Chemistry and Water: Challenges and Solutions in a Changing World

A White Paper from the 6th Chemical Sciences and Society Symposium (CS3)

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1 About the Chemical Sciences and Society Symposium (CS3)

The Chemical Sciences and Society Symposium (CS3) brings together some of the best minds in chemical research from around the world and challenges them to propose innovative solutions to society's most pressing needs in health, food, energy, and the environment. This unique gathering boasts an innovative format, aiming to set the course of international science, and rotates among participating nations.

Chemistry and Water: Challenges and Solutions in a Changing World summarizes the outcomes of the sixth CS3 which was held in September 14-18, 2015 in Leipzig, Germany focusing on water, health and the environment, detection of pollutants, recovery of resources, and water treatment. Top water chemists and engineers from China, Germany, Japan, the United States, and the United Kingdom assembled in Leipzig to identify major scientific and technological research challenges that must be addressed on a national and global level to advance the field of water chemistry in a way that best meets societal needs for a sustainable future development.

The CS3 initiative is a collaboration between the Chinese Chemical Society (CCS), the German Chemical Society (GDCh), the Chemical Society of Japan (CSJ), the Royal Society of Chemistry (RSC), and the American Chemical Society (ACS). The symposia series is supported by the National Science Foundation of China (NSFC), the German Research Foundation (DFG), the Japan Science and Technology Agency (JST), the UK Engineering and Physical Sciences Research Council (EPSRC), and the U.S. National Science Foundation (NSF).

This White Paper was compiled and written by science writer Michael Gross in consultation with the German Chemical Society, and reviewed by the 2015 CS3 participants.

2 Executive Summary

Water provision for a world population that is still growing in numbers – while also becoming more urbanised and affluent and living longer – is one of the grand challenges of the 21st century. Climate change affecting hydrological cycles around the world in different ways, from catastrophic droughts to widespread flooding, adds to the problems. To cope with these challenges, chemistry can provide innovations in the fields of water analysis, treatment and resource recovery that can make valuable contributions towards improving sustainable water use and supply security around the world.

At the 6th Chemical Sciences and Society Symposium (CS3), 40 experts from China, Germany, Japan, the UK and the USA came together and discussed these issues covering four core areas: Water, health and the environment, detection of pollutants, water treatment, and recovery of resources from wastewater.

Water, health and the environment are vital on all levels from local problems to global issues and, in a world of increasingly rare resources, are closely interlinked, as expressed in the slogan: "one water, one health, one environment." Sustainable use of water resources and an in-depth understanding of natural processes that attenuate water pollution and can be managed with minimised chemical treatment are prerequisites for safeguarding both human health and a healthy environment.

Pollution from agricultural, urban, and industrial sources threatens the reliable and safe provision with drinking water (water security). While pesticides and industrial chemicals remain significant risks, the wastewater-borne discharge of pharmaceuticals and chemicals from consumer products receives growing attention. Nanoparticles and microplastics add to the burden of anthropogenic contaminants in the environment. While water-borne microbial and viral pathogens are of particular concern in developing countries, their potential threats have to be taken into account everywhere. All of these challenges are exacerbated by global change including climate change, land use change, and the growth, urbanization and demographic shifts of human populations.

Meeting these challenges requires interdisciplinary and inter-sectorial thinking, both in the response to situations of acute crises and long-term planning. This means that chemical expertise and analytical innovation have to be applied in context with medical provision, sociological understanding, and an overarching management of water quality, health and environmental protection. Natural attenuation of pollutants in environmental compartments needs to be better understood both on the catchment scale to maintain the carrying capacity of the natural environment (precautionary principle) and on the treatment scale as an energy-efficient remediation strategy in engineering. On the catchment scale, it is still insufficiently understood in which compartments and under which conditions contaminant turnover occurs most efficiently ("hot spots and hot moments"). In water treatment, the beneficial effect of natural attenuation is only starting to be exploited. Impulses from different directions - advanced and innovative analytical chemistry, bioanalytical high-throughput screening approaches, computational chemistry to foster our understanding of processes and for the design of better degradable drugs, as well as green chemistry to avoid the use of polluting solvents - have important roles to play in overcoming these challenges.

All sustainable water management pillars on the **detection of pollutants** as crucial foundation that requires both robust and simple as well as sophisticated advanced analytical methods. To this end, relevant target analytes, that is, pollutants that constitute a risk must be identified.

Analytical detection includes the monitoring of known chemicals of concern, but also the lookout for emerging ones. On one hand analytical methods need to comply with requirements of national and international regulations such as the European Water Framework Directive. On the other hand we need proactive efforts for the development of innovative analytical tools to identify and quantify so far overlooked water contaminants such as transformation products, nanoparticles, and microplastics.

The development of detection methods should be driven by the growing diversity of substances arising from natural and anthropogenic processes, with the focus on ensuring water quality that is suitable for its desired use ("fit for purpose"). This requires a suite of different tools that include both, detection techniques for specific chemical structures, and broader, effect-based environmental screening techniques.

Across the whole detection chain (from sampling to end point), the standardisation of both chemical analytical methods and bioassays to screen for toxic effects needs to be harmonized to improve the reliability and comparability of results. A prominent research gap are the validation criteria for the identification of transformation products as well as for non-target methods, which still need to be defined.

Ideally, the requirement to detect manufactured chemicals in wastewater should already be considered in product development, in a holistic approach that covers the whole lifecycle of a compound.

Detecting hazards arising from mixtures of chemicals is an important challenge. Current risk assessment considers chemicals one by one. In reality, however, we are facing thousands, maybe millions of chemicals that may contribute to mixture effects, even if their individual concentrations are too low to detect. Therefore, we need to not only to understand how chemicals act together in mixtures but also to develop detection methods that account for mixtures. Bioanalytical techniques, such as cell-based bioassays, yield measures of the impact of the total burden of chemicals and complement chemical analyses of specific chemicals. Toxicity measurements at the molecular level (ecotoxicogenomics) can facilitate the screening. Moreover, recent developments in high-resolution mass spectrometry offer new possibilities to broaden our view to cover compound mixtures including yet unknown micropollutants and their transformation products. This broad approach could become a powerful tool for a more integrative chemical assessment, which can be used for the evaluation of treatment technologies and pollution control.

Water analytics needs the specific development of combined ("hyphenated") techniques (e.g. GC-MS, LC-MS) towards use in environmental research. For example, compound-specific isotope analysis by GC- or LC-IRMS can measure isotope ratios as evidence of contaminant transformation when other approaches fail (e.g. on the catchment scale or in complex engineered systems). In contrast, for routine analysis development of faster, cheaper and easier to use detection methods and instruments, especially for use by non-specialists in the field, should be a priority.

Water analysis data also needs better databases and more integrated data management, including shared analytical data and computational analysis for faster compound identification. Implementing this across countries is a major challenge.

