Drinking Water Microbiology and Ecophysiology group, and Titular Professor at the ETH Zurich.
Co-authors: Michael Berney, Frederik Hammes, Hans Peter Füchslin

The microbiological safety of drinking water is assessed by allowing bacteria to grow into visible colonies. However, this method is time-consuming and often significantly underestimates the number of microorganisms contained in water. A flow cytometry-based method developed at Eawag is more rapid and reliable – and also more versatile.

In most cases, the current approach to microbial safety, originally developed more than 100 years ago, offers adequate protection against drinking water contamination. It is based on two microbiological parameters that can be readily determined [1]: the number of aerobic mesophilic bacteria (i.e. environmental bacteria requiring oxygen and moderate temperatures for growth; known as the heterotrophic plate count/HPC) and the occurrence of the intestinal bacterium *Escherichia coli* (Fig. 1). In Switzerland, water is also required to be tested for another group of intestinal bacteria, the enterococci. The HPC is used to determine levels of viable bacteria and thus to assess the general microbiological quality and safety of drinking water. In piped water supplies, for example, the HPC is required to be less than 300 colony-forming units (cfu)/ml. The presence of *E. coli* or enterococci is regarded as evidence of fecal contamination; accordingly, a 100 ml water sample has to be shown to be completely free of *E. coli* and enterococci.

Fig. 1: Aerobic mesophilic bacteria from a water sample that have formed colonies on a solid medium (left). Colonies of the intestinal bacterium *Escherichia coli* cultured on an agar plate with a selective nutrient medium, allowing differentiation between *E. coli* and related coliform bacteria (right).



Photos: Martina Bauchrowitz, Eawag

One major disadvantage of these methods, however, is the considerable time involved, since bacterial cells in water have to be allowed to grow into visible colonies on solid nutrient media (agar plates): in the case of *E. coli,* this takes 18–24 hours, and determination of the HPC requires 3–10 days, depending on the particular technique used. If water is to be additionally tested for specific pathogenic microorganisms such as the Legionella or cholera bacterium, similar techniques are used; depending on the individual pathogen, the time required increases to several days or even weeks. Although a variety of molecular biological methods have been developed over the past 20 years for the rapid detection of indicator microorganisms and selected pathogens, these also have their drawbacks: trained personnel are required, detection limits are not low enough, or the tests are too costly for routine analysis (for a detailed overview see Chapter 8 of [1]). There is thus still a lack of methods permitting rapid, reliable and low-cost monitoring of microbiological water quality. For the past 5 years or so at Eawag, we have been exploring the possible applications of flow cytometry (see Box) in microbiological drinking water analysis. Our experience with this technology to date has been highly encouraging. Three of the methods developed in our group are of particular interest: determination of the total bacterial cell count, assessment of microbial viability and rapid detection of pathogens.

Flow cytometric cell enumeration superior in many ways to the conventional method. The legally required method involves determining the microbial content of water by means of the HPC. In water considered safe, this value lies between 0 and 100 cfu/ml. In reality, however, the HPC underestimates the quantity of bacteria present by at least 2 orders of magnitude. This has been known for more than 30 years as a result of comparisons with direct microscopic counts. Thus, while most of the bacteria

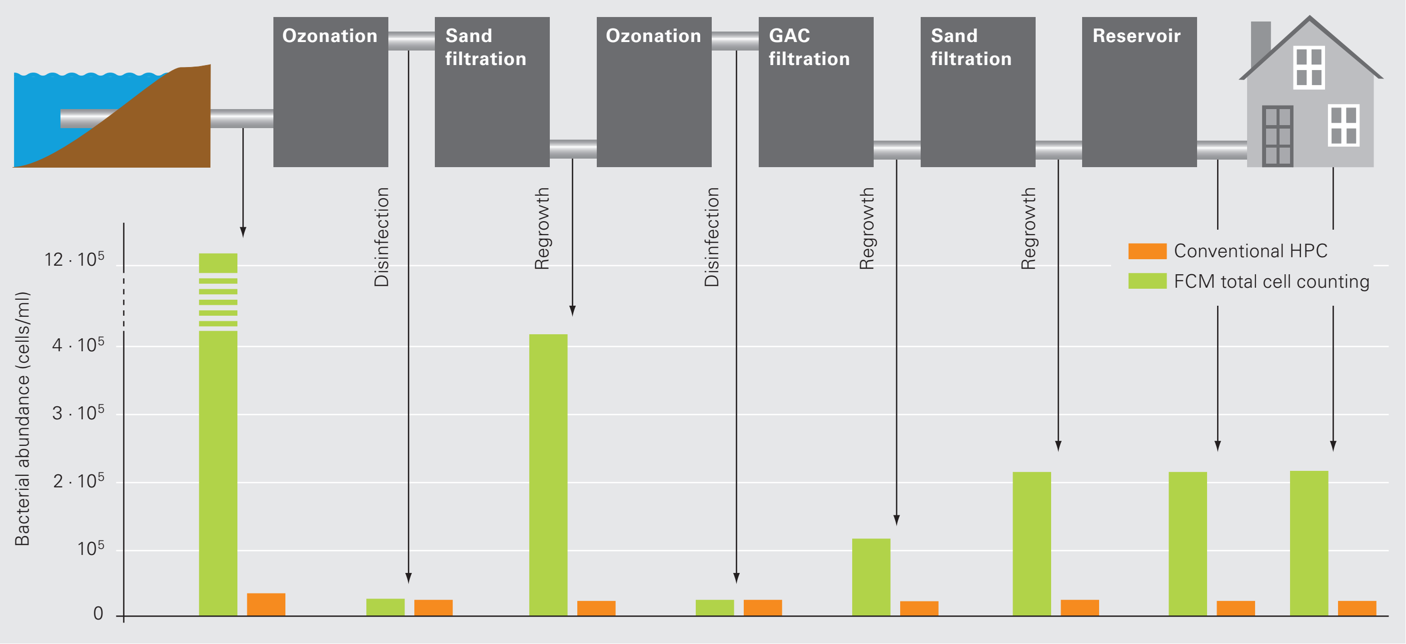


Fig. 2: Bacterial cell counts at various stages of the treatment and distribution of drinking water from Lake Zurich, determined by flow cytometry (FCM) and the legally required heterotrophic plate count (HPC) method. GAC: granular activated carbon.

present in water are active and capable of reproduction, only 1/100 to 1/1000 of the bacteria form a colony with the HPC method. The reasons for this are manifold and mostly unknown.

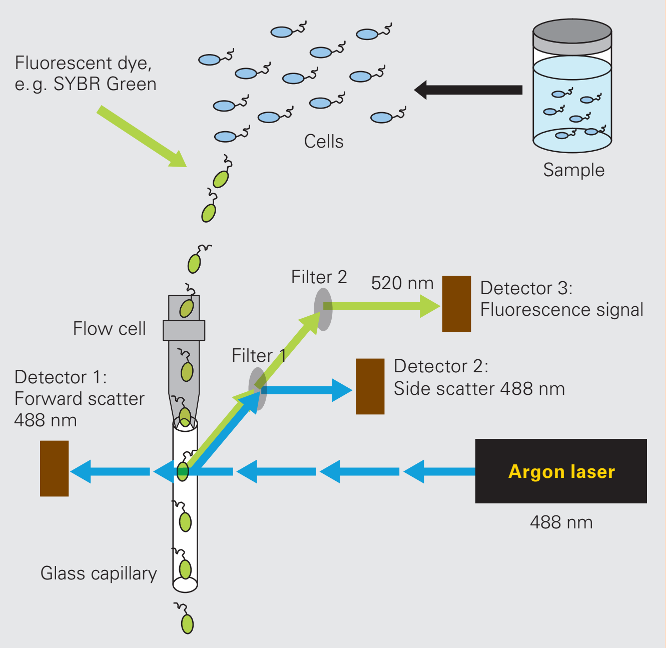
With our new method, however, after staining with a DNA-binding fluorescent dye, the microorganisms can be reliably enumerated within only 15 minutes. A comparison of the two methods, carried out in cooperation with the Zurich Waterworks (Fig. 2), shows that the cell counts determined in the flow cytometer, which were also checked against microscopic counts, provide a more realistic picture than the results of the HPC method [2]. Our conclusions are confirmed by another study, which involved the internal drinking water supply system at Eawag [3], and

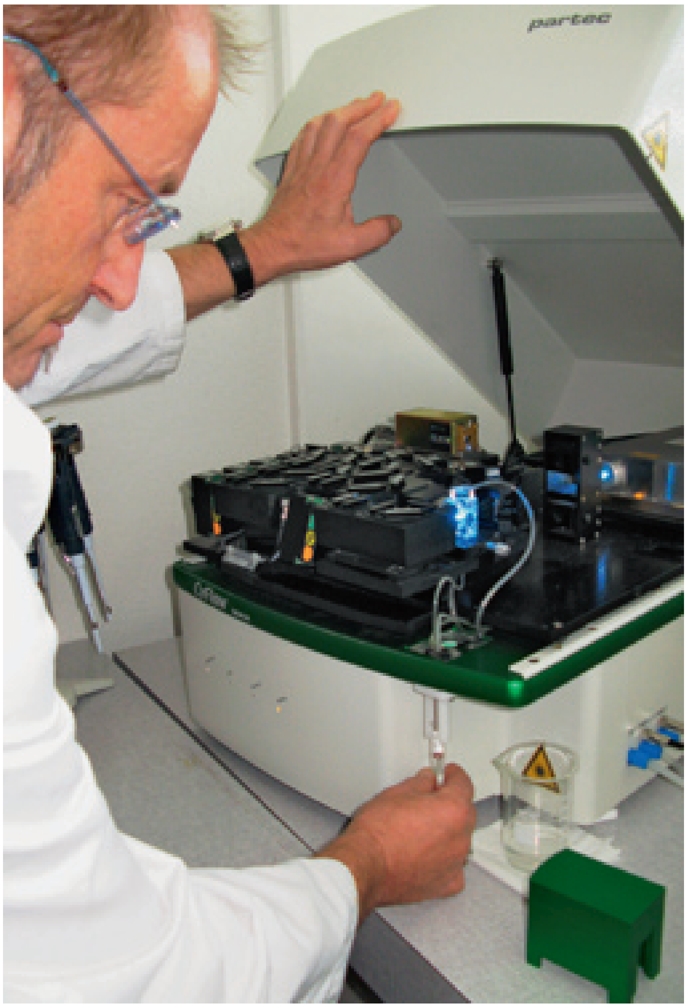
Counting up to 1000 cells per second with flow cytometry

For more than 20 years, flow cytometry has been employed in medical practice, e. g. for counting blood cells. In contrast, it is not widely used in microbiology, presumably mainly because bacteria are much smaller than human cells and thus more difficult to detect. Recently, however, technically refined and less expensive devices have started to be used for microbiological monitoring of biotechnological processes and in the food industry.

The principle of flow cytometry is relatively simple: a beam of light (usually from a laser) is passed through a stream of microorganisms flowing in single file through a glass capillary. When the light beam strikes a cell, part of the radiation is scattered and – redirected by lens, mirror and filter systems – is picked up by a light detector. Thanks to electronic signal detection, up to 1000 particles per second can be counted, with the required sample volume generally being less than a millilitre.

In addition, the cells can be stained with fluorescent dyes. These bind to certain cell components, such as DNA, proteins or cell surface structures, making it possible, for example, to distinguish living (= labelled) from dead or inactive (= unlabelled) cells.





Eawag technician Hans-Ueli Weilenmann at the flow cytometer.

Dye	Target	Mechanism of action
Propidium iodide	DNA	Can penetrate the perforated cell membrane of dead cells but is excluded from living cells with intact membranes.
Ethidium bromide	DNA	Only stains dead cells, as the dye is actively pumped out of living cells.
SYBR Green I Cyanine	DNA	Stains both dead and living cells. Discriminates between bacteria with high (HNA) and low nucleic acid content (LNA). It was formerly assumed that HNA bacteria are living whereas LNA bacteria are inactive or dying. According to our findings, this theory is false.
DiBac4(3) Bis(1,3-dibutylbarbiturate) trimethine oxonol	Proteins	Only penetrates cells with a collapsed membrane potential and with impaired energy and transport metabolism.
CFDA Carboxyfluorescein diacetate		Substrate cleaved by esterases to form a fluorescent compound in active cells.

Fluorescent dyes suitable for use as indicators of specific microbial activities.

also by the fact that concentrations of adenosine triphosphate (ATP – a compound occurring as an energy carrier in every living cell) correlate strongly with the bacterial cell counts determined cytometrically but poorly with the HPC values. We therefore believe that the cytometric technique developed at our institute is superior to the conventional HPC method in many respects. It is already being routinely used by the Zurich Waterworks (alongside the legally mandated plating methods).

Labelling of active cells by fluorescent dyes. Given that most of the microorganisms present in water are unable to reproduce on the nutrient media used today, it is only too easy to maintain that these cells are inactive or even dead and therefore not relevant for microbiological water safety. However, there is a great deal of evidence indicating that these microorganisms are capable of growing with naturally available carbon compounds – so-called assimilable organic carbon (AOC). For this reason, drinking water professionals need to know not only how many microorganisms are present in a water sample but also how viable they are.

For medical and microscopic applications, a large number of fluorescent dyes have been developed which indicate specific physiological activities of cells. Some of these dyes are also suitable for determining the viability of microbial cells, as has been shown by experiments involving laboratory strains. We are currently also assessing an initial selection of viability indicators (see Table) for environmental microorganisms.

We have shown that on average 60 – 90 % of the microorganisms in water are biochemically active and living; this is a markedly greater proportion than was determined using the HPC method [4, 5]. The dye carboxyfluorescein diacetate (CFDA), which is transformed by ester-cleaving enzymes into a fluorescent compound in active cells, shows particularly good correlations with ATP concentrations in the water sample (Fig. 3). Overall, we are therefore confident of finding, in the near future, an appropriate combination of dyes permitting reliable routine assessment of microbial viability in water.

Dangerous pathogens detected by immunomagnetic beads. While the total number of environmental bacteria ranges from 100 000 (drinking water) to 1 000 000 (lake water) cells per millilitre, the number of microbial pathogens – even in the event of contamination – is several orders of magnitude lower. For example, in order to detect a cell of the fecal indicator bacterium *E. coli* in 100 ml of drinking water, one would need to be able to pick it out from approx. 10 million other cells in the flow cytometer. Using the method developed at Eawag, this is indeed possible within about 2 hours, given a sufficiently low detection limit. For

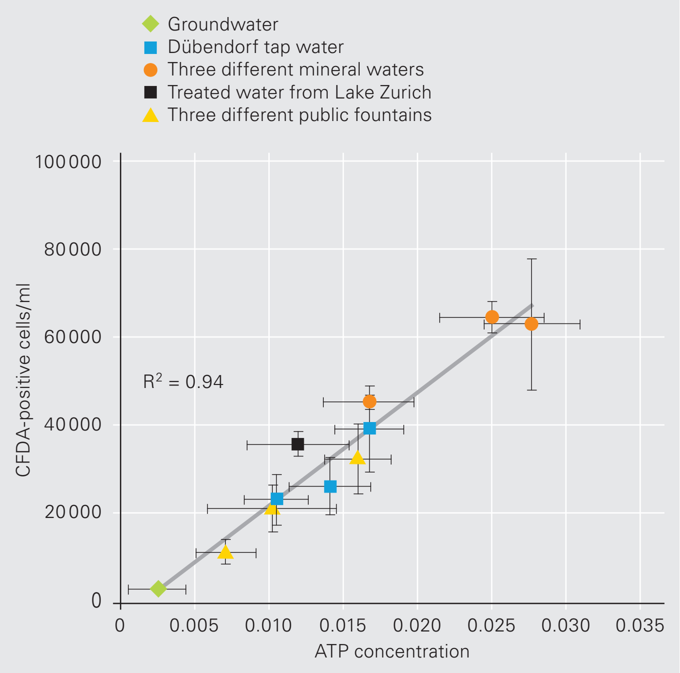


Fig. 3: Correlation between ATP concentration and the number of viable cells identified by the CFDA dye.

this purpose, the microorganisms contained in a water sample are first enriched on a membrane filter and then removed again in a concentrated form. After the addition of immunomagnetic beads (these are coated with antibodies that bind exclusively to specific structures on the surface of the pathogen), the infectious microorganisms of interest attach to these beads can be separated from the cell concentrate with a magnet and subsequently enumerated in the flow cytometer.