Water treatment has been remarkably successful in coping with growing wastewater streams and improving the water quality in industrialised countries in the second half of the 20th century. In order to address challenges of the 21st century, research and development need to unfold at the basic level (i.e., materials like novel membranes, engineered biology, sorbents, catalysts), intermediate level (i.e., technology transfer, upscaling), and facility level (i.e., integrated processes, energy recovery) for producing safe water in a quality suitable for its intended use. These range from the design of advanced water treatment systems to dealing with complex wastewater streams to the development of more basic, affordable systems to safeguard water supplies in developing countries. The water infrastructure of the future should become more flexible to adapt to local needs and rapidly changing environmental conditions. For instance, both increases and decreases in population can challenge established water infrastructures.

The challenges of financing new water treatment projects and technologies at the interface between public facilities and industry must be addressed.

While some rapidly growing economies like China have the opportunity to adopt new technologies and approaches in establishing their future water management, the use of established wastewater collection, treatment and disposal strategies as widely used in the industrialised world is still being favoured by a rather conservative industry. This conservatism may represent a barrier to innovation for the introduction of new technology and management approaches that might be more appropriate when new challenges arise.

Pilot- and demonstration-scale facilities for all levels of testing new technologies should be established. We need to define cumulative risk-based criteria, which allow us to identify water quality based on potential adverse effects (reduced toxicity, for example). This needs to go hand in hand with the development of effect-based analytical methods highlighted above.

Wastewater treatment and management is in a process of transitioning from a necessity for protection of human health and the environment towards an opportunity for the **recovery** of valuable resources. Resources that are or could be recovered from municipal wastewater include energy (from carbon, nitrogen and heat), a range of metals (e.g. gold, lithium), nutrients (like phosphate and nitrogen), other salts and chemicals, besides but most importantly – water of the desired purity. Focusing on these opportunities can help to provide further incentives for water treatment and make it more attractive for investment. To move forward from the burden of cleaning to the opportunity of mining wastewater streams, implementation and support of the resource recovery concept is needed on all levels, from fundamental research to establishing it in practice.

While a lot of progress has already been made in important aspects, CS3 participants identified a number of specific technologies and capabilities that research and development in this field needs to address, including technologies to produce and extract energy from water constituents, new chemical methods to characterize and monitor composition and variability of constituents in feed stocks of resource recovery facilities as well as methods for an *a priori* assessment of energy yield and potential to use as a feed stock. In addition, the further development of technologies for highly efficient recovery and reuse of nutrients and metals (rather than solely their removal from water streams) plays an important role.

To achieve the overarching goal of sustainable water supplies supporting human and environmental health, the issues of detection, treatment, and recovery of resources have to be addressed in a collaborative way, together with the industrial, agricultural and domestic sources of pollution and the downstream use of the resources recovered. A few promising examples are presented in this White Paper in selected case studies. Spreading these opportunities further to ensure that people everywhere can make efficient and sustainable use of their water resources will require strategic long-term, transnational cooperation informed by the fundamental work from all the related disciplines including engineering and chemistry.

3 Introduction

Water is an essential prerequisite for life on our planet. Humans like all other terrestrial species depend on regular access to clean water for their survival. While 71 percent of the surface of the Earth is covered by oceans, the freshwater resources contained in aquifers, lakes, rivers and glaciers only account for 3 percent of the total planetary water. All the water on Earth combined in a liquid spherical drop would only measure 1,391 km (864 miles) across. The corresponding freshwater drop would barely cover 203 km (127 miles).[1]

Freshwater is a renewable resource, thankfully, as the hydrological cycle keeps producing it. However, the cycle does not necessarily deliver the water where and when it is needed, and thus freshwater at suitable quality is a scarce resource in many parts of the world.

As the world population has expanded exponentially since the Industrial Revolution and grown to numbers that arguably challenge the limits of planetary resources,[2] in many regions water has become a key resource limiting the extent to which communities and economies can thrive. The global demand for freshwater has grown with the spread of industrialisation and the associated living standard. Although in most developed countries stagnant or declining per capita water usages are seen, population growth and urbanisation especially in developing countries has frequently progressed without considering the limitations of the locally available water resources and infrastructures. Thus, related problems are not globally distributed but occur on a local/regional level. This trend is set to continue and it has been predicted to cause widespread water shortages within this century.

Additional challenges arise from pollution, which by the middle of the 20th century has rendered many freshwater courses unusable for human or animal consumption. Since then, wastewater treatment plants and the renaturation of some rivers that have in the past served as drains for municipal and industrial waste, like the river Rhine or river Emscher in Germany, have improved the situation in recent decades. Such improvement is not yet seen globally, however, and in addition chemicals and materials such as bioactive chemicals, antimicrobial resistant microorganisms and microplastics bring new challenges.

Climate change is already affecting the hydrological cycle in many parts of the world. The severe droughts currently affecting California, Australia and certain parts of China, for example, are three of many examples of water scarcity that may be a preview of problems that will soon spread to additional regions. In other areas, the opposite problem can occur as higher ocean temperatures increase the frequency of severe storms, and thus lead to flooding, as has been observed in southern France in the autumn of 2015. In such cases, the existing infrastructure may prove unable to cope with the unexpected changes in water availability.

Human activity may also make extremely strong El Niño events more likely. The current El Niño is already at least as strong as the record event in 1997-98. This weather anomaly affects precipitation patterns around the globe. Indonesia has already suffered severe drought and wildfires. Drier conditions will also affect India, Vietnam, Australia, South Africa, and parts of Chile. Harvest losses in South Asia in particular have the potentials to cause substantial humanitarian crises like the drought in the Sahel region in East Africa in the 1990s.[3]

In trying to secure water resources for themselves, populations have often come in conflict with others and have also caused significant damage to natural ecosystems. For instance, the rivers Euphrates and Tigris in Mesopotamia cross several countries. Dam projects under consideration in Turkey are threatening water security downstream in Iraq on top of the threats by the major political and military conflicts in the region.

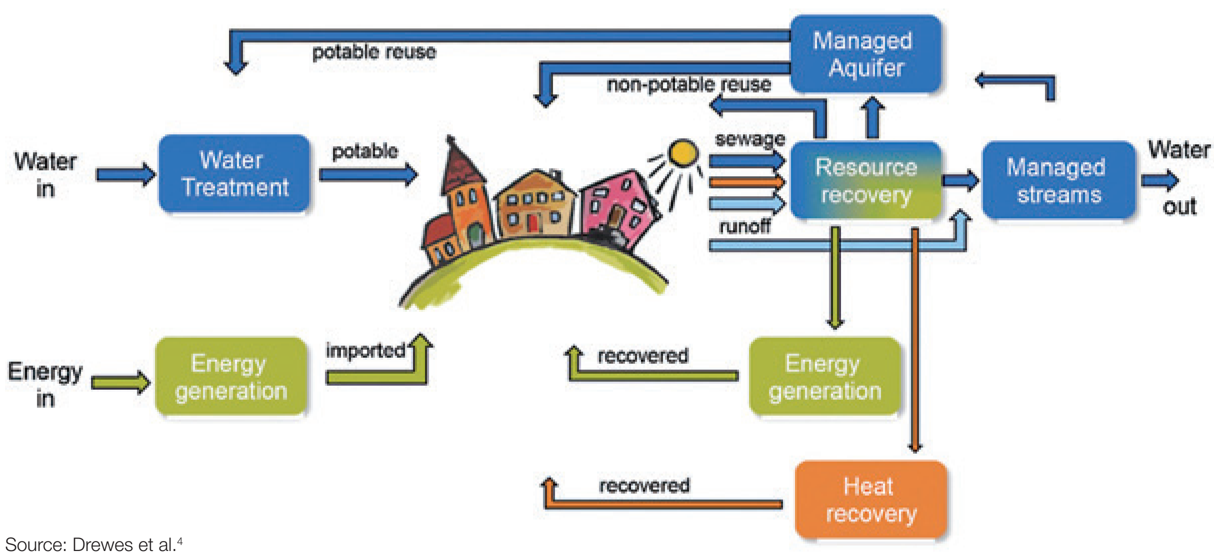
One challenge for the coming decades will be to provide the increasing quantities of freshwater required by a growing population in spite of increasing disturbances from climate change, conflict, and other anthropogenic disruptions of the Earth systems. A second challenge is to ensure the quality of freshwater by mitigation and remediation of pollution and salinization. A third challenge is to extract energy and valuable chemicals from previously "used" water (including closed and semi-closed water cycles), and produce a socially and economically viable source of freshwater for a range of different uses.