Using this method, we obtained a recovery rate of more than 95 % for the intestinal parasite *Giardia lamblia,* which affects 200 million people per year worldwide – and this was achieved not only in water but also in fecal samples [6]. At present, the detection limit is around 10 cells per litre of water, with no false-positive findings. Using the same approach, we are also able to detect *Legionella* [7], diarrhoea-producing *E. coli* O157 strains, Cryptosporidium oocysts and cholera bacteria. Our next goals are to broaden the range of pathogens that can be detected and to lower the detection limits significantly.

Flow cytometry – a technology with tremendous potential for the future. We are convinced that, in the coming years, a number of the methods developed at Eawag will be successfully established in practice. They will make it possible for the first time to obtain comprehensive and realistic data on the fate of microorganisms in drinking water treatment and *distribution.* Simpler and less expensive types of flow cytometers have now become available which are well suited for water analysis. If further progress is made in this field, there will doubtless soon be devices that allow rapid routine determination of a wide range of microbiological safety parameters, perhaps even including viruses. In addition, online analysis would now appear to be a not-too-distant prospect.

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We wish to thank everyone who, over the past few years, has contributed to the successful development of this research field, and in particular Franziska Bosshard, Iris Hülshoff, Hans-Anton Keserue, Stefan Kötzsch, Eva Siebel, Marius Vital, Yingying Wang and Hansulrich Weilenmann at Eawag. We are also grateful to Oliver Köster and Hans-Peter Kaiser of the Zurich Waterworks (WVZ) and the Wave 21 team.

This work was financially supported by the FOEN, the FOPH, Eawag, the EU TECHNEAU project, the Spiez Laboratory and the Zurich Waterworks.

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Removing trace organic contaminants

With modern analytical methods, new trace contaminants of anthropogenic and natural origin are constantly being discovered in water. But are these substances effectively removed at today's drinking water treatment facilities? Two methods – activated carbon filtration and chemical oxidation – are assessed here.

Andreas Peter, an environmental chemist, completed his doctoral thesis on taste and odour compounds in the Water Resources and Drinking Water department in 2008 and is a co-founder of the Eawag spin-off Aquality.
Co-author: Urs von Gunten

The list of trace organic contaminants detectable in water resources is an ever-lengthening one, as ever-improving analytical methods make it possible to measure compounds occurring in extremely low concentrations (in the nanogram to microgram per litre range). These compounds are among the roughly 100 000 synthetic organic chemicals registered in the European Union, of which around 30 000–50 000 are in everyday use. But it is not only synthetic substances that are problematic – various natural contaminants are also undesirable in drinking water (see Box: "Sources of trace contaminants").

Sources of trace contaminants

The synthetic compounds detectable in drinking water derive from a wide variety of applications:

- *Agriculture* – e.g. the pesticide atrazine, which is frequently found in groundwater.
- *Transport* – e.g. the fuel additive MTBE (methyl tert-butyl ether), which is added to petrol in high concentrations as an antiknock agent.
- *Medicine* – e.g. pharmaceuticals that cannot be readily broken down at wastewater treatment plants and are then discharged into receiving waters: iodinated radiocontrast agents, antibiotics, analgesics, beta-blockers and antirheumatics; also natural and synthetic hormones, such as 17β-ethinyl estradiol, which is used as an oral contraceptive.
- *Industrial chemicals* – e.g. tri- and tetrachloroethylene, which are widely used for cleaning purposes.

In addition to these man-made substances, there are a number of natural trace contaminants. These include, for example, 2-methylisoborneol or geosmin, which give drinking water an undesirable odour but are otherwise harmless; they are produced by algae and bacteria, particularly in eutrophic (i.e. nutrient-rich) surface waters. Of greater concern are the cyanotoxins synthesized by cyanobacteria, such as the oligopeptides known as microcystins; cyanobacteria also prefer eutrophic waters (see also the article by Rolf Kipfer on p. 8).

In order to keep concentrations of contaminants as low as possible, Switzerland accords high priority to the protection of waterbodies and thus resources; to mention just three examples, these measures include effective wastewater treatment, the use of protection zones to safeguard groundwater wells (see also the lead article on p. 4) and the treatment of road runoff prior to infiltration. The goal is, wherever possible, to supply drinking water with no or only minimal treatment. Thus, 400 of 1000 million m^3 of drinking water per year can be piped untreated into Switzerland's distribution system.

At locations where this is not possible or where drinking water is withdrawn from lakes, it first has to be treated. For this purpose, physical, chemical and biological processes are used, often in combination – flocculation, sedimentation, (biological) filtration, adsorption, chemical transformation and oxidation/disinfection. We wished to find out whether the drinking water treatment methods currently used are also capable of removing the trace contaminants that have only recently been discovered in water resources. This study was part of the cross-cutting Eawag research project Wave 21 (drinking water in the 21st century).

Separating or destroying contaminants. From the wide range of treatment methods available (see Box on p. 26), we chose to study two of the most effective processes in detail – activated carbon filtration and chemical transformation by oxidation. These two methods differ essentially in their mechanism of action. With activated carbon filtration, substances are separated unchanged by being adsorbed on activated carbon and/or are biodegraded in an activated carbon reactor. In contrast, undesirable compounds are generally transformed into less dangerous degradation products by the addition of oxidants and disinfectants (chlorine, chlorine dioxide, ozone, hydroxyl radicals) or by ultraviolet (UV) irradiation. The effectiveness of these two methods depends firstly on the

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A good sense of smell is essential: analysis of odour compounds at the sniffing port.

properties of the materials or chemicals used (e.g. powdered or granular activated carbon) and secondly on the physicochemical material constants of the contaminants – e.g. whether they are polar, readily water-soluble or apolar, poorly water-soluble compounds. In addition, the effectiveness of the treatment process is influenced by the composition of the raw water. For example, the process may be adversely affected by the presence of natural organic matter (NOM), i.e. breakdown products of bacteria, plants or animals, such as humic substances or polysaccharides, which occur as particles or dissolved in water.

Apolar contaminants effectively retained by activated carbon filter. Active carbon filtration is a widely employed method of drinking water treatment. For this process, powdered activated carbon is mainly used to allow a flexible response to peak loads, while filters with granular activated carbon are more suitable for routine use on account of the lower operating costs and greater ease of management.

Our experiments demonstrated that apolar organic contaminants are indeed effectively retained on activated carbon. On a pilot scale, we tested the efficiency of a 1.5 m activated carbon filter in removing the potent odour compound IPMP (2-isopropyl-3-methoxypyrazine). IPMP is a foul-smelling substance mainly produced by terrestrial bacteria. Over a period of 2 hours, raw water was spiked with IPMP at a concentration of 1.5 µg/l. Both the fresh carbon and the filter that had already been used for half a year and was saturated with natural organic matter almost completely adsorbed the apolar IPMP in the top 50 cm (Fig. 1A).

Polar substances competing with natural organic matter for free adsorption sites. In contrast, more readily water-soluble substances such as the petrol additive MTBE (methyl *tert*-butyl ether) were only partly retained on saturated carbon (Fig. 1B). Free adsorption sites are evidently lacking for the removal of this polar contaminant. In the course of filtration, the sites are occupied by natural organic matter, leading to a reduction in removal efficiency after a number of months. The higher the content of natural organic matter in water, the more rapid is the loss of efficiency. At the same time, biofilms may develop on the surface of the activated carbon, which have both negative and positive effects. On

Alternative methods for removal of trace contaminants

Another set of methods suitable for the separation of trace contaminants is membrane filtration (see Table). However, since most of these compounds have molecular weights well below 1000 Da, only membranes with a pore size in the nanometre range can be considered, and even these do not represent an absolute barrier for trace contaminants. In addition, calcium and magnesium are also retained by nanofiltration, leading to partial softening of drinking water. At the same time, to ensure that the membrane remains permeable, water has to be pretreated for nanofiltration.