Urban infrastructure must be designed and improved to enable a sustainable urban water cycle that links treatment facilities, natural resources, and a reliable provision, and supports addressing these challenges (Figure).

Chemistry can make valuable contributions to addressing and mitigating these challenges. It can offer new and improved solutions to the fields of water quantity, quality and reuse through the development of new methods of desalination of brackish and seawater and through advanced purification of previously used water; advanced analysis and detection of pollutants at levels that can protect human health and the environment, new physico-chemical and biochemical processes that can improve and produce sustainable water reuse, and chemicals and processes that facilitate the recovery of energy and valuable chemicals from used water streams.

Compared to the situation in the 20th century, the role of chemistry is now expanding, as solutions to water issues are increasingly requiring a multi-disciplinary approach which is underpinned by chemistry. An example of this is wastewater treatment, which has been traditionally developed using biological-based solutions. Now, however, chemistry based solutions are increasingly required to recover products in contemporary design of wastewater treatment facilities.

In this manner, the discipline of chemistry can help to ensure a safe supply of clean water, supporting water security, which according to the United Nations is defined as "the capacity of a population to safeguard



Source: Drewes et al.[4]

sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability" (UN-Water, 2013).[5]

The participating scientists at the 6th Chemical Sciences and Society Symposium (CS3) held in Leipzig, Germany, in September 2015 discussed these issues focusing on four core areas:

1) Water, health and the environment,
2) Detection of pollutants,
3) Water and wastewater treatment, and
4) Recovery of resources from wastewater.

This White Paper summarises the discussions held at the symposium and records recommendations for research and policy improvements that could help guide sustainable water management.

4 Water, health and the environment

Water, environmental health and human health are intrinsically linked. Their protection is vital on all levels from local problems to global issues. In a world of increasingly scarce resources, this interdependence is most vividly captured in the slogan "one water, one health, one environment." The vision expressed at the symposium is that to achieve an ideal, sustainable use of water resources, and to safeguard both human health and a healthy environment, we will need an in-depth understanding of natural processes for contaminant attenuation that can be managed with an appropriate use of chemical treatment.

4.1 The status quo

Currently, more than 40 percent of the world population are experiencing water scarcity. That includes one fifth of humanity living in areas with physical water scarcity, i.e. absence of sufficient freshwater resources, and another quarter exposed to economic water shortages, i.e. living in countries that lack the infrastructure to make adequate use of available resources.

Climate change and deforestation can threaten the natural water supplies of areas not previously prone to drought. Unusual droughts are currently impacting California and have reportedly contributed to the current conflict in Syria.

Lack of water supply, sanitation and hygiene (WASH) takes a significant toll on health and well-being and comes at a large financial cost, including a sizable loss of economic activity. As of 2014, 750 million people did not have access to safe drinking water. According to WHO figures (2015), an estimated 500,000 people per year still die from diarrhoea caused by contaminated water.

Natural ecosystems also suffer from a decline in water availability and quality, due to man-made alterations of water courses, pollution and over-use. Entire lakes have dried up, causing the loss of habitat for wildlife, and ecosystem services are at risk.

The post-2015 Sustainable Development Goals (SDGs) now replacing the Millenium Development Goals (MDGs) from 1990 expand the water agenda to include the industrialised world and include targets like ecosystem protection, limits to pollution and rapid response to water-borne hazards.

Still, the current supply is insufficient globally and the demand keeps growing, challenging utility providers and policy makers to catch up. As populations increase, urbanization grows and climate change effects are felt more strongly, there will be an increasing need to rely on water sources of lower chemical quality to meet the water demand, in both developed and developing countries.

4.2 The challenges ahead

Globally, the world will have to produce water, food, and energy for 9-10 billion people in 2050.[6] While this is considered possible, it will require a boost of innovation and global cooperation.

Global changes including climate change, land use change, globalised trade and the growth, migration and demographic shifts of human populations are exacerbating the challenges in this field at the local level. The lack of international governance of water-related issues seriously hinders strategic responses and damage limitation.[7]

Water is abundant in some places but scarce in many others, motivating large-scale water transfer projects, which may solve supply problems but may also have unwanted impacts (for example the Colorado River in the US).

Threats to the reliable and safe provision of drinking water include pollution from geogenic, agricultural, urban, and industrial sources.

Pharmaceuticals, industrial chemicals and chemicals from consumer products in wastewaters receive growing attention as they may escape detection and treatment and display potential adverse effects on environmental and human health. This has been demonstrated, for instance, for some hormones and endocrine disrupting chemicals (EDCs). EDCs are an issue because they may lead to subtle effects on the ecosystem already at concentrations in the nanogram level[8] and they may act together in mixtures at very low concentrations, too low to be individually detectable, but measurable as mixture effect.

Emerging chemicals are perceived as a concern, with some evidence of effects in the aquatic environment. Addressing this challenge requires streamlined toxicity screenings, improved risk assessments, and a better understanding of the total exposure to and effects of mixtures. While a lot of research in this direction is already underway e.g. in the UK, the US and in EU-sponsored programmes, more of it is still needed on cumulative exposures, endocrine disruption at very low levels, and how to assess mixtures of chemicals to sensitive populations and life stages.

Pesticides and industrial chemicals remain significant risks on a global scale, just as nitrate mostly from agricultural activities and arsenic and fluoride from geogenic sources. At the same time, the locations and conditions where these chemicals are attenuated (“hot spots”, “hot moments”) on the catchment scale are still little understood.

Microscopically small plastic particles (microplastics) have in recent years received attention due to their possible negative impact on the environment. These particles mostly arise from the breakdown of larger plastic items in rivers and oceans, but there are concerns about microparticles contained in cosmetics and from synthetic clothing fibres that can be washed into the domestic wastewater system. Therefore, the use of microparticles in consumer goods has been criticised and is now being reduced. Plastic pollution was initially identified as a problem in the oceans, where most of the plastic waste that escapes proper treatment will end up and accumulate in the major ocean gyres. However, recent research has also discovered microplastics pollution in freshwater bodies such as North America’s Great Lakes,[9] Lake Garda in Italy,[10] and even in Arctic ice.[11] As progress in technology leads to further miniaturisation, it is possible that many other kinds of micro- and nanoparticles will find their way into water systems and might have new and unknown impacts.