Reverse osmosis, which has not been used to date in Switzerland, does not completely remove trace contaminants either. Use of this method is only appropriate in the case of extreme water quality problems, as it is highly energy intensive and generates large quantities of a contaminated concentrate (10–20% of the treated water volume), which has to be disposed of. In other cases, raw waters with contaminant concentrations subject to seasonal variation can be treated with powdered activated carbon in combination with ultrafiltration. Here, trace contaminants are adsorbed on powdered activated carbon, added as required, with a particle size sufficiently large to be retained in the subsequent ultrafiltration process.

Separation method	**Separation performance**
Microfiltration > 60 nm	Particles
Ultrafiltration 1.5 – 60 nm (MWCO 1000 – 1000 000 D)	Bacteria, viruses, humic substances, colloids
Nanofiltration 0.5 – 1.5 nm (MWCO 100 – 1000 D)	Viruses, humic substances, Ca^{2+}, Mg^{2+}, molecules
Reverse osmosis < 0.5 nm (MWCO < 100 D)	Molecules, ions

Typical separation performance of membrane processes.
MWCO = Molecular weight cut-off in daltons.

the one hand, biofilms occupy valuable adsorption sites. On the other, they degrade assimilable organic carbon (AOC) contained in water, thereby depriving microorganisms of their food source and increasing the biological stability of the water.

Hydroxyl radicals: particularly potent oxidants. While activated carbon filtration is a process subject to ageing over time, oxidation processes are constantly regenerated through continuous addition of fresh oxidants. In drinking water treatment, various chemical oxidants are used, such as ozone, hydroxyl radicals (extremely short-lived molecules formed when ozone decomposes in an aqueous solution), chlorine and chlorine dioxide. We therefore studied in detail how effective individual oxidants are against trace contaminants. Their effectiveness depends not only on their stability in water (i.e. whether they also react with natural organic matter), but also on how rapidly they can transform the target compounds. With the exception of hydroxyl radicals, oxidants attack specific functional groups; accordingly, the oxidation rate can be roughly estimated on the basis of the chemical structure of the contaminants. For precise calculations of kinetics, however, the specific rate constants have to be determined experimentally in advance. The majority of contaminants react most rapidly with hydroxyl radicals, followed by ozone, chlorine dioxide and chlorine. In assessing effectiveness, however, account must also be taken of oxidant exposure (the product of required contact time and concentration), for which the following sequence applies (in descending order): chlorine > chlorine dioxide > ozone > hydroxyl radicals.

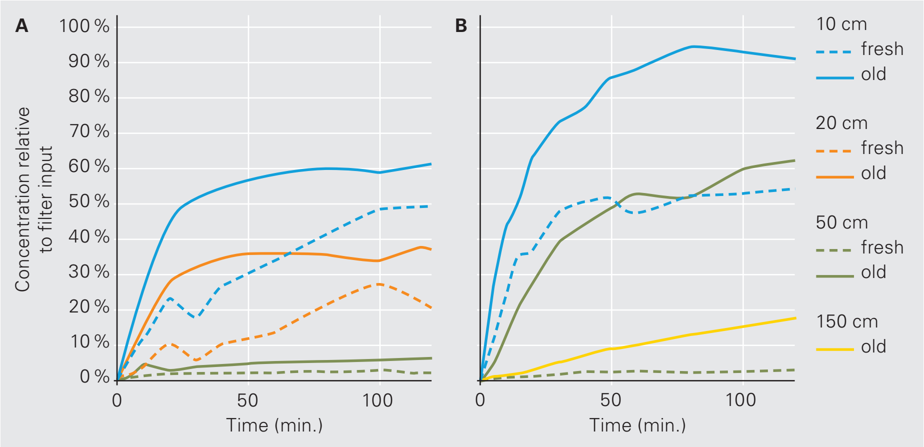


Fig. 1: Removal efficiency of an activated carbon filter for (A) the odour compound IPMP and (B) the petrol additive MTBE (pilot study with Lake Zurich water). Dashed lines = fresh filter; solid lines = saturated, 7- to 8-month-old filter.

Unwanted by-products of oxidation. One of the problems associated with chemical oxidation is the formation of undesirable by-products. Reactions with natural organic matter in water may produce (readily) assimilable organic carbon compounds that promote the growth of microorganisms – which is undesirable from the viewpoint of drinking water safety. For this reason, oxidation processes are frequently combined with biological filtration, so as to keep these substances to a minimum at the treatment stage. However, toxic transformation products may also be formed, such as halogenated organic compounds, nitrosamines and inorganic halogenates.

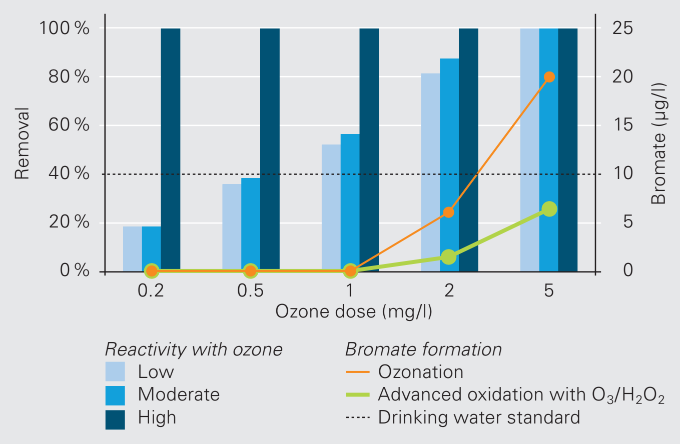
Overall, ozone is the oxidant of choice, as the end products of oxidation are frequently toxicologically less problematic and biologically better degradable than the original substances. However, undesirable substances, such as the potentially carcinogenic bromate, can also be produced when ozone is used. Bromate formation is particularly pronounced with high doses of ozone and in waters with high concentrations of bromide (> 50 µg/l). The association between contaminant removal and bromate formation is illustrated in Fig. 2.

Ozone-resistant contaminants effectively removed and bromate formation minimized by advanced oxidation. For contaminants that react slowly with ozone, very high ozone doses (> 2 mg/l) are sometimes required (Fig. 2) to achieve a removal rate of 90 %. However, the more ozone is added, the more bromate is formed. We found that it is possible to remove ozone-resistant compounds more effectively, while at the same time keeping bromate formation to a minimum, by using an advanced oxidation process (AOP) (Fig. 2). This method is based on the oxidizing power of hydroxyl radicals, which react with an organic contaminant as soon as they encounter it, regardless of its chemical structure. In advanced oxidation of drinking water, hydroxyl radicals can be produced in various ways: by a combination of ozone and hydrogen peroxide (O_3/H_2O_2), ozone and UV light (O_3/UV) or UV light and hydrogen peroxide (UV/H_2O_2).

As shown in Fig. 2, the contaminants studied were almost completely removed following the addition of O_3/H_2O_2, without the bromate quality standard of 10 µg/l being exceeded. With UV-based processes, bromate formation is actually negligible, although the UV doses required are considerably higher than those normally used for UV disinfection. In addition, the removal of contaminants with UV/H_2O_2 requires about ten times as much energy as O_3/H_2O_2. Ozone-based treatment steps can easily be upgraded with advanced oxidation processes in response to increased concentrations of contaminants in raw water.

Conclusions. With the series of processes generally used in this country for lake water treatment, the majority of trace contaminants are almost completely eliminated. This is mainly due to the removal efficiency of ozonation and activated carbon filtration [1, 2]. However, the quality of raw water can significantly influence the effectiveness of drinking water treatment and therefore is a major factor in the selection of individual treatment processes. ○ ○ ○

Fig. 2: Contaminant removal (bars) and bromate formation (curves) during ozonation and advanced oxidation (pilot study with Lake Zurich water, containing 20 µg/l bromide). The contaminants are grouped according to their reactivity with ozone: low (e. g. atrazine, MTBE and the odour compound geosmin); moderate (e. g. IPMP); high (e. g. the pharmaceuticals diclofenac and sulphamethoxazole).



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Tomorrow's drinking water treatment

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Co-author: Hans-Peter Kaiser, Zurich Waterworks (WVZ)

Most of the country's water treatment facilities, which were built in the middle of the 20th century, need to be renewed. As part of the cross-cutting Eawag project Wave 21 (Drinking water in the 21st century), two new process combinations involving membrane filtration have been tested.