Water-borne microbial and viral pathogens continue to pose serious public health problems in many countries. For example, in 1996 an outbreak of diarrhoea linked to drinking water supplies affected more than 8,000 of the around 10,000 residents of the town Ogose in Japan. Norovirus and other pathogens are frequently detected in lakes such as South Lake Biwa/Japan, which is used for drinking water, recreation and fishing. Flooding caused by the 2011 tsunami also caused widespread contamination problems. In northern England, an outbreak of cryptosporidium occurred in 2015.

4.3 Why is chemistry needed?

The discovery of new chemistry will improve public health through better access to safe drinking water treatment and sanitation, while overcoming economic water scarcity in a manner consistent with the United Nations’ post-2015 Sustainable Development Goals (SDGs).

Meeting these challenges requires collaborative thought and action, both in the response to acute crisis situation and long-term planning. Development and regulatory approval of novel pharmaceuticals, for instance, should ideally not only take into account

Case study Germany: Rebuilding a river environment

Untreated wastewater streams have gradually killed many river environments in the early and mid 20th century. In Germany, a large scale project to restore one of the worst affected rivers is now approaching completion.

Until the early 19th century, the river Emscher was a fairly unremarkable little river winding its way through 109 km of rural landscape from its source at Holzwickede until it joins the river Rhine near Duisburg. Its misfortune was its location as the long axis of the Ruhrgebiet area, running between the parallel rivers Lippe and Ruhr that define the borders of this zone, became heavily industrialised with coal mines and steel foundries. Due to the frequent earth movements above the deep coal mines, it was impractical to build large networks of closed sewers. Thus, the river Emscher, with its central location, became the open air sewer of a large area of heavy industry and rapidly growing cities. As early as 1882, a letter from a group of concerned citizens to the Prussian parliament documents the dying of the river and the unhygienic circumstances when there was flooding into the cities.

Throughout most of the 20th century, the Emscher, now largely canalised in standardised concrete troughs, was legendary for its pungent smell and toxic water, and there was no trace of life left in it. Due to the ground subsidence caused by mining, the river could no longer feed into the river Rhine at the original location and had to be diverted to a new location further downstream, at lower altitude.

After the demise of the coal mines, however, the situation changed in that it was now more feasible to build a closed canalisation parallel to the river. Starting in 1992, a huge regeneration project, currently estimated at € 4.5 billion, took off to establish wastewater treatment for all outflows that go into the river and to channel untreated waste separately from it, leading it into one of four major treatment plants lined up along the course of the river. Some stretches of the river have already been cleaned up and renatured. The closed sewage canal is due to be completed by 2017, and the whole project, including renaturation of tributaries, is expected to finish by 2020.

their efficiency and side-effects, but also any metabolites that are likely to be excreted, as well as their fate. Similar considerations also apply to chemicals in disinfectants and cleaning products. Existing 'old' pharmaceuticals should be re-evaluated in the context of their environmental risks. At the same time, sustainable solutions are still needed for addressing more 'traditional' chemical contaminants (e.g. arsenic, nitrate, atrazine) in low-income settings as well as in highly developed agriculture.

- Chemical research should be connected to relevant insights from other fields, including ecological and epidemiological studies. Thus, chemical insights and analytical capability have to be applied in context with medical provision, sociological understanding, and environmental management surrounding water, health and the environment.

- Link cutting edge bioanalytical research (e.g. selective and sensitive high-throughput techniques) to water chemistry and treatment research, to ensure that bioassays yield information that is useful to water science.

- A better understanding is needed of "hot spots" and "hot moments" of natural pollutant attenuation in all environmental compartments both in order to maintain and optimize the carrying capacity of the natural environment (precautionary principle) and as an energy-efficient bioremediation strategy in engineering.

- Computational chemistry can be a useful tool to estimate the potential toxicological importance of emerging contaminants for which there is no animal or human health data available and thereby prioritise emerging chemical contaminants for further monitoring and experimental research.

- Ideally, pollution would be avoided. Green chemistry can help to reduce e.g. the use of solvents in industry and thus the pollution with chemicals.

5 Detection of pollutants

The ability to detect any pollutants that may be present in water is a crucial foundation of all sustainable water management, environmental health, and maintaining a safe drinking water supply. It requires a broad range of tools including robust and simple as well as sophisticated advanced analytical methods. It also needs to continuously adapt as new types of contaminants are produced as a consequence of new technologies. Chemistry should be at the forefront of innovation to deliver novel cutting-edge techniques allowing for fast and accurate identification of new chemical threats.

5.1 The status quo

Progress in analytical techniques over the past decades has made it easier to detect many different compounds at very low concentrations. There have been some exceptional analytical developments and applications in the environmental field, e.g. mass spectrometry (omics) and sensing approaches. However, to manage water resources sustainably, one needs to understand which pollutants constitute a risk, and what is relevant to monitor. Monitoring pollutants that may contaminate water has been a rapidly moving target, as the number of commercially deployed chemicals has grown and the use of substances such as pesticides has spread to developing countries.

5.2 The challenges ahead

The unstoppable growth in the number of chemicals that are produced and used in industrial production, and/or in consumer products poses a formidable challenge to the detection of contaminants in water. Due to rapid progress in electronics, nanotechnology, and other areas of science, new pollutants and products or their environmental transformation have arisen. While major industrial markets have legislation in place for the registration and testing of new substances, these systems may be overwhelmed by the introduction of thousands of new substances and transformation products and also have to catch up with “orphan” and legacy chemicals.

Globally, the spread of intensive agriculture and aquaculture, the increasing use of chemicals in everyday life (e.g. in personal care products) and the advent of emerging pollutants has also increased the demand for better detection methods.

The predicted growth in demand for safe water brings another challenge. This growth will increasingly lead to direct re-use and/or desalination plants. Therefore, the purity of the water delivered to the consumer will depend not just on natural processes but also on the detection and removal of all undesirable components.

Legislation can also be a driver in expanding the requirements for detection. For instance, the EU water framework directive (2000/60/EC and 2013/39/EC) identified 45 chemicals, including heavy metals, industrial chemicals, pesticides and others, as priority substances for detection, due to their potential impacts on the ecosystem.

Further challenges arise from the complex mixtures of chemically-diverse substances found in environmental and water samples at very low concentrations. The effects of toxic substances in mixtures on biological systems are complex, they may act independently or additively, or interact in a complex manner leading possibly to synergistic or antagonistic effects. Therefore, mixture toxicity cannot be derived from simple concentration measurements nor toxicity assays for single compounds. *In vivo* bioassays can be applied to environmental mixtures but their use is prohibitive and counters the animal welfare considerations. A new approach examining the toxicity of emerging contaminants on a cellular and molecular level with high-throughput *in vitro* assays, can significantly speed up the screening of environmental samples. The emerging field of ecotoxicogenomics, proteomics and metabolomics show some promise for the future.[12]

Detection includes the monitoring of known problems, while being alert for and aware of new paradigms to deal with emerging ones (targeted and non-target analysis).

On one hand, to keep the known problems under control, analytical methods need to be focused on the specific requirements of national and international regulations, such as the European Water Framework Directive. On the other hand, proactive efforts are needed for the development of innovative analytical tools to identify and quantify water contaminants that have been overlooked so far. Both aims require innovative pre-concentration techniques and analytical instruments as well as bioanalytical methods with high accuracy, selectivity, sensitivity, and precision.

Successful detection and elimination of a growing number of pollutants in times of growing demands requires system-level cooperative thinking. Thus, understanding of the environmental impacts of newly manufactured chemicals should be integrated into their design. Developers of a new chemical must consider not only its analysis and detection but also how the chemical will interact with the environment.

Detecting dangers arising from the cumulative effect of compounds present in mixtures is an important challenge. Current risk assessment tends to consider chemicals one by one. In reality, we are facing thousands, maybe millions of chemicals that may contribute to synergistic effects, even if their individual concentrations are too low to detect.

5.3 Why is chemistry needed?

Chemical research and expertise can help to improve and adapt detection methods across the procedural chain from sampling through to data management.

Chemists have already developed techniques that provide sensitive and selective measurements, often in real time, of complex environmental matrices. Researchers are now aiming to undertake screening with an ultimate goal of full profiling of the environmental matrix.

- Standardisation of chemical analysis methodology, as well as bioassays or molecular-level screening methods must be prioritised in order to improve the reliability and comparability of results. Validation criteria for the identification of transformation products, for the analysis of nanoparticles and microplastics as well as for non-target methods still need to be defined.

- The development of detection methods should be driven by the growing variety of substances arising from both natural and anthropogenic processes, with the focus on ensuring water quality that is suitable for its desired use (fit for purpose). This approach requires both specific detection techniques and broader environmental screening techniques. Determination of the needed tools must be driven by the environmental issue being examined.

- Ideally, the requirement to detect and capture manufactured chemicals in wastewater should already be considered in product development, in a holistic approach that covers the whole lifecycle of a compound. For newly developed molecular compounds such as pharmaceutical proteins or nanoparticles, Material Safety Data Sheets (MSDS) must contain information that facilitates detection and removal of the compound and/or its transformation products from water.

- More research is needed in the area of chemical mixtures. Chemists need to develop multi-step analytical techniques that allow separation and identification of the numerous components of these complex mixtures. We need a better understanding of the mixture effects of chemicals on human and environmental health. Therefore, the trans-disciplinary collaboration with toxicologists and modellers will play an important role.

- Bioanalytical techniques, such as cell-based bioassays, yield measures of the impact of the total burden of chemicals and complement chemical analyses of specific components. Moreover, recent developments in high-resolution mass spectrometry offer new possibilities to analyse yet unknown micropollutants and their transformation products. However, there are still major needs to develop new strategies for validation and standardization, as well as for data evaluation and interpretation that will promote our ability to predict the impact of new chemicals and materials on human health and the environment.

- In terms of instrumentation and methods, GC-MS and LC-MS technologies are in widespread use and have been for many years. New developments such as compound-specific isotope analysis by GC- or LC-IRMS can exploit information from natural abundance of isotopes as evidence of contaminant transformation when other approaches fail (e.g. on the catchment scale or in complex engineered systems[13]). Moreover, 2D- approaches (LCxLC) and ion mobility mass spectrometry could improve the selectivity for the analysis of structurally closely related compounds in complex matrices. At the same time, the application of new discoveries in material science, electronics, computational chemistry, and other scientific fields into developing a new generation of analytical instruments should be a priority.

- Scientists also need to develop better methods for analyses that are not directed at a specific target substance. The open question is how to compare and validate non-target analyses and how to evaluate, store, and handle data for unknown pollutants. At the moment it is hard to identify compounds, and we need to develop strategies for inter-laboratory comparisons and new in-silico methods for a better prediction of MS spectra.

- To improve analysis of water pollutants, better databases and more integrated data management, including shared analytical data, open access resources, and computational analysis are needed. Comparability of sampling methods is another important aspect. Implementing these recommendations across countries is a major challenge.

- The development of faster, cheaper and easier to use detection methods and instruments, e.g. real-time sensor networks enabling comprehensive environmental monitoring and fast response, especially by non-specialists in the field, should be another priority.

6 Recovery of resources

As we enter the 21st century, used water treatment processes should be viewed as preparing water for reuse, and regarding chemicals and materials in the water as sources for recovering useful energy or materials. Separating grey water into pure water and inorganic and organic chemicals is not only a necessity for the protection of human health and the environment, it should also be seen as an opportunity to recover valuable resources. In a sustainable, environmentally friendly economy, all resources contained in a wastewater stream, including water, should ideally be recycled.

Energy should also be regarded as a resource to be retrieved from wastewater. This is done today by recovering methane from wastewater solids treatment. However, other ways of harvesting the energy content of used water may be more efficient than those currently in use, for example anaerobic digestion (or newer processes such as anaerobic membrane bioreactors), where energy is truly harvested through the production of methane. Developing and applying these methods could convert used water to reusable water with the added advantage of transformation into an energy producing process.

The most abundant resource to be recovered is of course water of the desired purity. The water quality to be achieved from the treatment process is dependent on its end use, whether destined for release into natural systems, irrigation in non-food or food agriculture, reuse within an industrial process or for potable reuse as drinking water.

Materials that are or could be recovered already include a range of metals (e.g. gold, lithium), nutrients (e.g. phosphorus, nitrogen, potassium), other salts and chemicals, and – more controversially – possibly even some organic molecules such as steroid hormones, pharmaceutical drugs or lipids.

Focusing on these opportunities can help to provide further incentives for water reuse and make it more attractive for private and public investment.

The colours of water	
Grey water:	all wastewater from domestic or office sources that does not contain faecal contamination, i.e. all streams except those from toilets.
Black water:	wastewater that does contain discharge from toilets.
Green water:	water naturally stored in soil that is taken up by plants or evaporates.
Blue water:	water extracted from watercourses, wetlands, lakes and aquifers.

6.1 The status quo

Currently, the situation regarding the management of biosolids (sewage solids) differs widely globally and is very country specific. Furthermore, it is also dependent on whether municipal or industrial wastewater/sludge is considered. In many countries the majority of biosolids are land applied in agricultural settings, incinerated, or sent to landfill, in some countries a fair amount of resource recovery takes place. However, some treatment plants are demonstrating the potential for resource recovery. Thus, the 175 kW Demosofc fuel cell generator installed at a treatment plant in Turin, Italy, generates enough energy to supply a quarter of the plant's need. The fuel cell runs on biogas resulting from anaerobic digestion in the plant. Similar prototype plants using energy recovery are running at Osaka, Japan and Strass, Austria, as well as in several locations in the UK.

Phosphorus and nitrogen are recovered in some innovative water treatment plants, including Stoke Bardolph and Minworth in the UK (see Case Study on Anammox, page 25).