In Switzerland, about 43 % of drinking water is sourced from springs, 40 % from groundwater and 17 % from lakes. Treatment is required mainly for lake and spring water in order to ensure high-quality drinking water supplies. Depending on the quality of the raw water, more or less elaborate processes may be necessary: for example, if spring water is only occasionally affected by mild turbidity, simple sand filtration or membrane treatment will be sufficient. However, if the raw water is also contaminated with microorganisms and/or trace organic compounds, processing frequently involves a series of steps.

For example, to treat water from Lake Zurich, the Lengg water facility uses two ozonation and two sand filtration steps, together with activated carbon filtration (Combination A in Fig. 1). As part of the cross-cutting project Wave 21 (Drinking water in the 21st century), potential alternatives are being studied by Eawag in cooperation with Zurich Waterworks (WVZ) and the engineering company WABAG (Winterthur). The requirement specified by WVZ was that the drinking water treated with the new process combination should be of the same excellent quality as that now supplied by the existing facility (see the article by Erich Mück, p. 32).

Sand filters replaced by membranes. Membrane filtration – in particular, ultrafiltration (see the Table on p. 26) – is a reliable modern option for the removal of microorganisms, but it does not represent a significant barrier to trace contaminants, taste and odour compounds, or assimilable organic carbon (AOC). However, these substances can be effectively removed by the combination of ozonation and activated carbon filtration. Thus, two possible new process chains suggest themselves, depending on whether membrane filtration is employed as the final step (Combination B in Fig. 1) or as a pretreatment, upstream of ozonation/activated carbon filtration (Combination C in Fig. 1). Combination B was

Fig 1: Flow diagram of process steps at the existing Lengg lake water treatment facility (Combination A) and two potential alternative process chains that could replace the Lengg facility (Combinations B and C).

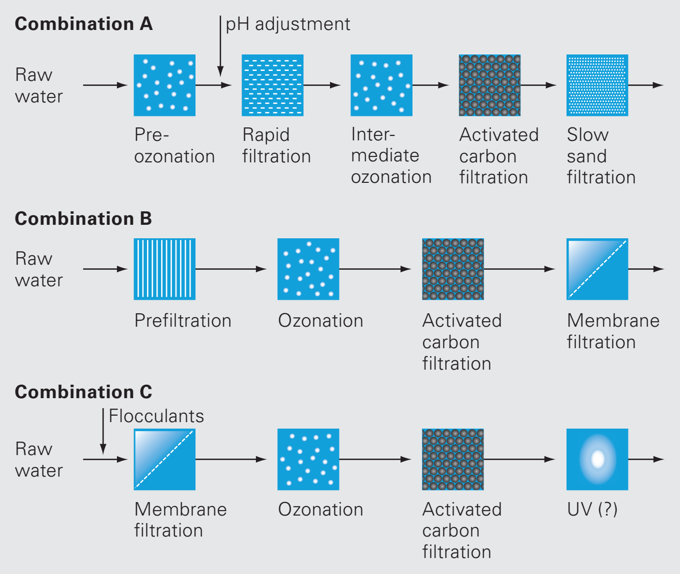
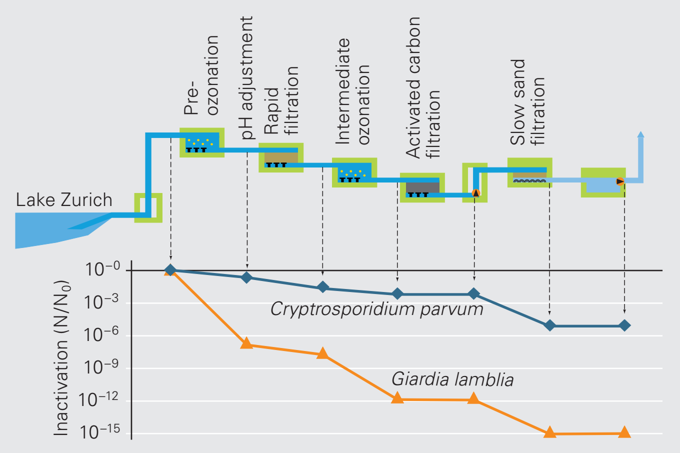


Fig. 2: Inactivation rates determined for *Giardia* and *Cryptosporidium* at the existing Lengg lake water treatment facility. N = number of cells after treatment, N_0 = number of cells before treatment. Example: 10^{-2} represents 100-fold reduction.



HACCP analysis

The Hazard Analysis and Critical Control Points (HACCP) system is a preventive approach designed to assure food safety for consumers. With regard to drinking water supplies, it is first necessary to assess potential hazards associated with raw water (Lake Zurich water, in the case of the Lengg facility), the various treatment steps and the distribution system. This involves not only determining the efficiency of the individual steps but also identifying undesirable by-products that are formed during treatment and characterizing the microbiological stability of the water produced – particularly since the WVZ supplies water without chlorination.The second phase involves the definition of critical control points and the establishment of critical limits for the monitoring of drinking water. Among the critical control points, for example, is the residual ozone content. This is a measure of the inactivation of pathogenic microorganisms that occurs during ozonation.

In this study, three groups of risks were defined:

► *Group I:* Factors posing a hazard to consumers' health. This category comprises toxic contaminants (e. g. cyanobacterial toxins and nitrite) for which a limit is specified on health grounds; pathogenic bacteria, viruses and parasites; and also – though not dangerous to health – heterotrophic bacteria (see the article by Thomas Egli on p. 20).

► *Group II:* Factors that can give rise to complaints from consumers, possibly damaging customers' confidence in the water utility. This category includes in particular taste and odour compounds and particulate matter.

► *Group III:* Factors that do not cause health problems and are not noticed by consumers. Since consumers expect their drinking water to be of high quality, water suppliers also make reasonable efforts to remove these substances. The priority III category includes the gasoline additive MTBE (methyl tert-butyl ether), the anticorrosive agent benzotriazole and radiocontrast agents used in medicine.

implemented as a pilot plant (constructed by WABAG) at the Lengg facility, where it has been tested over the past 2 years under near-real-life conditions. In parallel, to provide a better understanding of the Combination C process chain, experiments were also carried out on a small-scale membrane system.

As drinking water is a foodstuff, water suppliers are required to adopt the HACCP approach to quality assurance (see Box), and we therefore proceeded in accordance with this system in our study. The hazard analysis indicated that Lake Zurich water does not contain micropollutants which would need to be continu-

The membrane module in the pilot plant tested at the Lengg lake water facility.

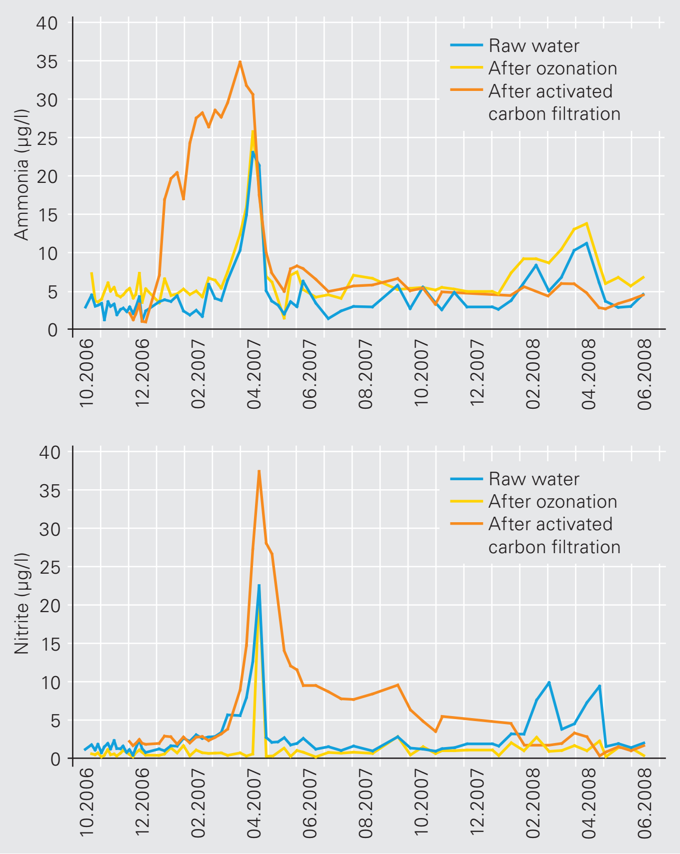

Ruedi Keller, Zurich

ously removed in order to comply with drinking water standards. Nevertheless, we observed in detail the behaviour of a number of relevant parameters during treatment. These are discussed in more depth below.