Elsewhere, the recovery of activated carbon, gold, silver, palladium and platinum from sewage sludge has been demonstrated. One water treatment plant at Suwa, Japan, has reportedly recovered 2 kg of gold per tonne of ash from sewage incineration. This suggests the precious metal is 50 times more concentrated in the ash than in the ores extracted from some of the world's most productive mines.[23] This content may be unusually high, as the catchment of the plant includes industrial sites that use precious metals. At another treatment plant run by Toyota at Nagano, an annual turnover of 70 tonnes of ash has yielded 22 kg of gold. Researchers in Japan are actively developing new approaches to the recovery of other valuable materials from wastewater including sewage (see Case Study page 26).

6.2 The challenges ahead

In the very near future, some resources must be recovered from used water to avoid supply shortages and/or political tensions over finite, natural supplies. These include most notably phosphorus, as the principal mineral reserves of the element are found in a disputed region (Western Sahara) and man-made or naturally induced shortages are possible with what is largely a single source supply. Moreover, all efforts to make the global economy more sustainable and circular would have to be based on the recovery of resources such as phosphorus that are currently going to be wasted on a gigantic scale.

Recovery of minor metals from sewage is possible, but requires methodological improvements to become more cost-efficient. The most promising metals for recovery are silver, copper, gold, iron, palladium, manganese and zinc. Researchers in Japan are also looking at the potential of much rarer elements including selenium, tellurium and vanadium.

In the recovery of water for direct reuse, as well as with any substance that comes in contact with the food chain, the challenge will be to provide strong confidence of hygienic purity of the materials recovered. Moreover, public perception and acceptance of related projects/technologies will be of significant importance.

The strategic goal in this area should be to reframe the entire treatment process and to move forward from the burden of cleaning up used (waste) water streams before disposal, to mining them for their valuable contents. Thus, implementation and support of the resource recovery concept is needed on all levels, from fundamental research to establishing it in practice.

To move forward the reusable water concept, the following key points must be considered:

- Resources in used water include water, energy, nutrients, metals, salts and other valuable materials.
- Resource recovery facilities must strive towards energy-positive operation and resource recovery needs to consider system-level implementation while addressing multiple objectives and scales.
- The discovery of new chemistry, including the development of advanced materials, to extract and utilize recovered or produced materials from used water must be encouraged. New chemical and process engineering pathways and design principles must be developed to facilitate resource recovery.
- Different techno-economic approaches to identify best methods and cost benefit, appropriate to the environment e.g. size, source – municipal vs industrial, drivers/enablers/inhibitors e.g. legislative, governmental, infrastructure limitations – explain why each of the 5 countries represented at this meeting is different in what has been done to date.

- R&D towards implementation and provision of an adequate institutional framework and marketing to increase the use of recovered materials is necessary.

Ultimately, an efficient implementation of resource recovery from used water flanked by a proper risk assessment of recycled products could be a major step towards the goal of a circular economy.

6.3 Why is chemistry needed?

While considerable progress has already been made in many important areas, CS3 participants identified a number of specific technologies and capabilities that research and development in this field needs to address, to facilitate further progress, including:

- technologies to produce and extract energy from water constituents with consideration of energy storage and approaches compatible with contemporary energy grids;
- new chemical methods to characterize and monitor composition and variability of constituents in feed stocks of resource recovery facilities; inline sensing as well as off site;
- accommodating variability of the potential resource in the waste and influence on processing to extract and purify.
- methods for an *a priori* assessment of energy yield and potential to use as a feed stock;
- technologies that will facilitate highly efficient recovery and reuse of nutrients (rather than solely their removal from water streams) with consideration of bioavailability and chemical form;
- technologies related to facilitate highly efficient recovery and reuse of metals with consideration of their speciation, purity and value;
- new chemical methods and technologies to facilitate materials production;
- techno-economic new materials and engineering processes to extract energy from organic matter in the used waters, to make the overall process net energy positive;
- analytical methods for crude matrices and technologies to assess products and their potential as a feed stock (e.g. for bioplastics, enzymes, bioactive chemicals production) for recovery of chemicals (coagulants) or conversion into other products.

Case study UK: Simplifying the nitrogen cycle

A bacterial process discovered less than 20 years ago can help to remove nitrogen compounds from water more efficiently.

The cyclic path which a given nitrogen atom from the air may take through fertiliser, plants, animals or humans, wastewater, and eventually back into the air can be incredibly complex, not least because it switches between the fully reduced state (in ammonia) to the fully oxidised state (in nitrate) several times. The Haber-Bosch process of making nitrogen from the air usable, for instance, produces ammonia, which then is oxidised to make nitrate fertilisers. At the tail end of the pathway, ammonia in wastewater is similarly oxidised to nitrate before it is reduced back to molecular nitrogen.

The surprise discovery of anaerobic ammonia oxidation (anammox) in the mid 1990s and its development as an industrial scale water treatment process offered the opportunity to reduce the complexity and the cost of removing ammonia from wastewater and reconverting it into molecular nitrogen. In the first step of the anammox process, Nitrosomonas bacteria convert part of the ammonia to nitrite, then anaerobic (anammox) bacteria react nitrite with the remaining ammonia to form molecular nitrogen. This second step occurs on a large scale in oxygen-depleted parts of the oceans and is estimated to account for between one third and half of the natural production of nitrogen gas.

Following a prototype plant developed at Delft, two more anammox treatment plants were developed in the Netherlands. In the UK, a major treatment plant at Minworth near Birmingham, serving a population of 1.7 million, has recently adopted this approach. The plant was optimised to achieve drastic phosphorus removal in combination with nitrogen removal using anammox. It achieved a capacity of 50 tonnes of nitrogen removed per day, representing more than 90 percent of the N present in the wastewater stream.

The process was shown to have a lower whole life cost than conventional methods of ammonia removal, as well as taking up less space and requiring less aeration and chemicals. The plant also produces less sludge and carbon dioxide than conventional methods, based on the fact that the anammox bacteria are relatively slow growing. The plant became fully operational in 2013.

Case study Japan: Mining the sewage sludge

What if the wastewater stream is not a burden to be disposed of but a resource to be mined? Japan has the most advanced facilities to mine the biosolids left after wastewater treatment and incineration of the sludge.

A facility at Shimane is already recovering phosphate from sewage sludge, crystallising it as magnesium ammonium phosphate (MAP). At least two facilities are known to recover gold from the ashes of incinerated sludge, both recovering enough of the metal to make the process profitable. However most of the sewage in Japan (77 percent) remains unutilised, ending up just being disposed of as waste.

Existing physico-chemical separation methods are not very well adapted to the task of specifically extracting one ion or compound present at low concentration in a highly complex and poorly predictable mixture. Moreover they often require substantial amounts of energy and/or additional materials, resulting in a poor economical and ecological balance overall.

Therefore, researchers in Japan are now investigating biological methods for the recovery of valuable elements, including the microbial metal metabolism. Microbes can leach materials from solid, volatilise them, adsorb them or mineralise them. These phase transfer processes may involve chemical transformations such as oxidation / reduction, methylation or hydrogenation.

As an example of microbial element recovery from wastewater, Michihiko Ike and colleagues at Osaka University have developed a process to mineralise selenium. This element is present in industrial wastewater streams e.g. from copper production. In its soluble forms such as selenates and selenites it is highly toxic and should therefore be removed. It is also sufficiently rare and valuable to warrant its specific extraction from wastewater and subsequent recycling. Existing technologies are quite inefficient at recovering it.