Pathogenic microorganisms. At the existing treatment facility, several steps are used to inactivate (ozonation) or retain microorganisms (rapid and slow sand filtration). The same applies to organisms that cause diarrhoea, such as *Giardia lamblia* and *Cryptosporidium parvum*. During normal operation of the sand filter, a surface layer known as a *Schmutzdecke*, mainly consisting of retained biological material, assures a 5-log removal of *Giardia* (i.e. 100 000-fold reduction). Overall, under stable operating conditions, the existing process chain at the Lengg water facility achieves a 15-log removal of *Giardia* (Fig. 2), thereby clearly exceeding the minimum requirement of a 3-log (99.9 %) reduction specified by the US Environmental Protection Agency (EPA). Occasionally, however, the surface layer has to be removed, particularly when excessive hydraulic resistance develops. For a short period thereafter, the performance of the sand filter is impaired – until an effective layer has formed once again.

In contrast, membrane filtration yields a consistently high log removal of microorganisms. It is known, for example, that ultrafiltration provides a 5-log removal of *Giardia lamblia* [1] and that ozonation offers an additional 5-log inactivation. Thus, in total, a 10-log reduction is attained with the two new process chains B and C – regardless of the position of the membrane step.

Fig. 3: Ammonia and nitrite concentrations in the activated carbon filter of Combination B (see Fig. 1).



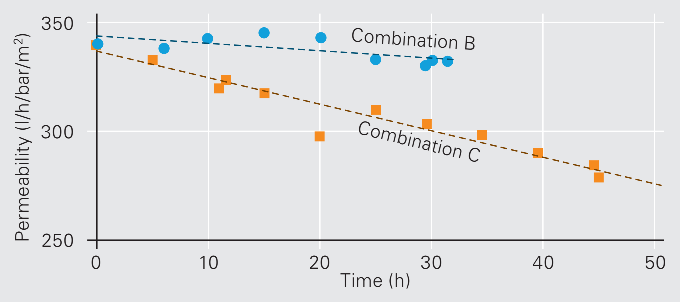
Nitrite formation. In the pilot plant with downstream membrane filtration (Combination B), nitrite was formed in the activated carbon reactor in the spring, a few months after the system came into operation (Fig. 3). In this process chain, coarse particles – mainly phytoplankton – are removed by prefiltration. However, a portion of the phytoplankton passes through and is subsequently destroyed in the ozonation step. The proteins released are finally biodegraded in the activated carbon reactor. In this process, ammonia is also formed, which in turn is converted to toxic nitrite by nitrifying bacteria. If no nitrite-oxidizing bacteria have yet been established in the reactor, the nitrite remains in the water and is not further oxidized to nitrate. However, the limit specified for ammonia and nitrite in drinking water (100 µg/l) was not exceeded.

In the following spring, by contrast, nitrite formation was not observed (Fig. 3). We therefore assume that this was merely a temporary problem, which may occur during the running-in period of the activated carbon filter. Nitrite-oxidizing bacteria most likely also became established in the reactor later on.

It may be possible for nitrite formation to be completely avoided by placing membrane filtration at the start of the process chain, so that the phytoplankton is already removed at this stage. Whether this is indeed the case is to be investigated more closely in the second pilot phase, in which Combination C is also to be tested as a pilot plant at the Lengg lake water facility. Small-scale experiments have shown that performance, i.e. membrane permeability, declines more rapidly when this step is at the beginning rather than at the end of the treatment chain (Fig. 4). In order to guarantee stable operation with Combination C, it might be necessary to pretreat the water by flocculation before it flows through the membrane filter (Fig. 1) [2].

Cyanobacterial toxins. If the phytoplankton also includes cyanobacteria (blue-green algae), these are likewise destroyed in the ozonation step. In this process, cyanotoxins are released from the cyanobacterial cells. Although these substances are immediately oxidized by the ozone, it is possible that some of the toxins will

Fig. 4: Loss of membrane permeability, depending on whether ultrafiltration is performed at the beginning (Combination C, Fig. 1) or end (Combination B, Fig. 1) of the process chain.



	Risk category under HACCP system	Combination A: existing facility	Combination B: downstream membrane step	Combination C: upstream membrane step
Raw water-related risks				
Pathogenic microorganisms	I	+	+	+
Cyanobacterial toxins	I	+ (destroyed by intermediate ozonation and activated carbon)	Could possibly be problematic in the future	+
Taste and odour compounds	II	+	+	?
Particulate matter < 100 µm	II	+	++	++
Micropollutants	III	++	+	+
Treatment-related risks				
Ammonia and nitrite	I	+	Nitrite formation may occur during start-up of activated carbon filtration, then +	?
Biological stability	I	++	?	?
Bacterial count	I	+	+	+
Disinfection by-products	I	+	+	

Effectiveness of the three process combinations studied (see Fig. 1). ++ = excellent performance, + = good performance, ? = needs to be evaluated.

remain in the cells and only be dissolved in the water in the subsequent treatment steps. In future, cyanobacterial blooms could in principle become more abundant as a result of climate change, but the extent of any such increase is difficult to predict. What are the implications for drinking water treatment at the Lengg facility? Since membrane ultrafiltration does not represent a barrier to cyanotoxins, treatment chain B – with downstream membrane filtration – involves a greater risk than the other two process combinations A and C.

Biological stability and cell count. Another important parameter in drinking water treatment is biological stability. Water is described as biologically stable when the content of assimilable organic carbon (AOC) is too low to permit the growth of microorganisms in the distribution network. Drinking water of this quality – such as that currently produced at the Lengg treatment facility – can be supplied unchlorinated. At the Lengg facility, AOC concentrations are reduced by biodegradation in three different steps (rapid sand filtration, activated carbon and slow sand filtration). On account of the slow sand filter in particular, the biological stability of the drinking water produced is slightly better than that of water treated with only one biological step (activated carbon filtration) in pilot plant B. However, although the AOC content of water from the pilot plant is somewhat higher than in Lengg water, it is still below the limit defined for stable water. Whether this is in fact sufficient remains to be established.

With the upstream membrane filtration in Combination C, there is also a risk that cells or cell colonies could be released from the biofilm in the activated carbon reactor, with the limit for microorganisms in drinking water being exceeded as a result. This could be prevented by regular backwashing of the activated carbon filter and optionally with an additional UV disinfection step at the end of the process chain.

Chemical spills. Although the likelihood of a chemical spill has been considerably reduced by the Major Accidents Ordinance, the possibility of such an accident leading to contamination of Lake Zurich cannot be entirely ruled out. Accordingly, the new process chain for lake water treatment should be able to retain as many potential contaminants as possible. This is ensured by the combination of ozonation and activated carbon filtration.

Next steps. On the basis of our analysis, we have prepared an initial qualitative comparison of the risks associated with the three different combinations of water treatment processes (Table). However, as not all the possible risks were evaluated in this study, no definitive conclusions can yet be drawn. The next step will therefore include detailed pilot experiments with process chain C. Other risks that would naturally also need to be taken into account in a final assessment arise from special operational situations such as filter flushing, plant start-up and switching operations and the complete shutdown of the facility or failure of an individual treatment step. Additional points to be considered, apart from the quality of the drinking water produced, include process engineering (flexibility and modularity), operational (maintenance and running efforts), financial (investments) and environmental aspects (space requirements, energy consumption, waste and wastewater generated and chemicals consumed). ○ ○ ○

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Erich Mück, engineer and Director of Zurich Waterworks (WVZ).
Co-authors: Ulrich Bosshart, Hans-Peter Kaiser, Oliver Köster (all WVZ staff)

Fruitful partnership between research and practice

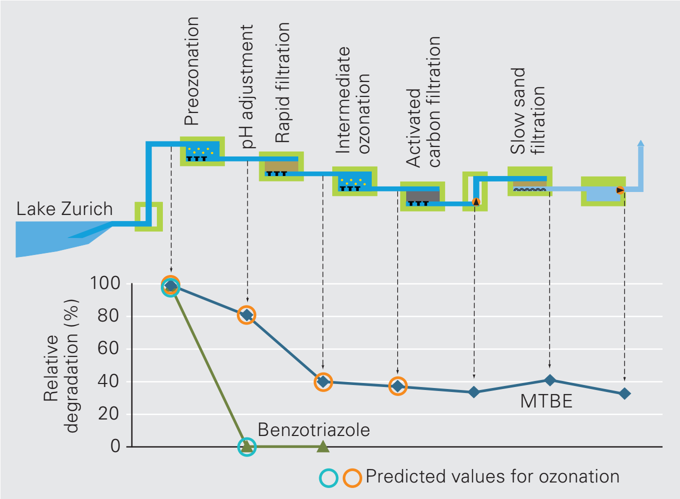
For some years, Zurich Waterworks (WVZ) has collaborated with Eawag and an industrial partner; this partnership has become even closer in the course of the cross-cutting Eawag project Wave 21. But what are the ingredients of a successful project that brings together such a variety of interests and aims? Here, we present a first-hand account.

Drinking water is a commodity dependent on consumer confidence. According to a survey conducted in 2006 by the Swiss Gas and Water Industry Association (SVGW), drinking water is highly approved of by more than 95 % of the Swiss public. However, consumers are acutely sensitive to quality issues, which can have a severe and lasting impact on the image of drinking water. This lesson was painfully learnt in Zurich during the typhoid epidemic of 1884, which claimed several dozen lives. Following this experience, WVZ began, somewhat reluctantly, to collaborate with a variety of research establishments – the Federal Institute of Technology (ETH) and the University of Zurich, and also with Robert Koch at the Imperial Health Office in Berlin. In addition to its partnership with the ETH Zurich, which has continued down to the present day, WVZ has collaborated with Eawag since 1995. This collaboration, initially focusing on the question of ozonation, has since expanded into a variety of other projects. Although WVZ can draw on a large number of experienced and well-qualified professional staff, new challenges are constantly arising which can be more effectively addressed in partnership with the research and industrial sectors. This is true in particular when special expertise or a major investment of time is required to deal with a problem. But what does it take to ensure that this type of collaboration is successful? Answers are provided by three case studies.

Ozonation: an effective treatment step for lake water facilities? As drinking water is subject to the Foodstuffs Act, water suppliers are required to assess the performance of individual treatment steps in accordance with the HACCP method (see Box on p. 29). This also applies to ozonation. However, if quantitative conclusions are to be drawn concerning the disinfectant effects of ozone and its efficiency in removing micropollutants, knowledge of ozone reactor hydraulics and of removal/disinfection kinetics is necessary. This expertise was contributed to the WVZ project by the Eawag working group led by Urs von Gunten (see also the article by Andreas Peter on p. 24). As there was a need both for laboratory experiments and for studies on the ozone reactor in the treatment plant at the water facility, and measurements were carried out by both partners, the procedure called not only for extremely close cooperation between the participants but also for sharing of the data collected. Subsequently, the results of the laboratory experiments were linked in a model with the theoretical accounts of removal and disinfection processes in the ozone reactor. The accuracy of the predictions generated by this model was ultimately confirmed by the WVZ measurements (Fig. 1).

Thanks to this joint project, WVZ is now in a position to determine inactivation rates for all microorganisms with a known inactivation rate constant, and removal rates for micropollutants with known removal rate constants in all the ozone plants at WVZ facilities [1–4]. Also under development is an additional online

Fig. 1: Predicted (circles) and observed (triangles and rhombs) degradation of micropollutants in treatment steps at the Lengg lake water facility.



module that determines the removal rate constant of ozone in Lake Zurich water and continuously adjusts the ozone dose required for the treatment process. In a follow-on study involving the Eawag working group led by Willi Gujer, ozone reactor hydraulics was simulated using a three-dimensional model, which further improved the modelling predictions. WVZ will apply this model for future construction of reactor chambers.

Altogether, the ozonation project ran for 7 years. WVZ incurred external costs of just under CHF 400 000. As well as several Eawag scientists, a WVZ employee devoted 10–15 % of his time to these studies throughout this period.

New method sought for determining biological stability of water. When drinking water is produced from surface waters, an important objective is to ensure the biological stability of the water. If it is to be supplied to consumers without any further safety measures (e.g. chlorination), microbial regrowth in the distribution network can only be prevented by minimizing nutrient levels in the piped water. Since the growth of microorganisms in drinking water is normally limited by the availability of carbon compounds, the goal was to develop a rapid and low-cost method allowing readily assimilable organic carbon (AOC) to be determined in the microgram-per-litre range.

The test developed at Eawag in the working group led by Thomas Egli uses flow cytometry to monitor the growth of a natural microbial consortium promoted by AOC (see also the article by Thomas Egli on p. 20); this in turn is used to assess the AOC content of water. In addition, the method was combined with the determination of further parameters: total bacterial cell count, dissolved organic carbon, temperature, pH and heterotrophic count [5–7]. The new methods are of interest both for research and for drinking water treatment practice and have already been introduced at WVZ.

In this project, WVZ provided CHF 150 000 in funding for an Eawag researcher for 2 years and bore the internal analytical costs of CHF 30 000. In addition, one WVZ employee was involved in the project (10–15 % commitment). An Eawag staff member who took part in this project is now employed by WVZ.

Use of pioneering technologies at lake water facilities – Wave 21. The initial question posed by WVZ was what affordable and sustainable processes could be used to supply drinking

Zurich Waterworks

Zurich Waterworks (WVZ) sets high standards, not only for drinking water quality but also for its own operations. Accordingly, for the past 15 years, WVZ has been certified to ISO 9000 (quality management system with integrated occupational health & safety/environmental management certification and accredited laboratory). WVZ has set itself the goal of permanently supplying the public with drinking water of excellent quality, as cost-effectively as possible. The organization’s efforts over the years have earned WVZ a high level of confidence among consumers, compared with other water utilities across Switzerland; both nationally and internationally, it is perceived as an exemplary water supplier. WVZ plays a key role in the network of Swiss water utility laboratories, aquaeXpert [8], which is supported by the Swiss Gas and Water Industry Association (SVGW) and has been joined by Eawag as a partner. This network is an important tool for developing and sharing knowledge and making this expertise available to other water suppliers.

Details of WVZ organization (2007)
Established: 1868
285 employees
Approx. 820 000 users in 67 communes
Water consumption: 53 million m^3 per year
1 groundwater, 1 spring water and 2 lake water facilities
Daily supply capacity: 500 000 m^3
Length of network: approx. 1544 km
Costs: CHF 117 million
Income: CHF 120 million
Price per m^3 (incl. charges): CHF 2.50

Area supplied by WVZ. As well as operating within its core area in Zurich, WVZ collaborates with contractual partners in the regions shaded in grey. The extent of water supplies to these regions ranges from coverage of peak demand to 100 % provision.