The prototype technology developed at Osaka uses the bacterial strain Pseudomonas stutzeri NT- I to reduce the soluble selenium compounds to elemental selenium, Se(0). This gram-negative aerobe was originally identified from biofilms present in drains carrying waste water containing selenium.[1] Remarkably, the bacterium secretes Se(0) as nanoparticles, which are insoluble and harmless and can be easily removed from the liquid medium. A pilot scale reactor was built to demonstrate the potential of this technology. The researchers also investigated the option to recover selenium via a methylated gaseous product that can be easily trapped in from the gas phase.[2]

Bacterial reduction to a less soluble state could similarly be applied to a range of other metals including: chromium, vanadium, tellurium, palladium, platinum, uranium and technetium. Large-scale application of such recovery methods could turn cost-intensive wastewater treatment into a new profitable mining operation.

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7 Water and wastewater treatment

Nature does a lot of hard work in producing water of sufficient quantity and quality for humanity, by distilling sea-water to turn it into fresh water, and removing many contaminants by filtration of water through soils and sediments to yield potable water abstracted from aquifers and springs. Given sufficient time, biological degradation that occurs naturally within the existing hydrological cycle will remove most natural pollutants to a sufficient extent. It is the excess burden on these systems by enormously disproportionate populations relative to the capacity of the environment – especially in arid regions – and the release of anthropogenic chemicals that produce the greatest concerns and challenges for the future.

Until the 1900s, disposal of wastewater was largely based on the faith in the natural purification power of water streams combined with the dilution factor of large rivers and oceans. Only when the accumulation of pathogens and industrial pollutants in rivers and the bioaccumulation of toxic metals like mercury in the food chain were recognised as a problem, did the necessity of treating wastewater before release become widely accepted.[14]

7.1 The status quo

Water treatment plants are used to produce a water quality suitable for drinking. Wastewater treatment plants are used to treat used water to a level suitable for discharge into the environment, where it becomes part of the natural hydrological cycle again. In industrialised countries, the treatment of used water has been remarkably successful in improving water quality in rivers since the 1970s. In other locations, however, 80 percent of the world's sewage is still discharged into the environment without treatment.[15]

The desalination of brackish water and seawater is increasing rapidly all over the world with more plants in design and construction every day. Although desalination is energy intensive, in some regions it is the only source of water available, and desalination by reverse osmosis often requires less energy than transporting freshwater over long distances.

In comparison to this highly energy-intensive treatment of seawater, used water streams offer the potential to be transformed from treatment plants that consume energy, to chemical factories and clean water generators that can also produce net energy. In addition, they should become a source of nitrogen and phosphorus for agriculture. This can reduce nutrient pollution of inland waters, and in the case of phosphorus reduce the world-dependence on a few, finite sources of minable phosphate rock. Wastewater also contains more energy (in the form of organic carbon and nitrogen) than is needed to recover this energy even with current technologies, and thus there is an untapped potential to obtain net energy based on the organic matter content in the water.

7.2 The challenges ahead

As the demand for clean water grows, water and wastewater treatment have to expand their reach to keep emerging contaminants from human consumption and entering the environment. New materials have to be developed, including membranes, sorbents, catalysts, and microbial strains for biotechnological processes to remove or degrade unwanted chemicals and materials in the water. At the intermediate level, technology transfer and upscaling are the key demands. At the facility level, integration of chemical and biological processes with resource recovery concepts needs to be optimised. These facilities range from advanced water treatment systems needed to deal with complex water streams, to more basic, affordable systems that safeguard water supplies and protect human health in developing countries.

The water infrastructure must become more flexible to adapt to local needs and rapidly changing environmental conditions. For instance, both increases and decreases in population can challenge established water infrastructures. Global trade allows manufacturing in one region to generate pollution in a distant region, effectively exporting water pollution problems.[7]

Water challenges present opportunities. The removal of emerging contaminants like endocrine disruptors and numerous other substances from used water, before they can enter into the environment, has become a prominent issue. Prescription drugs and illegal substances like cocaine are found in used water in detectable quantities, to an extent that detailed analysis of these contaminants has become an opportunity as a valuable source of public health data.[16] Hydraulic fracturing (fracking) has provided a method for extracting methane from subsurface formations, but heavily contaminated production fluids from these mining operations pose additional challenges. In some regions, there is insufficient water for both fracking and agriculture.

Important issues identified in this field include the development of more cost- and energy-efficient technologies (i.e., novel membranes, catalysts, absorbents), investment for scale-up of new methods emerging from fundamental research, and a comprehensive understanding of water systems, including protection of source waters, flexible and minimal use of chemicals, and adaptation of treatment to the intended use of the water (fit for purpose).

The challenges of overcoming institutional barriers, financing and maintaining infrastructure, aging infrastructure as well as financing new wastewater treatment projects and technologies at the interface between public facilities and industry must also be addressed.

Some rapidly growing economies like China have the opportunity to use new technologies and approaches in establishing new water management concepts when they develop new cities (see Case Study on p. 20). China has launched a national programme on water pollution control running from 2006 to 2020, and covers all aspects of water management, from preventing pollution at the source to environmental restoration.

Recent scientific developments show promise for economically reducing nutrients in used water and energy savings in water treatment plants, such as using anammox (anaerobic ammonia oxidation)[17] for nitrogen removal and surface-modified biochar[18] for sorption of nitrogen and phosphorus from polluted water. Such technologies can help to greatly improve the efficiency of wastewater treatment plants. Further research and development into new approaches should be encouraged.

Established wastewater treatment processes as widely and successfully used in the industrialised world are often favoured by a change-adverse industry. This conservatism may represent a barrier to innovation and the introduction of new technology and management approaches required when new challenges arise.

7.3 Why is chemistry needed?

Chemists already have an important role to play in selecting of appropriate treatment and in understanding treatment processes. In addition they can help to:

- develop improved methods for energy-efficient water desalination and re-use treatments;
- invent new materials and approaches for energy extraction from used water, in order to make used water treatment plants energy sustainable or net energy producers;
- develop novel membranes[19] for efficient removal of emerging contaminants, seawater desalination, and as methods to capture nutrients;

Case study China: Complete water cycle management

With its rapidly advancing economy and urbanisation, China has the opportunity to create new models of urban water cycles designed for sustainability.

In its glory days as capital of the Tang dynasty (AD 618-907) and starting point of the Silk Road, Xi'an did not suffer from water shortage, as it does nowadays. There was more than enough water running down from the nearby Qinling Mountains and feeding eight rivers passing near the city. However, due to climate change and fast development, as well as over-utilization and improper management of the water resources, the ancient beauty of "eight rivers surrounding the capital" disappeared to a great extent and deterioration of water environment has become a major problem restricting the sustainable development of the city.

The "eight-rivers" project is a major investment to restore sustainable water management to the city. The $1.58 billion project includes the creation of 28 lakes, including some surrounded by parks designed to imitate Tang dynasty landscapes known from ancient illustrations. It follows an integrated plan that uses all kinds of water – natural precipitation, rivers, and water reclaimed from wastewater streams to create a quasi-natural water cycle in the urban environment and provide both reliable water resources and attractive landscapes for leisure activities.