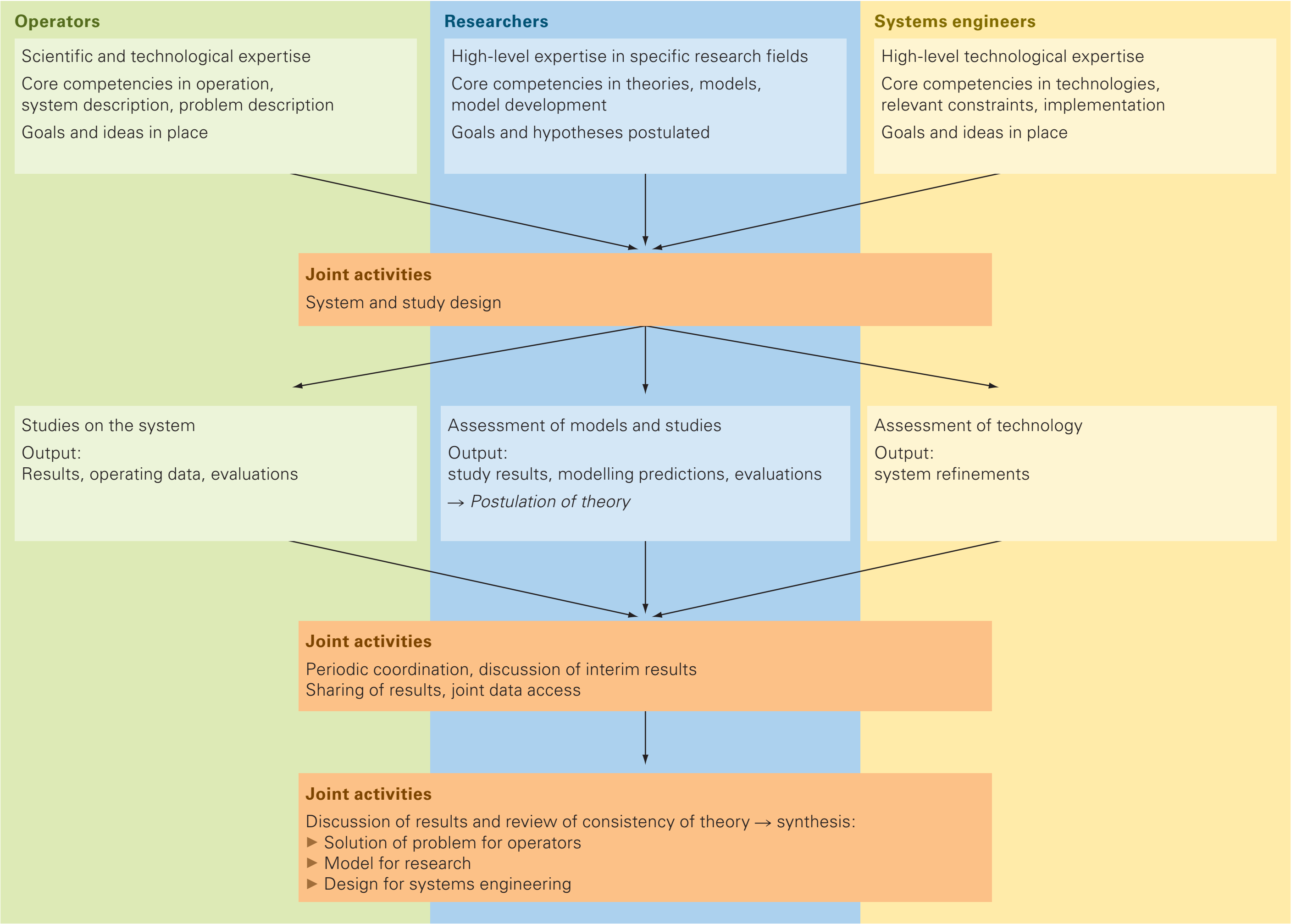


Fig. 2: Model for collaboration between WVZ, Wabag and Eawag in piloting of new treatment processes.

water without chlorination and of the same excellent quality as that produced today. It seemed promising to tackle key issues identified by WVZ in combination with the Eawag research project Wave 21 (Drinking water in the 21st century). For this cooperation, another partner was engaged – Wabag (Winterthur), a systems engineering company with whom WVZ had already successfully conducted two pilot projects since 2003. The three partners formed a project team, which not only specified the design of the pilot plant and the testing procedure but also discussed the data and results and coordinated the various activities (Fig. 2). This collaboration between researchers, water facility operators and systems engineers made it possible to test a pioneering treatment system. Comprising prefiltration, ozonation, activated carbon filtration and membrane filtration steps, it has been in operation since the end of 2006. The tests conducted on this pilot plant are to be completed by the end of 2008.

Although the data collected have not yet been fully evaluated, the benefits for WVZ are already apparent: for example, several new analytical methods have been developed for assessment of the individual treatment steps. The use of ozone-enriched water and static mixers for the ozonation process is superior to the injection system involving diffusors that has been used to date. With the aid of advanced oxidation (based on ozone and hydrogen peroxide), the removal of certain micropollutants can be increased. New tests permit the characterization of activated carbon filtration. Not least, the modelling of processes occurring during filtration was improved by studies on membrane fouling (deposition of natural organic matter on membranes). In 2009, WVZ will pilot another process chain, consisting of initial membrane filtration followed by ozonation and activated carbon filtration, and possibly including UV disinfection as a final step.

Until the end of 2008, WVZ's participation in the Wave 21 project involves five employees with a commitment of 10–20 % each and one with a 30 % commitment. In addition, WVZ contributed approx. CHF 1.2 million in funding for the construction and operation of the pilot plant and CHF 200 000 per year for laboratory analysis. Wabag deployed two of its employees, with a total commitment of about 30 %.

Conclusions: requirements, opportunities and risks. The main "driver" for successful projects is certainly an ongoing open dialogue among the partners. At the same time, it is not always easy to communicate specific problems and individual interests clearly and comprehensibly, or to understand and accept the other parties' viewpoints. For example, a production facility has to comply with certain stringent requirements which impose clearly defined limits on scientific freedom. On the other hand, freedom is necessary to promote innovation so this balancing act needs to be performed.

In our experience, a number of other factors are required for a successful innovation project:

- A common project goal, within which each partner can also identify its own individual sub-goals.
- Partners focusing on their core competencies.
- Periodic meetings to discuss results and the next steps.
- Team spirit, which is further strengthened by shared experiences.
- Team members with experience in the other partners' field of activity, specifically in the research environment.
- Partners located in close proximity to each another.
- Establishment of closer links among the partners in several small-scale projects.

Although the approach described calls for a major investment of human resources, these costs are certainly offset by the knowledge acquired. Another welcome side effect is the fact that WVZ no longer has any difficulty in recruiting highly qualified specialists from the academic sector as employees. The collaboration between WVZ, Eawag and Wabag is thus in every respect a success story, which should now be further developed so as to ensure high-quality and sustainable drinking water supplies. ○ ○ ○

Pilot plant for treatment of Lake Zurich water at the Lengg facility.

WVZ

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**A complete list and pdf files of all Eawag publications are available: http://library.eawag-empa.ch/eawag_publications.html
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In Brief

Eawag News survey

Many thanks to everybody who took part in our recent Eawag News readers' survey. As expected, most of the responses came from Europe and, in particular, Switzerland and Germany. However, subscribers from 35 other countries also took advantage of this opportunity to tell us what they thought about Eawag News. It is gratifying to hear that Eawag News is read with interest all over the world – from Ethiopia to the US and from Argentina to South Korea. As well as indicating that we are on the right track, your comments suggest various ways in which the publication could be improved. A detailed analysis will be included in the next issue of Eawag News. Prizes were sent to the winners of the draw at the end of September.

Facades: a source of water pollution

For many years, agriculture was regarded as the prime suspect when pesticides were detected in rivers and streams. Studies carried out by Eawag and Empa now show that built-up areas also account for a considerable proportion of such inputs. For example, substances can be leached out of facade paints and renders (photo: model building) and enter the environment in rainwater, possibly producing toxic effects in organisms. In cooperation with manufacturers, cantonal authorities and other partners, the researchers have studied these leaching processes and are currently discussing ways of tackling the problem.

Realignment of engineering activities

Almost two years ago, faced with personnel changes and an increasingly competitive environmental engineering field, Eawag's engineering departments launched an intensive process of strategic planning. The broad-based discussions yielded a strategy paper, which was approved by the Directorate in August. In future, engineering activities at Eawag will be focused on two thematic priorities: process engineering and urban water management. Two departments are being established with different, clearly defined research topics. The Process Engineering department, led by Hansruedi Siegrist, will be concerned with processes in the wastewater and – together with the Water Resources & Drinking Water department – drinking water sector. The Urban Water Management department, headed up by Max Maurer, is to focus on the sustainable management of urban water.

New guidebook on appropriate sanitation in developing countries

Clean toilets save lives. But with billions of people lacking access to basic sanitation around the world, which toilet best meets each person's and family's need? A new guidebook produced by Eawag and the Water Supply and Sanitation Collaborative Council (WSSCC) sheds light on the diverse sanitary systems and technologies which can help people across the developing world lead healthier and happier lives.

Launched in conjunction with the World Toilet Summit & Expo in Macao, the Compendium of Sanitation Systems and Technologies is a unique, all-in-one planning and reference tool on the best, most appropriate and most sustainable sanitation systems and technologies. Abundant information exists about many sanitation technologies, but it is scattered in dozens of books and journals and often not known by the engineers and decision-makers working in sanitation. The Compendium solves this problem by presenting a range of options in one document; it is useful as a starting point to make well informed decisions during the planning process. The Compendium also promotes a systems approach – as sanitation devices and technologies should always be considered as parts of an entire system. The publication may be downloaded free of charge at www.sandec.ch