By 2012, half the planned lakes were already completed, and the remaining ones are due to be built within five to ten years. It will serve a still growing conglomeration of over eight million inhabitants.

In a separate model project, a university campus in the eastern suburb of Xi'an serving 30,000 to 35,000 people is equipped with its own reservoir as part of a lake landscape and a wastewater treatment and reclamation plant supplying reclaimed water for toilets, gardening and the lake, while the limited amount of groundwater is used only for drinking water supply.

Analyses showed that storage of the reclaimed water in the reservoir lake reduced the water's inorganic salt content and its toxicity at various trophic levels, though organic content slightly increased in the lake water. The mechanisms behind these changes in the water cycle are still under investigation.

Experiences in China show that quasi-natural water cycles like these can augment the capacity of available water supplies and improve the water quality.

Further reading: X. C. Wang et al., Water Cycle Management: A New Paradigm of Wastewater Reuse and Safety Control, Springer 2015.

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- advance continued adaption of natural treatment processes for technical use, such as anammox, surface-modified biochar-[18] and iron-based[20] treatments, biofuel production, and solar energy-based electrochemical treatments.[21,22]
- define cumulative risk-based criteria, which allow fast screening and identification of toxic compounds that impair water quality (utilizing ecotoxicogenomics, for example).

With all treatment technology, one has to keep in mind the potential benefits of recovering resources from the materials removed (see next section) as well as the cost benefits. Pilot- and demonstration-scale facilities at all levels of testing of new technologies should be established.

Case study USA: Producing drinking water

Where natural water sources are sparse, as in the arid south west of the US, conversion of wastewater and/or salt water into drinking water may become necessary.

We all like our drinking water to come from natural sources, based on the assumption that the environmental filters of the natural hydrological cycle are Nature's perfect cleaning regime. Thus it is only in times of need that people resort to cleaning up salty, brackish or wastewater to turn it into drinking water.

This need has hit parts of Texas after a prolonged severe drought had depleted the groundwater supplies to a problematic level. When the town of Big Spring, Texas, considered its options, indirect potable reuse (IPR) – letting treated waste effluent percolate through natural buffer systems to replenish the aquifers – wasn't an option as the heat would have evaporated most of that water. Therefore, the local water utility built what became the first direct potable use (DPR) water facility in the US, which opened in May 2013. It can treat up to two million gallons (9.1 million litres) of wastewater per day to drinking water standard.

In practice, however, the cleaned-up water produced is mixed into another stream of raw water from natural sources, and the mixture then gets the standard filtering procedures for drinking water.

Shortly afterwards, a second Texan community, Wichita Falls, embarked on a DPR project. In this case, however, the required treatment facility was already in place and served to clean up brackish lake water. The town only had to invest into a pipeline to connect the wastewater treatment plant to the existing drinking water production plant.

In the pioneering communities in Texas, good communications work combined with the obvious situation of need produced by prolonged drought ensured a broad acceptance of the DPR water. In another Texas town, however, similar plans were put on hold after a backlash in the public opinion.

Other US states and countries affected by water scarcity are watching this development with interest. California, which has suffered from extreme drought for the last five years, is already using indirect potable reuse for more than 50 years, in that recycled water is used to replenish aquifers. Further IPR and DPR schemes are under consideration for treated wastewater streams that have so far been discharged into the Pacific.

Elsewhere in the world, direct treatment of contaminated water to produce drinking water is also part of the routine in emergency responses and in acute drought crises. Depending on the situation, desalination plants may also offer a solution, although the energy cost of the process is often the limiting factor.

8 Outlook

To achieve the overarching goal of clean, sustainable water supplies supporting human and environmental health, the issues of detection, treatment, and recovery of resources have to be addressed in an integrated manner, mindful of the industrial, agricultural and domestic sources of pollution and the downstream use of the resources recovered.

Watersheds extend across national boundaries and the hydrological cycle extends around the globe. Deforestation in one country can lead to drought in another.

Moreover, globalised trade can shift "virtual water" and "virtual pollution" over large distances as manufacturing migrates to low-income countries and unfolds its environmental impact there, often under less stringent regulatory frameworks.[7]

Failures in managing water and the environment can lead to disastrous consequences in distant places and future times.

Therefore, global water security needs strategic long-term, transnational cooperation on a level that does not exist yet.

Strategies to enhance water security must be informed by the fundamental work from all related disciplines. Chemistry, in particular, can provide not only technological know-how for detection and removal of contaminants, it can also help to understand the complex effects that contaminants are likely to exert in the environment, and to develop new ways of mitigating them.

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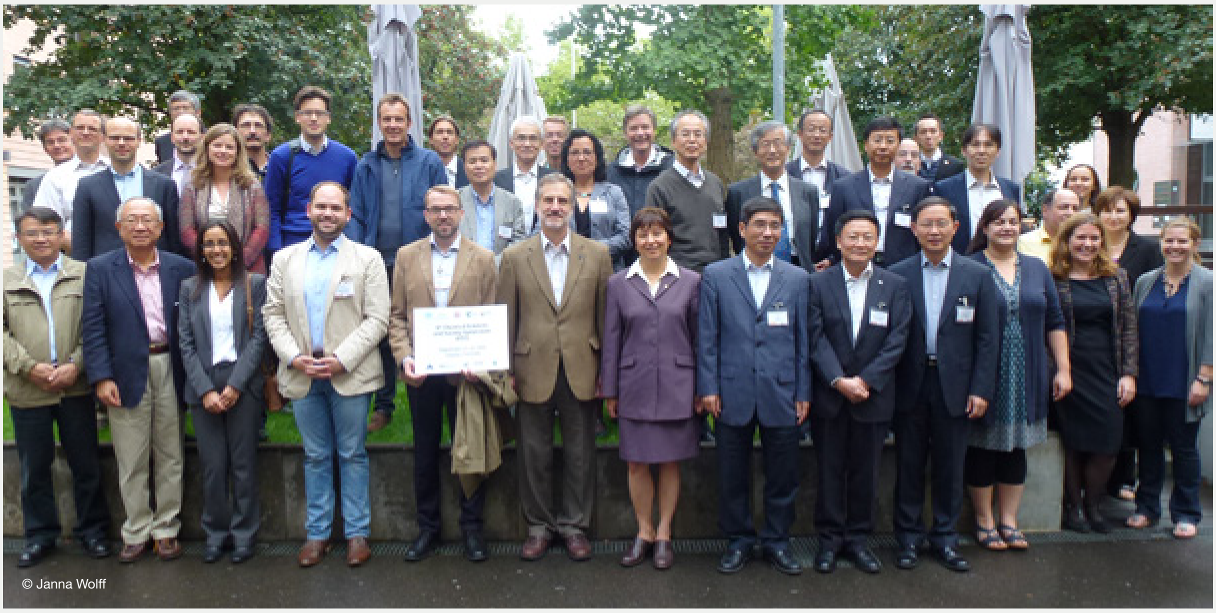
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